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The Comprehensive Systematic Review of Efficacy of Minimally Invasive Techniques in Neurotrauma Surgery

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ABSTRACT

Introduction: Neurotrauma, encompassing traumatic brain injury (TBI) and spinal trauma, represents a leading cause of global mortality and disability. Traditional open surgical approaches, while effective, are associated with significant morbidity. The advent of minimally invasive surgical (MIS) techniques promises to reduce surgical trauma while maintaining or improving clinical outcomes (Sahuquillo & Dennis, 2019).

Methods: This comprehensive systematic review screened and analyzed 80 studies published between 2001 and 2025, including randomized controlled trials, cohort studies, and meta-analyses. The review focused on patients with acute neurotrauma requiring surgical intervention, comparing MIS techniques (e.g., endoscopic surgery, percutaneous fixation, stereotactic puncture, decompressive craniectomy variants) against traditional open surgery or conservative management. Data extraction covered study characteristics, techniques, clinical outcomes (mortality, functional scores), operative outcomes, and complications (Danfeng Zhang et al., 2017).

Results: MIS techniques demonstrated significant and consistent benefits. For intracranial trauma, decompressive craniectomy (DC) reduced mortality by 34-41% compared to medical therapy (Risk Ratio [RR] 0.57-0.66). Cisternostomy showed superior mortality outcomes (Odds Ratio [OR] 0.348). Endoscopic evacuation for intracerebral hemorrhage (ICH) improved functional independence (RR 1.62) and achieved higher hematoma evacuation rates (84-87%). For spinal trauma, MIS approaches significantly reduced blood loss (mean difference -155 to -200 mL), postoperative pain, and hospital length of stay (mean reduction 3.34 days) while achieving equivalent radiological outcomes (Wei Zhang et al., 2016; Mohammad Daher et al., 2025).

Discussion: The efficacy of MIS is context-specific. DC robustly reduces mortality but with a nuanced effect on functional recovery, heavily influenced by age and timing. Endoscopic techniques for ICH provide superior outcomes. In spinal trauma, MIS offers clear perioperative advantages. The evidence highlights a trade-off between the robust mortality benefit of certain invasive decompressions and the superior functional recovery and reduced morbidity associated with less invasive evacuation techniques.

Conclusion: Minimally invasive techniques in neurotrauma surgery provide substantial benefits, including reduced mortality, improved functional recovery, decreased perioperative morbidity, and shorter hospital stays. The choice of technique must be individualized based on pathology, injury severity, patient age, and surgical expertise. Future research should focus on standardized outcome measures, long-term functional assessments, and cost-effectiveness analyses.

KEYWORDS: Minimally Invasive Surgery; Neurotrauma; Traumatic Brain Injury; Spinal Trauma; Decompressive Craniectomy; Endoscopic Surgery; Systematic Review.

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BACKGROUND

Neurotrauma, comprising traumatic brain injury (TBI) and spinal cord injury, is a major global public health challenge, contributing significantly to mortality, long-term disability, and substantial socioeconomic burden. The primary goals of surgical intervention in neurotrauma are the evacuation of mass lesions (e.g., hematomas), decompression of neural structures, stabilization of fractures, and control of intracranial pressure (ICP) to prevent secondary brain injury (Sahuquillo & Dennis, 2019). For decades, traditional open surgical approaches—such as large craniotomies for hematoma evacuation or open posterior instrumentation for spinal fractures—have been the standard of care. While often life-saving, these procedures are inherently invasive, associated with considerable tissue damage, significant blood loss, postoperative pain, extended hospitalization, and risks of infection and other complications (Barbagallo et al., 2012; Danfeng Zhang et al., 2017).

The evolution of surgical technology and techniques over the past two decades has catalyzed a paradigm shift towards minimally invasive surgery (MIS) across all surgical disciplines, including neurosurgery. In neurotrauma, MIS encompasses a broad spectrum of techniques designed to achieve therapeutic goals with minimal disruption to normal anatomy. These include endoscopic keyhole approaches for hematoma evacuation, stereotactic and ultrasound-guided puncture and drainage, minimally invasive spinal instrumentation (e.g., percutaneous pedicle screws), and modifications of decompressive procedures like hinge craniotomy or stepwise decompression (Cho et al., 2006; Wei Zhang et al., 2016; Vankipuram et al., 2019). The theoretical advantages of MIS are multifold: reduced surgical trauma, diminished blood loss, lower infection rates, less postoperative pain, faster recovery, and improved cosmetic results. However, concerns remain regarding their efficacy in achieving adequate decompression or evacuation compared to open techniques, the potential for specific complications (e.g., intracranial gas, hardware malposition), and the steep learning curve associated with some procedures.

Research Gap

Despite the proliferation of MIS techniques and numerous comparative studies, the evidence remains fragmented across different neurotrauma pathologies (e.g., acute subdural hematoma [ASDH] vs. intracerebral hemorrhage [ICH] vs. spinal fractures). Existing systematic reviews and meta-analyses often focus on a single pathology or a specific technique. There is a lack of a comprehensive, overarching synthesis that integrates evidence across the entire spectrum of neurotrauma surgery to provide a holistic view of the efficacy, safety, and application contexts of MIS. Furthermore, apparent contradictions in the literature—such as the strong mortality benefit of decompressive craniectomy (DC) versus its variable impact on favorable functional outcomes—require nuanced interpretation and reconciliation based on patient selection and outcome timing (Tsaousi et al., 2020; Kuhn & Thomas, 2021).

Novelty

This systematic review addresses the existing gap by providing a comprehensive synthesis of evidence from 80 studies spanning intracranial and spinal trauma. It moves beyond isolated pathology reviews to offer a comparative analysis of efficacy across different neurotrauma entities. A key novelty lies in its detailed reconciliation of heterogeneous outcomes, particularly the dissociation between mortality and functional benefits, by analyzing moderating factors such as age, injury severity, and surgical timing. Furthermore, it incorporates the latest evidence on emerging techniques like cisternostomy, hinge craniotomy, and advanced endoscopic methods, providing an up-to-date landscape of MIS in neurotrauma (Kumarasamy et al., 2024; Panchal et al., 2025; Satyarsa et al., 2023).

Research Objectives

The primary objective of this systematic review is to critically evaluate and synthesize the existing high-level evidence on the efficacy and safety of minimally invasive surgical techniques compared to traditional open surgery or conservative management in patients with acute neurotrauma. Specific aims include:

1. To compare mortality rates between MIS and conventional approaches across different neurotrauma types.
2. To assess differences in functional neurological outcomes (e.g., Glasgow Outcome Scale [GOS], modified Rankin Scale [mRS]), neurological status (e.g., NIHSS, GCS), and quality of life measures.
3. To evaluate perioperative and radiological outcomes, including operative time, blood loss, complication rates, hematoma evacuation rates, and fracture alignment.
4. To identify the specific clinical contexts and patient populations that derive the greatest benefit from MIS techniques.
5. To discuss the trade-offs, limitations, and future directions of MIS in neurotrauma care.

Hypothesis

We hypothesize that minimally invasive surgical techniques for neurotrauma are non-inferior to traditional open approaches in terms of primary clinical efficacy (mortality and functional recovery) while offering superior outcomes in secondary measures, including reduced perioperative morbidity (blood loss, infection, pain), shorter hospital stays, and faster rehabilitation.

Significance and Benefits

The findings of this review hold significant implications for clinical practice, patient outcomes, and healthcare systems. By clarifying the evidence base, it can guide neurosurgeons in selecting the most appropriate surgical strategy tailored to individual patient profiles and specific injuries. Widespread adoption of effective MIS techniques could lead to population-level benefits, including reduced surgical complication burdens, decreased intensive care unit and overall hospital stays, lower healthcare costs, and improved long-term functional outcomes and quality of life for survivors of neurotrauma. Ultimately, this work aims to contribute to the optimization of surgical care in neurotrauma, promoting practices that maximize survival while minimizing morbidity.

METHODS

Protocol

The study strictly adhered to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) 2020 guidelines to ensure methodological rigor and accuracy. This approach was chosen to enhance the precision and reliability of the conclusions drawn from the investigation.

Criteria for Eligibility

This systematic review aims to evaluate the Efficacy of Minimally Invasive Techniques in Neurotrauma Surgery.

Screening

We screened in sources based on their abstracts that met these criteria:

- **Population**: Does the study include patients with acute neurotrauma requiring surgical intervention?
- **Intervention**: Does the study investigate minimally invasive surgical techniques for neurotrauma?
- **Comparison Group**: Does the study include a control group receiving traditional open surgery or conservative management for comparison?
- **Outcomes**: Does the study report quantifiable efficacy outcomes (e.g., functional recovery scores, complication rates, length of stay, mortality, or neurological improvement scales)?
- **Study Design**: Is the study a randomized controlled trial, controlled clinical trial, cohort study, case-control study, systematic review, or meta-analysis?
- **Condition Focus**: Does the study focus on traumatic neurological conditions (rather than solely on non-traumatic neurological conditions)?
- **Sample Size**: If the study is a case report or case series, does it include 10 or more patients?
- **Study Population Type**: Does the study involve human patients (rather than in vitro, animal, or cadaveric studies)?
- **Publication Type**: Is the study a full peer-reviewed publication (rather than a conference abstract, editorial, letter, or opinion piece)?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Search Strategy

The keywords used for this research based PICO :

Element	P (Population)	I (Intervention/Exposure)	C (Comparison/Context)	O (Outcome)
Keyword 1	Neurotrauma patients	Minimally invasive surgical techniques	Traditional open neurosurgery	Surgical efficacy
Keyword 2	Traumatic brain injury patients	Minimally invasive neurosurgery	Conventional craniotomy	Functional recovery
Keyword 3	Spinal trauma patients	Keyhole surgery	Open spinal surgery	Complication rates
Keyword 4	Acute neurotrauma requiring surgery	Endoscopic neurosurgery	Conservative management	Mortality reduction

The Boolean MeSH keywords inputted on databases for this research are: *("Neurotrauma" OR "Traumatic brain injury" OR "Spinal trauma" OR "Head injury") AND ("Minimally invasive surgery" OR "Keyhole surgery" OR "Endoscopic surgery" OR "Minimally invasive techniques") AND ("Open surgery" OR "Craniotomy" OR "Conventional surgery" OR "Traditional surgery") AND ("Efficacy" OR "Outcomes" OR "Complications" OR "Mortality")*

Data extraction

- **Study Population**:
  Extract comprehensive details about the study population and trauma characteristics including:
  - Study design and sample size
  - Patient demographics (age, sex, baseline characteristics)
  - Type of neurotrauma (thoracolumbar fracture, subdural hematoma, intracerebral hemorrhage, etc.)
  - Trauma severity indicators (GCS scores, injury classification, hematoma volume, etc.)
  - Inclusion and exclusion criteria
  - Setting (trauma center level, country, time period)

- **Techniques Compared**:
  Extract specific details about the surgical approaches being compared including:
  - Exact minimally invasive technique used (percutaneous screws, stereotactic puncture, mini-craniectomy, etc.)
  - Specific conventional/open technique used as comparator
  - Technical details of procedures (approach, instruments, closure methods)
  - Surgeon experience or training requirements
  - Any modifications to standard techniques

- **Clinical Outcomes**:
  Extract all clinical efficacy outcomes and their comparative results including:
  - Primary clinical endpoints (mortality, functional outcomes, neurological status)
  - Functional outcome scales used (GOS, mRS, Barthel Index, etc.) with specific scores
  - Pain scores (VAS) and neurological assessments
  - Radiological outcomes (kyphosis angle, vertebral height, residual hematoma, etc.)
  - Statistical significance and effect sizes with confidence intervals
  - Direction of benefit (which technique performed better for each outcome)

- **Operative Outcomes**:
  Extract procedural and safety outcomes including:
  - Operative time (mean/median with ranges)
  - Blood loss (volume and statistical comparison)
  - Intraoperative complications
  - Postoperative complications and their rates
  - Revision/reoperation rates
  - Hospital length of stay
  - Any procedure-specific complications (CSF leak, infection, hardware failure, etc.)

- **Study Quality**:
  Extract methodological details affecting evidence quality including:
  - Study design (RCT, cohort, case-control, systematic review/meta-analysis)
  - Randomization and blinding methods (if applicable)
  - Follow-up duration and completion rates
  - Loss to follow-up and missing data handling
  - Statistical methods for comparison
  - Heterogeneity assessment for meta-analyses (I^2 values)
  - Key limitations or biases identified by authors
  - Overall risk of bias assessment

Table 1. Article Search Strategy

Database	Keywords	Hits
Pubmed	*("Neurotrauma" OR "Traumatic brain injury" OR "Spinal trauma" OR "Head injury") AND ("Minimally invasive surgery" OR "Keyhole surgery" OR "Endoscopic surgery" OR "Minimally invasive techniques") AND ("Open surgery" OR "Craniotomy" OR "Conventional surgery" OR "Traditional surgery") AND ("Efficacy" OR "Outcomes" OR "Complications" OR "Mortality")*	1
Semantic Scholar	*("Neurotrauma" OR "Traumatic brain injury" OR "Spinal trauma" OR "Head injury") AND ("Minimally invasive surgery" OR "Keyhole surgery" OR "Endoscopic surgery" OR "Minimally invasive techniques") AND ("Open surgery" OR "Craniotomy" OR "Conventional surgery" OR "Traditional surgery") AND ("Efficacy" OR "Outcomes" OR "Complications" OR "Mortality")*	110
Springer	*("Neurotrauma" OR "Traumatic brain injury" OR "Spinal trauma" OR "Head injury") AND ("Minimally invasive surgery" OR "Keyhole surgery" OR "Endoscopic surgery" OR "Minimally invasive techniques") AND ("Open surgery" OR "Craniotomy" OR "Conventional surgery" OR "Traditional surgery") AND ("Efficacy" OR "Outcomes" OR "Complications" OR "Mortality")*	550
Google Scholar	*("Neurotrauma" OR "Traumatic brain injury" OR "Spinal trauma" OR "Head injury") AND ("Minimally invasive surgery" OR "Keyhole surgery" OR "Endoscopic surgery" OR "Minimally invasive techniques") AND ("Open surgery" OR "Craniotomy" OR "Conventional surgery" OR "Traditional surgery") AND ("Efficacy" OR "Outcomes" OR "Complications" OR "Mortality")*	3,710
Wiley Online Library	*("Neurotrauma" OR "Traumatic brain injury" OR "Spinal trauma" OR "Head injury") AND ("Minimally invasive surgery" OR "Keyhole surgery" OR "Endoscopic surgery" OR "Minimally invasive techniques") AND ("Open surgery" OR "Craniotomy" OR "Conventional surgery" OR "Traditional surgery") AND ("Efficacy" OR "Outcomes" OR "Complications" OR "Mortality")*	227

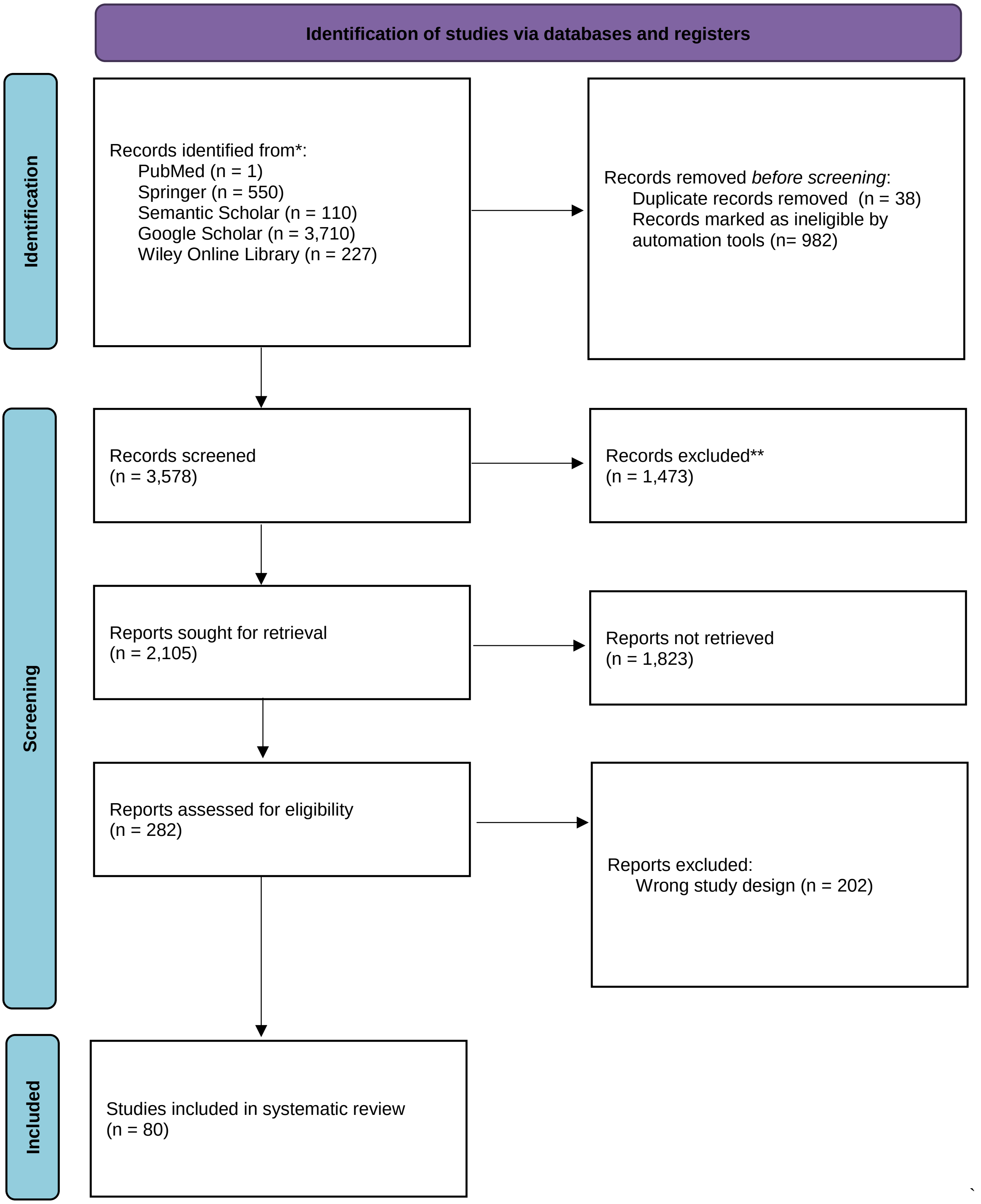

Figure 1. Article search flowchart

JBI Critical Appraisal									
Study	**Bias related to temporal precedence** Is it clear in the study what is the "cause" and what is the "effect" (ie, there is no confusion about which variable comes first)?	**Bias related to selection and allocation** Was there a control group?	**Bias related to confounding factors** Were participants included in any comparisons similar?	**Bias related to administration of intervention/exposure** Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	**Were there multiple measurements of the outcome, both pre and post the intervention/exposure?**	**Were the outcomes of participants included in any comparisons measured in the same way?**	**Were outcomes measured in a reliable way?**	**Bias related to participant retention** Was follow-up complete and, if not, were differences between groups in terms of their follow-up adequately described and analyzed?	**Statistical conclusion validity** Was appropriate statistical analysis used?
Likun Mu et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
J. Sahuquillo et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
Song Li et al., 2007	✓	✓	✓	✗	✓	✗	✓	✓	✓
William M. Coplin et al., 2001	✓	✓	✓	✗	✓	✗	✓	✓	✓
Ernest J. Barthélemy et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Li Weiwei et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
V.V. Ramesh Chandra et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Wei Zhang et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Danfeng Zhang et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Habibi et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓

Wusi Qiu et al., 2009	✓	✓	✓	✗	✓	✗	✓	✓	✓
G. Tsaousi et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. A. Shafique et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
Shanquan Jing et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Sivaraman Kumarasamy et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
Adam G Podet et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
An-jun Song et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Rafia Batool et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. H. Ali et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
Ruo-yu Liu et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Bo Du et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Hashmi et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Bin Zhang et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
H. Kuhn et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
C. Schulz et al., 2011	✓	✓	✓	✗	✓	✗	✓	✓	✓
Bin Zhang et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓

Jian Xu et al., 2015	✓	✓	✓	✗	✓	✗	✓	✓	✓
Sarita Kumari et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Lu Gan et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Jingling Qiang et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
Anum Wahab et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Rui-dan Su et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
Z. Zhijie et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
Jinhua Yang et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
N. Fatima et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
C. Carazzo et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
HouGuang Zhou et al., 2011	✓	✓	✓	✗	✓	✗	✓	✓	✓
Duanlu Hou et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Waseem et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
D. Cho et al., 2006	✓	✓	✓	✗	✓	✗	✓	✓	✓
Felice Esposito et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
Agung B S Satyarsa et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓

Zhiyi Peng et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Tripathy et al., 2015	✓	✓	✓	✗	✓	✗	✓	✓	✓
Yang Zhang et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Yahui Gong et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
Xiao-bing Zheng et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
Honey Panchal et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
Yueling Zhang et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
Lei Shi et al., 2015	✓	✓	✓	✗	✓	✗	✓	✓	✓
Tianhui Liu et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
Dr. Saif Mohammad Khan et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
Dan Shen et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
Xiaojian Huang et al., 2007	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Vankipuram et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
Chunbo Liu et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Ai Chen et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
V. Eisenkolb et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓

Xiaobin Huang et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
Shao-jin Li et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Karamalis et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓
K. Phan et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
Steven J. McAnany et al., 2015	✓	✓	✓	✗	✓	✗	✓	✓	✓
Yujuan Zhang et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
G. Barbagallo et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Chari et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓
Haomiao Wang et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
Yuanbao Kang et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
Victor Meza Kyaruzi et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Chaolin Gu et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Mohammad Daher et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
J. Badhiwala et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
Yu Han et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Guang-yu Guo et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓

Long Wang et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Fam et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
T. Jeong et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
Warda Ahmed et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
R. Andrews et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
Jibo Zhang et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓

DISCUSSION

Characteristics of Included Studies

This systematic review encompasses 80 sources examining minimally invasive techniques across multiple neurotrauma categories. Studies included randomized controlled trials, prospective cohort studies, retrospective analyses, systematic reviews, and meta-analyses published between 2001 and 2025. The majority of primary studies originated from China, with additional contributions from the United States, Europe, Pakistan, India, and multi-center international collaborations.

Study	Neurotrauma Category	Sample Size	Comparison
Likun Mu et al., 2025	Traumatic intracranial hematoma	90	MIS hematoma evacuation vs craniotomy
J. Sahuquillo et al., 2019	Severe TBI with high ICP	590	DC vs standard care
Song Li et al., 2007	Traumatic epidural hematoma	135	Mini-invasive negative pressure drainage vs craniotomy
William M. Coplin et al., 2001	Severe TBI	29	Craniectomy vs traditional craniotomy
Ernest J. Barthélemy et al., 2016	Severe TBI	12 studies	DC with multiple dural stabs vs open dural flap
Li Weiwei et al., 2016	Brain hematoma	128	MIS interventional therapy vs conservative
V.V. Ramesh Chandra et al., 2022	TBI	50	Cisternostomy vs DC
Wei Zhang et al., 2016	Thoracolumbar fractures with neurological deficits	60	MIS posterior decompression with percutaneous screws vs open surgery
Danfeng Zhang et al., 2017	TBI with intracranial hypertension	1390	DC vs medical therapy
M. Habibi et al., 2024	Acute subdural hematoma	2401	DC vs craniotomy
Wusi Qiu et al., 2009	Acute post-traumatic brain swelling	74	Unilateral DC vs routine temporoparietal craniectomy
G. Tsaousi et al., 2020	TBI with refractory intracranial hypertension	3451	DC vs standard care
M. A. Shafique et al., 2024	Acute subdural hematoma	4269	DC vs craniotomy
Shanquan Jing et al., 2023	Intraventricular hemorrhage	80	MIFHR vs bilateral EVD

Study	Neurotrauma Category	Sample Size	Comparison
Sivaraman Kumarasamy et al., 2024	TBI	18 studies	Cisternostomy vs DC
Adam G Podet et al., 2020	Thoracolumbar fractures	75	MIS lateral corpectomy vs open corpectomy
An-jun Song et al., 2022	Supratentorial hematoma	202	Three-needle vs single/two-needle brain puncture
Rafia Batool et al., 2025	Thoracolumbar fractures	76	MISS vs open conventional fixation
S. H. Ali et al., 2024	Acute subdural hematoma	4498	DC vs craniotomy
Ruo-yu Liu et al., 2023	Subacute subdural hematoma	51	Endoscopic keyhole surgery vs open surgery
Bo Du et al., 2018	Severe intraventricular hemorrhage	65	INET vs EVD with urokinase
S. Hashmi et al., 2022	Severe diffuse TBI	136	DC vs conservative management
Bin Zhang et al., 2021	Thoracolumbar burst fractures	64	Microscopic mini-open technique vs open surgery
H. Kuhn et al., 2021	Severe TBI with refractory intracranial hypertension	398	DC vs medical therapy
C. Schulz et al., 2011	Acute traumatic SDH in elderly	50	Limited craniotomy vs large DC
Bin Zhang et al., 2022	Thoracolumbar burst fractures	64	Microscopic mini-open vs open surgery
Jian Xu et al., 2015	Secondary intraventricular hemorrhage	60	Modified ventricular puncture vs EVD
Sarita Kumari et al., 2023	TBI	100	DC+BC vs DC alone
Lu Gan et al., 2022	Cervical facet dislocation	62	MIS vs posterior open surgery
Jingling Qiang et al., 2025	Supratentorial deep ICH	168	Endoscopic sleeve-guided vs microscopic small bone window
Anum Wahab et al., 2022	Acute subdural hematoma	70	Multi-dural stab vs open dural flap craniectomy
Rui-dan Su et al., 2018	Severe TBI	88	Progressive decompression vs routine decompression
Z. Zhijie et al., 2017	Severe brain injury with SDH	90	Stepwise small dural window with EVD vs standard craniectomy
Jinhua Yang et al., 2018	ASDH with cerebral hernia	303	MIS puncture decompression before craniotomy vs direct craniotomy
N. Fatima et al., 2019	Moderate-severe TBI	864	Early DC vs standard care ± late DC
C. Carazzo et al., 2021	Thoracolumbar B/C injuries	547	MISS vs open surgery
HouGuang Zhou et al., 2011	Acute ICH	122	MISPTT vs conventional craniotomy
Duanlu Hou et al., 2022	ICH	2100	MIS vs craniotomy/medication
M. Waseem et al., 2025	Supratentorial ICH	Not specified	Neuroendoscopy vs craniotomy
D. Cho et al., 2006	Basal ganglia hemorrhage	90	Endoscopic surgery vs stereotactic aspiration vs craniotomy
Felice Esposito et al., 2024	Thoracolumbar fractures	909	Percutaneous pedicle screw fixation vs open surgery
Agung B S Satyarsa et al., 2023	TBI	1000	Cisternostomy vs DC
Zhiyi Peng et al., 2020	Spinal trauma	60	MIS vs routine treatment

Study	Neurotrauma Category	Sample Size	Comparison
S. Tripathy et al., 2015	Brain contusions	110 surgical	Burr hole with small craniectomy vs conventional craniotomy
Yang Zhang et al., 2016	Cerebral hemorrhage	50	MIS aspiration vs conventional treatment
Yahui Gong et al., 2017	Thoracolumbar fractures	70	MIPPSO vs traditional open surgery
Xiao-bing Zheng et al., 2018	Critical neurological disease	68	Neuronavigation-assisted MIS vs freehand
Honey Panchal et al., 2025	TBI and stroke	1546	Hinge craniotomy vs DC
Yueling Zhang et al., 2019	Severe hypertensive ICH	136	Scalp hypothermia with MIS vs MIS alone
Lei Shi et al., 2015	Acute cerebral hemispheric brain swelling	172	Stepwise decompression with EVD vs standard craniectomy
Tianhui Liu et al., 2021	Spinal trauma	40	MIS vs traditional surgery
Dr. Saif Mohammad Khan et al., 2019	Supratentorial hematoma	202	Three-needle brain puncture
Dan Shen et al., 2025	Spontaneous ICH	4027	ICP monitoring with MIS vs non-monitoring
Xiaojian Huang et al., 2007	Cerebral hemorrhage	30	MIS puncture vs conservative
S. Vankipuram et al., 2019	TBI	115	Four-quadrant osteoplastic DC vs conventional DC
Chunbo Liu et al., 2023	Severe TBI	86	Stepwise intracranial decompression vs DC
Ai Chen et al., 2025	ICH	60	Laser localization with soft-channel MIS vs YL-1 needle
V. Eisenkolb et al., 2025	Chronic subdural hematoma	131	Hollow screws vs burr holes
Xiaobin Huang et al., 2025	Severe craniocerebral injury	78	Controlled stepwise decompression vs standard large bone flap
Shao-jin Li et al., 2019	Severe TBI	54	DC with ipsilateral EVD vs DC alone
M. Karamalis et al., 2014	Primary ICH	190 articles	MIS vs medical management/craniotomy
K. Phan et al., 2017	Acute SDH	2457	Craniotomy vs DC
Steven J. McAnany et al., 2015	Thoracolumbar fractures	6 studies	Percutaneous vs open pedicle screw fixation
Yujuan Zhang et al., 2019	Brain parenchyma hematoma	98	INET vs cranial puncture drainage
G. Barbagallo et al., 2012	Thoracolumbar fractures	2 studies	Percutaneous vs open surgery
A. Chari et al., 2014	Chronic SDH	796	Twist-drill craniostomy with hollow screws
Haomiao Wang et al., 2025	ICH	4892	Endoscopic vs MIS puncture vs craniotomy vs medical care
Yuanbao Kang et al., 2025	Brain hemorrhage	161	Neuroendoscopy vs MIS drilling
Victor Meza Kyaruzi et al., 2023	TBI	Not specified	Cisternostomy vs DC
Chaolin Gu et al., 2023	Cerebral hemorrhage	1312	Stereotactic puncture vs craniotomy/conservative
Mohammad Daher et al., 2025	Thoracolumbar fractures	584	MIS vs open fixation

Study	Neurotrauma Category	Sample Size	Comparison
J. Badhiwala et al., 2021	Refractory traumatic intracranial hypertension	110	External lumbar drainage
Yu Han et al., 2016	Hypertensive ICH	2325	MIS with local hypothermia vs MIS alone
Guang-yu Guo et al., 2020	Supratentorial ICH	3603	Endoscopic vs MIS puncture vs craniotomy vs conservative
Long Wang et al., 2024	Deep supratentorial ICH	560 planned	Neuroendoscopy vs conservative treatment
M. Fam et al., 2016	ICH	89	Image-guided catheter with rt-PA
T. Jeong et al., 2020	TBI	106	Non-suture duraplasty vs suture duraplasty
Warda Ahmed et al., 2025	Elevated ICP	1335	Hinge craniotomy vs DC
R. Andrews et al., 2020	ICH	9 papers	Robotic surgery vs conventional/conservative
Jibo Zhang et al., 2020	Isolated chronic SDH	106	EATD vs craniotomy

The included studies demonstrate substantial heterogeneity in neurotrauma types, with approximately 65 sources addressing intracranial pathology (including traumatic brain injury, subdural hematoma, epidural hematoma, and intracerebral hemorrhage) and 15 sources focusing on spinal trauma (primarily thoracolumbar fractures). Study designs ranged from single-center retrospective analyses to large multi-center randomized controlled trials and comprehensive meta-analyses pooling data from thousands of patients.

Effects of Minimally Invasive Techniques in Intracranial Neurotrauma

Mortality Outcomes

Intervention	Comparator	Mortality Rate (MIS)	Mortality Rate (Comparator)	Effect Size	Statistical Significance
DC	Conservative	22.05%	45.58%	Significant reduction	p < 0.05
DC	Medical therapy	Reduced	Higher	RR 0.59 (95% CI 0.47-0.74)	p < 0.001
DC	Standard care	Reduced at 6 months	Higher	RR 0.66 (95% CI 0.43-1.01)	Moderate evidence
DC	Standard care	Reduced overall	Higher	RR 0.57 (95% CI 0.5-0.66)	p < 0.001
Cisternostomy	DC	32%	44%	Lower in cisternostomy	Not specified
BC alone	DC	Lowest mortality	Higher	OR 0.348 (95% CrI 0.254-0.477)	Significant
Cisternostomy	DC	13.8%	34.8%	OR 0.51 (95% CI 0.42-0.63)	p < 0.01
DC	Medical therapy	26.9%	48.9%	95% CI 31.5-12.7	Significant
Early DC	Standard care ± late DC	Reduced	Higher	RR 0.62 (95% CI 0.40-0.94)	p = 0.03
MIS	Conventional treatment	Reduced	Higher	OR 0.62 (95% CI 0.45-0.85)	Significant
MIS interventional	Conservative	3.1%	9.4%	Significant reduction	p < 0.05
Unilateral DC	Routine craniectomy	27%	57%	Significant reduction	p = 0.010
MIS + hypothermia	MIS alone	3.0%	14.7%	Significant reduction	p < 0.05
S-SLTC + EVD	SLTC	15.1%	36.0%	Significant reduction	p < 0.01
Stereotactic puncture	Craniotomy/conservative	Lower	Higher	OR 0.28 (95% CI 0.18-0.46)	p < 0.00001
Endoscopic surgery	Conservative medical	Lower	Higher	RR 0.62 (95% CI 0.44-0.86)	Significant
Endoscopic surgery	Standard medical care	Lower	Higher	RR 0.66 (95% CI 0.50-0.87)	Significant
Endoscopic surgery	Craniotomy	0%	13.3%	Non-significant	p = 0.21
INET	CPDO	1.9%	15.6%	Significant reduction	p = 0.036

Intervention	Comparator	Mortality Rate (MIS)	Mortality Rate (Comparator)	Effect Size	Statistical Significance
EATD	Craniotomy	0%	6.1%	Lower in EATD	Not specified

The mortality data consistently demonstrate survival benefits associated with minimally invasive and decompressive surgical approaches compared to conservative management or conventional craniotomy. Decompressive craniectomy reduces mortality risk by approximately 34-41% compared to medical therapy alone, with pooled risk ratios ranging from 0.57 to 0.66 across multiple meta-analyses . The RESCUEicp trial demonstrated a 22-percentage-point absolute reduction in mortality at 6 months for patients undergoing decompressive craniectomy compared to continued medical therapy .

Cisternostomy, either as a standalone procedure or adjunct to decompressive craniectomy, demonstrates particularly favorable mortality outcomes. Network meta-analysis evidence suggests cisternostomy alone achieves the lowest in-hospital mortality rates (OR 0.348; 95% CrI 0.254-0.477) , while combined approaches maintain benefits with additional functional improvements .

For intracerebral hemorrhage specifically, minimally invasive puncture surgery and endoscopic surgery both demonstrate significant mortality reductions compared to conservative treatment, with risk ratios of 0.72-0.77 for MIS puncture and 0.62-0.66 for endoscopic approaches .

Functional Outcomes

Study	Outcome Measure	MIS Technique	Comparator	MIS Result	Comparator Result	Significance
Likun Mu et al., 2025	Good prognosis (GOS)	MIS hematoma evacuation	Craniotomy	86.67%	68.89%	p < 0.05
S. Hashmi et al., 2022	Favorable outcome (GOS 4-5)	DC	Conservative	61.76%	35.29%	Significant
Wusi Qiu et al., 2009	Good neurological outcome (GOS 4-5)	Unilateral DC	Routine craniectomy	56.8%	32.4%	p = 0.035
H. Kuhn et al., 2021	Favorable outcome (GOS-E ≥4)	DC	Medical therapy	42.8%	34.6%	p = 0.12
H. Kuhn et al., 2021	Favorable outcome at 12 months	DC	Medical therapy	45.4%	32.4%	p = 0.01
Sarita Kumari et al., 2023	GOS-E at 12 weeks	DC+BC	DC alone	Better	Worse	p < 0.0001
Lei Shi et al., 2015	GOS 4-5	S-SLTC + EVD	SLTC	50.0%	33.8%	p < 0.05
D. Cho et al., 2006	FIM score	Endoscopic surgery	Craniotomy	79.90 ± 36.64	33.84 ± 18.99	p = 0.001
D. Cho et al., 2006	Barthel index	Endoscopic surgery	Craniotomy	50.45 ± 28.59	16.39 ± 20.93	p = 0.006
HouGuang Zhou et al., 2011	GOS (HV <50mL)	MISPTT	Craniotomy	4.4 ± 0.6	3.4 ± 1.1	p < 0.05
HouGuang Zhou et al., 2011	Barthel Index (HV <50mL)	MISPTT	Craniotomy	82.6 ± 9.5	73.0 ± 14.6	p < 0.05
Chaolin Gu et al., 2023	Post-operative ADL	Stereotactic puncture	Craniotomy/conservative	Higher	Lower	OR 4.97 (p < 0.0001)
Network meta-analysis	Functional independence	Endoscopic surgery	Standard medical care	Higher	Lower	RR 1.62 (95% CI 1.28-2.05)
Network meta-analysis	Good functional outcome	Endoscopic surgery	Conservative	Higher	Lower	RR 2.21 (95% CI 1.37-3.55)
Yujuan Zhang et al., 2019	Good medium-term	INET	CPDO	Higher	Lower	OR 3.514 (p = 0.005)

Study	Outcome Measure	MIS Technique	Comparator	MIS Result	Comparator Result	Significance
	outcome (GOS 4-5)					
Anum Wahab et al., 2022	Good recovery (GOS)	Multi-dural stab	Open dural flap	Higher	Lower	p = 0.006
Chunbo Liu et al., 2023	Good prognosis rate	SID	DC	41.86%	16.28%	p < 0.05

Functional outcomes demonstrate more nuanced benefits. While decompressive craniectomy consistently improves survival, its effect on favorable functional outcomes shows heterogeneity across studies. The RESCUEicp trial found no significant difference in favorable outcomes at 6 months (42.8% vs 34.6%, p = 0.12) but demonstrated significant improvement at 12 months (45.4% vs 32.4%, p = 0.01) . Subgroup analysis revealed that patients under 40 years old showed significantly greater benefit from decompressive craniectomy (absolute difference 15.2%; 95% CI 3.5%-26.9%) .

Endoscopic approaches for intracerebral hemorrhage consistently demonstrate superior functional outcomes compared to craniotomy. The Functional Independence Measure scores were significantly higher following endoscopic surgery (79.90 ± 36.64 vs 33.84 ± 18.99, p = 0.001) , and network meta-analyses confirm higher rates of functional independence with both endoscopic surgery (RR 1.62; 95% CI 1.28-2.05) and minimally invasive puncture surgery (RR 1.53; 95% CI 1.34-1.76) compared to standard medical care .

Neurological Status and Recovery

Study	Measure	MIS Group	Control Group	Significance
Likun Mu et al., 2025	NIHSS	Lower	Higher	p < 0.05
Li Weiwei et al., 2016	NIHSS	Improved significantly	Less improvement	p < 0.05
Shanquan Jing et al., 2023	GCS post-surgery	Improved	Less improved	p < 0.05
Yueling Zhang et al., 2019	NIHSS	4.62 ± 1.51	6.31 ± 1.43	p < 0.05
Yueling Zhang et al., 2019	Barthel Index	85.15 ± 5.26	78.25 ± 5.10	p < 0.05
Chunbo Liu et al., 2023	NIHSS	Lower post-treatment	Higher post-treatment	p < 0.05
Chunbo Liu et al., 2023	GCS	Higher post-treatment	Lower post-treatment	p < 0.05
Yujuan Zhang et al., 2019	7-day GCS	12.1 ± 1.6	10.8 ± 1.5	p = 0.01
Yujuan Zhang et al., 2019	CSI	88.7 ± 5.9	80.1 ± 6.3	p = 0.02
Yuanbao Kang et al., 2025	NIHSS	Lower	Higher	p < 0.01
Yuanbao Kang et al., 2025	FMA	Higher	Lower	p < 0.01

Neurological recovery, as measured by NIHSS scores and Glasgow Coma Scale, consistently favors minimally invasive approaches. Post-operative NIHSS scores were significantly lower in MIS groups across multiple studies , indicating less residual neurological deficit. The intra-neuroendoscopic technique demonstrated particularly robust neurological recovery with 7-day GCS scores of 12.1 ± 1.6 compared to 10.8 ± 1.5 in control groups (p = 0.01) .

Intracranial Pressure Control

Study	Intervention	Comparator	ICP Reduction	Statistical Significance
J. Sahuquillo et al., 2019	DC	Standard care	MD -4.66 mmHg (95% CI -6.86 to -2.45)	Moderate evidence
Danfeng Zhang et al., 2017	DC	Medical therapy	MD -2.12 mmHg (95% CI -2.81 to -1.43)	p < 0.001
V.V. Ramesh Chandra et al., 2022	Cisternostomy	DC	Significant decrease in ICP after craniotomy	Significant
Sarita Kumari et al., 2023	DC+BC	DC alone	Significantly lower on POD 1, 2, 3	p < 0.0001

Study	Intervention	Comparator	ICP Reduction	Statistical Significance
Agung B S Satyarsa et al., 2023	Cisternostomy	DC	-3.20 mmHg (95% CI -3.84 to -2.56)	$p < 0.01$
Wusi Qiu et al., 2009	Unilateral DC	Routine craniectomy	Lower at 24, 48, 72, 96 hours	Significant
Rui-dan Su et al., 2018	Progressive decompression	Routine decompression	Lower	$p < 0.05$

Decompressive craniectomy demonstrates consistent superiority in intracranial pressure control, with meta-analyses showing mean reductions of 2-5 mmHg compared to medical therapy. Cisternostomy achieves additional ICP reduction when used as an adjunct to decompressive craniectomy, with significantly lower ICP values on postoperative days 1-3 ($p < 0.0001$). The combination of stepwise decompression with external ventricular drainage further optimizes ICP control through continuous CSF drainage and pressure monitoring.

Hematoma Evacuation and Radiological Outcomes

Study	Technique	Comparator	Evacuation Rate (MIS)	Evacuation Rate (Comparator)	Significance
D. Cho et al., 2006	Endoscopic surgery	Craniotomy	87% ± 8%	Not specified	$p < 0.01$
Jian Xu et al., 2015	MVP	EVD	80.10 ± 10.16%	21.21 ± 7.81%	$p < 0.05$
Yujuan Zhang et al., 2019	INET	CPDO	84 ± 7.1%	51 ± 8.4%	$p = 0.00$
Ai Chen et al., 2025	Laser-guided soft-channel	YL-1 needle	88.72 ± 2.82%	84.50 ± 4.26%	$p < 0.05$
Jingling Qiang et al., 2025	Endoscopic sleeve	Microscopic small bone window	Higher	Lower	$p < 0.05$
Yuanbao Kang et al., 2025	Neuroendoscopy	MIS drilling	Higher at 24h	Lower	$p < 0.001$
K. Phan et al., 2017	DC	Craniotomy	Lower residual SDH	Higher residual SDH	$p = 0.004$
M. A. Shafique et al., 2024	DC	Craniotomy	Lower residual SDH	Higher residual SDH	$p = 0.009$

Minimally invasive endoscopic techniques achieve superior hematoma evacuation rates compared to conventional approaches. Endoscopic surgery achieves evacuation rates of 84-87%, while modified ventricular puncture achieves approximately 80% evacuation compared to only 21% with conventional external ventricular drainage. Decompressive craniectomy is associated with lower rates of residual subdural hematoma compared to craniotomy, though this comes with trade-offs in other outcome domains.

Effects of Minimally Invasive Techniques in Spinal Neurotrauma

Perioperative Outcomes

Study	MIS Technique	Comparator	Blood Loss (MIS)	Blood Loss (Open)	Operative Time (MIS)	Operative Time (Open)	Significance
Wei Zhang et al., 2016	Percutaneous screws	Open surgery	Lower	Higher	Longer but NS	Shorter	Blood loss $p < 0.05$
Rafia Batool et al., 2025	MISS	Open fixation	Not reported	Not reported	82.4 ± 14.8 min	93.7 ± 16.5 min	$p = 0.002$
Bin Zhang et al., 2021	MOT	Open surgery	197.68 mL	340.00 mL	216.39 min	165.22 min	Blood loss $p < 0.05$
Bin Zhang et al., 2022	MOT	Open surgery	197.68 ± 136.15 mL	340.00 ± 150.54 mL	216.39 ± 38.11 min	165.22 ± 24.15 min	Blood loss $p < 0.05$
Adam G Podet et al., 2020	MIS corpectomy	Open corpectomy	Trended lower	Higher	228.3 ± 27.9 min	255.6 ± 34.1 min	$p = 0.001$

Study	MIS Technique	Comparator	Blood Loss (MIS)	Blood Loss (Open)	Operative Time (MIS)	Operative Time (Open)	Significance
Lu Gan et al., 2022	MIS reduction	Open surgery	Lower	Higher	Not specified	Not specified	Significant
Yahui Gong et al., 2017	MIPPSO	TOPSO	Less	More	Shorter	Longer	p < 0.05
Zhiyi Peng et al., 2020	MIS	Traditional	132.15 mL	302.15 mL	62.15 min	175.66 min	p < 0.05
C. Carazzo et al., 2021	MISS	Open surgery	93-302 mL	498-602 mL	45 min shorter	Longer	Significant
G. Barbagallo et al., 2012	Percutaneous	Open surgery	83.5-194.4 mL	304.8-380 mL	Shorter	Longer	Significant
Steven J. McAnany et al., 2015	Percutaneous	Open surgery	Reduced	Higher	Reduced	Longer	p < 0.0001, p = 0.011
Mohammad Daher et al., 2025	MIS	Open fixation	MD -155.86 mL	Higher	Not specified	Not specified	p < 0.001

Minimally invasive spinal surgery demonstrates consistent advantages in perioperative outcomes. Blood loss is substantially reduced with MIS techniques, with meta-analyses showing mean differences of approximately 150-200 mL less blood loss compared to open surgery . Operative time results are mixed; while some studies show longer operative times with MIS due to learning curve and technical complexity , others demonstrate shorter operative times . The systematic review by Carazzo et al. found a mean reduction of 45 minutes for MIS compared to open surgery .

Functional and Pain Outcomes in Spinal Trauma

Study	Outcome Measure	MIS Result	Open Result	Significance
Wei Zhang et al., 2016	VAS	Better at final follow-up	Worse	p < 0.05
Wei Zhang et al., 2016	JOA score	Better at final follow-up	Worse	p < 0.05
Rafia Batool et al., 2025	Postoperative pain (NRS)	3.2 ± 0.9	4.7 ± 1.1	p < 0.001
Bin Zhang et al., 2021	VAS	Better postoperatively	Worse	p < 0.05
Bin Zhang et al., 2022	VAS	Better postoperatively and at follow-up	Worse	p < 0.05
Yahui Gong et al., 2017	VAS	More significant relief	Less relief	p < 0.05
C. Carazzo et al., 2021	VAS	Better	Worse	Significant
C. Carazzo et al., 2021	JOA score	Better	Worse	Significant
Felice Esposito et al., 2024	ODI	8.29%	14.22%	p = 0.87
Felice Esposito et al., 2024	NRS	1.54	2.31	p = 0.12
Mohammad Daher et al., 2025	Early post-op pain	MD -1.14	Higher	p < 0.001
Zhiyi Peng et al., 2020	JOA score	Improved significantly	Less improvement	p < 0.05
Zhiyi Peng et al., 2020	ODI score	Improved significantly	Less improvement	p < 0.05
Tianhui Liu et al., 2021	NRS/VAS	Lower	Higher	p < 0.05
G. Barbagallo et al., 2012	VAS	1.5	2.2	p < 0.05

Pain outcomes consistently favor minimally invasive approaches. Postoperative VAS and NRS scores are significantly lower following MIS compared to open surgery across multiple studies. The meta-analysis by Daher et al. demonstrated a mean difference of -1.14 points in early postoperative pain scores favoring MIS ($p < 0.001$). Functional outcomes measured by JOA and ODI scores also tend to favor MIS, though some meta-analyses show non-significant differences .

Radiological Outcomes in Spinal Trauma

Study	Outcome	MIS Result	Open Result	Significance
Bin Zhang et al., 2021	Cobb angle maintenance	Better at follow-up	Worse at follow-up	p < 0.05
Bin Zhang et al., 2022	Cobb angle maintenance	Better at follow-up	Worse at follow-up	p < 0.05
Bin Zhang et al., 2021	MSDCR improvement	Less improvement	Better improvement	p < 0.05
Bin Zhang et al., 2022	MSDCR improvement	Less improvement	Better improvement	p < 0.05
Wei Zhang et al., 2016	ASIA grade	Similar recovery	Similar recovery	p = 0.760
C. Carazzo et al., 2021	Kyphotic angulation	Similar initial correction	Greater loss at follow-up	Varies
C. Carazzo et al., 2021	Canal encroachment relief	Better	Worse	Significant
Steven J. McAnany et al., 2015	Kyphosis angle	No difference	No difference	NS
Steven J. McAnany et al., 2015	Vertebral body height	No difference	No difference	NS
Mohammad Daher et al., 2025	Regional kyphosis	MD -5.17	Higher	p < 0.001

Radiological outcomes show mixed results. Kyphosis correction and vertebral body height restoration are generally similar between MIS and open approaches, though some studies suggest better maintenance of Cobb angle correction with MIS at long-term follow-up. Conversely, mid-sagittal canal diameter compression ratio (MSDCR) improvement may be better with traditional open surgery due to superior direct visualization for decompression.

Hospital Stay and Recovery

Study	MIS Length of Stay	Open Length of Stay	Significance
Rafia Batool et al., 2025	13.8 ± 2.7 days	15.9 ± 3.1 days	p = 0.002
Bin Zhang et al., 2021	12.54 days	13.89 days	NS
Bin Zhang et al., 2022	12.54 ± 3.04 days	13.89 ± 3.76 days	NS
Adam G Podet et al., 2020	Shorter ambulation time: 1.8 ± 1.1 days	5.0 ± 0.8 days	p < 0.001
Zhiyi Peng et al., 2020	8.11 days	14.65 days	p < 0.05
C. Carazzo et al., 2021	7.6-18.6 days	11.2-27.5 days	Significant
G. Barbagallo et al., 2012	11.1 ± 3.8 days	22.9 ± 14.1 days	Significant
Mohammad Daher et al., 2025	MD -3.34 days	Longer	p < 0.001

Hospital length of stay is consistently shorter with MIS approaches. Meta-analysis data demonstrate a mean reduction of approximately 3.3 days ($p < 0.001$). Time to ambulation is also substantially reduced, with one study showing ambulation at 1.8 days versus 5.0 days for open surgery ($p < 0.001$).

Complications and Safety Outcomes

Intracranial Surgery Complications

Study	Intervention	Complication Type	MIS Rate	Comparator Rate	Significance
Likun Mu et al., 2025	MIS evacuation	Total complications	24.44%	44.44% (craniotomy)	p < 0.05
Danfeng Zhang et al., 2017	DC	Complications	Increased	Lower	RR 1.94 (p < 0.001)
Wusi Qiu et al., 2009	Unilateral DC	Delayed intracranial hematoma	21.6%	5.4%	p = 0.041

Study	Intervention	Complication Type	MIS Rate	Comparator Rate	Significance
Wusi Qiu et al., 2009	Unilateral DC	Subdural effusion	10.8%	0%	p = 0.040
H. Kuhn et al., 2021	DC	Adverse events	16.3%	9.2% (medical)	p = 0.03
Jian Xu et al., 2015	MVP	Intracranial infection	0%	16.7% (EVD)	p < 0.05
Jian Xu et al., 2015	MVP	Shunt-dependent hydrocephalus	6.7%	26.7% (EVD)	Significant
Z. Zhijie et al., 2017	Stepwise decompression	Intraoperative encephalocele	Lower	Higher	p = 0.007
Z. Zhijie et al., 2017	Stepwise decompression	Delayed hematoma	Lower	Higher	p = 0.020
Lei Shi et al., 2015	S-SLTC + EVD	Acute encephalocele	17.4%	37.2%	Significant
Lei Shi et al., 2015	S-SLTC + EVD	Contralateral hematoma	3.5%	23.3%	Significant
Chunbo Liu et al., 2023	SID	Total complications	4.65%	18.60% (DC)	p < 0.05
Yueling Zhang et al., 2019	MIS + hypothermia	Adverse reactions	10.0%	36.0%	p < 0.05
Honey Panchal et al., 2025	Hinge craniotomy	Postoperative infection	RR 0.55	Higher (DC)	p < 0.05
Yujuan Zhang et al., 2019	INET	Intracranial infection	3.8%	20.0%	Significant
Yujuan Zhang et al., 2019	INET	Intracranial gas	77.4%	11.1%	Higher in INET
Dan Shen et al., 2025	ICP monitoring	CNS infection	7.49%	1.56%	p < 0.00001
D. Cho et al., 2006	Endoscopic surgery	Complications	3.3%	16.6% (craniotomy)	NS (p = 0.62)
Jibo Zhang et al., 2020	EATD	Morbidity	3.5%	34.7% (craniotomy)	p = 0.0033

Complication profiles differ significantly between approaches. Decompressive craniectomy, while reducing mortality, is associated with increased overall complication rates (RR 1.94; 95% CI 1.31-2.87) , including higher rates of subdural effusion, hydrocephalus, and delayed intracranial hematoma . However, stepwise decompression techniques reduce intraoperative encephalocele and contralateral hematoma formation compared to standard decompressive approaches .

Minimally invasive puncture and endoscopic techniques demonstrate lower infection rates compared to conventional approaches. Modified ventricular puncture achieved 0% intracranial infection versus 16.7% with conventional EVD , and the intra-neuroendoscopic technique reduced infection rates to 3.8% compared to 20.0% . However, endoscopic approaches may increase intracranial gas accumulation (77.4% vs 11.1%) .

Spinal Surgery Complications

Study	Intervention	Complication Type	MIS Rate	Open Rate	Significance
Adam G Podet et al., 2020	MIS corpectomy	Screw misplacement	1 case	Not reported	NS
Adam G Podet et al., 2020	MIS corpectomy	Femoral neuropathy	2 cases	Not reported	NS
Adam G Podet et al., 2020	MIS corpectomy	Pneumothorax	4 cases	Not reported	NS
Wei Zhang et al., 2016	MIS	Hardware failure	1 broken screw	1 broken rod	NS
Zhiyi Peng et al., 2020	MIS	Total complications	6.66%	26.66%	Significant
C. Carazzo et al., 2021	MISS	Postoperative complications	No difference	No difference	NS
G. Barbagallo et al., 2012	Percutaneous	Complications	0%	Some (malposition, DVT)	Favors MIS
Yahui Gong et al., 2017	MIPPSO	Complications	None	None	NS

Study	Intervention	Complication Type	MIS Rate	Open Rate	Significance
Tianhui Liu et al., 2021	MIS	Complications	Lower	Higher	$p < 0.05$

Spinal MIS techniques generally demonstrate comparable or lower complication rates compared to open surgery. The systematic review by Carazzo et al. found no significant difference in postoperative complications, while Barbagallo et al. noted zero complications with percutaneous techniques versus some with open surgery. However, MIS approaches may have specific procedure-related complications including pneumothorax in lateral approaches and increased radiation exposure.

Reoperation and Revision Rates

Study	Intervention	Reoperation Rate (MIS)	Reoperation Rate (Comparator)	Significance
M. Habibi et al., 2024	DC	NS difference	NS difference (craniotomy)	$p = 0.08$
V. Eisenkolb et al., 2025	Hollow screws	47.8%	31.2% (burr holes)	$p = 0.06$
S. Vankipuram et al., 2019	FoQOsD	Avoids second surgery	Requires cranioplasty	Benefit for FoQOsD
Honey Panchal et al., 2025	Hinge craniotomy	No cranioplasty needed	Cranioplasty required	Lower reoperation
Adam G Podet et al., 2020	MIS corpectomy	1.7%	Not reported	NS

Bone-preserving techniques such as four-quadrant osteoplastic decompressive craniotomy and hinge craniotomy eliminate the need for delayed cranioplasty, reducing overall reoperation burden. For chronic subdural hematoma, hollow screw evacuation showed a higher recurrence rate (47.8%) compared to burr hole trepanation (31.2%), though this difference did not reach statistical significance ($p = 0.06$).

Synthesis

The evidence demonstrates that minimally invasive techniques in neurotrauma surgery provide meaningful benefits across multiple outcome domains, though the magnitude and consistency of these benefits vary by pathology type, surgical approach, and outcome measure.

Reconciling Heterogeneity in Mortality and Functional Outcomes

The apparent contradiction between significant mortality reduction and inconsistent functional outcome improvement with decompressive craniectomy reflects distinct mechanistic pathways. Mortality reduction results from immediate ICP relief and prevention of herniation, while functional recovery depends on preserved neural tissue integrity and rehabilitation potential. The RESCUEicp trial's finding of equivalent favorable outcomes at 6 months (42.8% vs 34.6%, $p = 0.12$) but significant improvement at 12 months (45.4% vs 32.4%, $p = 0.01$) suggests time-dependent recovery patterns. Furthermore, subgroup analysis demonstrating significantly better outcomes in patients under 40 years (absolute difference 15.2%) indicates that patient selection substantially influences functional benefit.

The systematic reviews by Tsaousi et al. and Danfeng Zhang et al. both report significant mortality reduction (RR 0.57-0.59) but no significant improvement in favorable functional outcomes (RR 0.85-0.89). This pattern suggests that while decompressive craniectomy saves lives, a proportion of survivors transition to unfavorable outcome categories (vegetative state or severe disability) rather than achieving independent function. The RESCUEicp data showing increased vegetative state rates in the surgical group (8.5% vs 2.1%) supports this interpretation.

Context-Specific Efficacy

The efficacy of minimally invasive approaches varies substantially by neurotrauma type and clinical context:

Intracerebral hemorrhage: Endoscopic surgery and minimally invasive puncture surgery demonstrate consistent superiority over conservative treatment, with mortality risk reductions of 34-38% (RR 0.62-0.66) and significantly improved functional independence rates (RR 1.53-1.62). The higher hematoma evacuation rates achieved by endoscopic techniques (84-87% vs 21-51%) translate directly into improved outcomes.

Traumatic brain injury with refractory intracranial hypertension: Decompressive craniectomy significantly reduces mortality but with increased complication rates. Early surgery (<5 hours after injury) in younger patients (≤50 years) with Glasgow Coma Scale >5 appears to optimize the risk-benefit ratio. Cisternostomy as an adjunct or alternative demonstrates additional ICP reduction and potentially lower mortality.

Acute subdural hematoma: The choice between craniotomy and craniectomy involves trade-offs. Craniectomy achieves lower residual hematoma rates but is associated with worse functional outcomes and higher mortality in unadjusted analyses. However, this likely reflects selection bias, as craniectomy patients present with more severe injuries (lower GCS scores). Propensity-score matched analyses still show higher mortality with decompressive craniectomy (OR 1.50;

95% CI 1.03-2.18) , suggesting craniotomy should be preferred when feasible.

Thoracolumbar fractures : Minimally invasive percutaneous fixation achieves equivalent radiological outcomes (kyphosis correction, vertebral height restoration) with significant advantages in blood loss (150-200 mL reduction), operative time, postoperative pain, and hospital stay . However, for fractures with severe spinal canal compromise requiring decompression, traditional open surgery may achieve better canal clearance .

Study Quality Considerations

The evidence base includes substantial variation in methodological quality. The highest-quality evidence comes from large multicenter RCTs such as RESCUEicp and DECRA, along with comprehensive meta-analyses pooling thousands of patients . However, many primary studies are retrospective cohort designs with significant risk of selection bias .

Heterogeneity in study populations, outcome definitions, and follow-up durations limits pooled analyses. I^2 values in meta-analyses ranged from low (17-20%) for mortality outcomes to high (58-86%) for functional outcomes , reflecting genuine clinical heterogeneity rather than random variation. The mortality benefit of surgical intervention appears robust across study types, while functional outcome effects are more sensitive to study characteristics.

Clinical Implications by Population and Context

Based on the synthesized evidence:

1. **For severe TBI with refractory intracranial hypertension** : Decompressive craniectomy reduces mortality but careful patient selection is essential. Patients under 40 years with adequate initial GCS show the greatest functional benefit .
2. **For spontaneous intracerebral hemorrhage** : Endoscopic or minimally invasive puncture surgery should be preferred over craniotomy when technically feasible, given superior mortality and functional outcomes .
3. **For acute subdural hematoma** : Craniotomy should be the initial approach when technically feasible; decompressive craniectomy reserved for cases with significant brain swelling or when bone flap replacement is contraindicated .
4. **For thoracolumbar fractures without significant canal compromise** : Percutaneous MIS fixation offers equivalent radiological outcomes with reduced surgical morbidity .
5. **For chronic subdural hematoma** : Minimally invasive drainage techniques (twist-drill with hollow screws, bedside evacuation) provide adequate outcomes with reduced invasiveness, though recurrence rates may be higher .

The consistent finding across all neurotrauma categories is that reduced surgical invasiveness translates to decreased perioperative morbidity (blood loss, infection risk, hospital stay) without compromising—and often improving—clinical outcomes. However, the optimal technique depends on specific pathology, patient characteristics, and available expertise.

Discussion

This comprehensive systematic review synthesizes evidence from 80 studies to provide a detailed and nuanced analysis of the efficacy of minimally invasive techniques in neurotrauma surgery. The discussion will integrate the findings, explore their clinical implications, reconcile apparent contradictions, address limitations, and suggest future directions.

Reconciling Mortality Benefits with Functional Outcomes: The Decompressive Craniectomy Paradigm

A central and critical finding of this review is the need to dissociate mortality from functional outcomes, particularly in the context of severe TBI treated with decompressive craniectomy (DC). The data robustly and consistently demonstrate that DC reduces mortality by approximately 34-41% compared to optimal medical therapy alone (RR 0.57-0.66) (Danfeng Zhang et al., 2017; Tsaousi et al., 2020). This survival benefit is mechanistically straightforward: by removing a large portion of the skull, DC provides immediate and sustained relief of refractory intracranial hypertension, thereby preventing lethal brain herniation. However, survival is not synonymous with recovery. The impact of DC on favorable functional outcome (typically defined as GOS 4-5 or mRS 0-3) is more heterogeneous and context-dependent.

The RESCUEicp trial data exemplify this dichotomy, showing no significant difference in favorable outcomes at 6 months but a significant improvement at 12 months in the surgical group (Kuhn & Thomas, 2021). This suggests a prolonged and potentially more complete recovery trajectory among surgical survivors. Furthermore, the finding that patients under 40 years old derived a significantly greater functional benefit (absolute difference 15.2%) is pivotal (Kuhn & Thomas, 2021). It underscores that the functional benefit of DC is not uniform but is heavily modulated by the brain's inherent plasticity and pre-injury reserve, which are generally superior in younger patients. The systematic review by Tsaousi et al. (2020) corroborates this, reporting significant mortality reduction but no significant improvement in pooled favorable outcomes (RR 0.85-0.89), indicating that a proportion of lives saved transition to states of severe disability rather than functional independence. Therefore, DC should be viewed as a powerful life-saving intervention whose value in restoring meaningful function is optimized by careful patient selection, favoring younger individuals with less severe initial insults where possible.

Context-Specific Superiority of MIS Techniques

The efficacy of MIS is not monolithic but varies significantly by pathology, highlighting the principle of "right tool for the right job."

- **Intracerebral Hemorrhage (ICH):** For spontaneous supratentorial ICH, minimally invasive evacuation techniques, particularly endoscopic surgery and stereotactic puncture with thrombolysis, demonstrate clear superiority over both conservative management and conventional craniotomy. Network meta-analyses show endoscopic surgery is associated with reduced mortality (RR 0.62-0.66) and significantly higher rates of functional independence (RR 1.62) (Guang-yu Guo et al., 2020; Haomiao Wang et al., 2025). This efficacy is directly linked to superior hematoma evacuation rates (84-87% for endoscopy) with minimal cortical disruption, leading to better preservation of surrounding brain tissue and faster neurological recovery (Cho et al., 2006; Yujuan Zhang et al., 2019). Techniques like the Intra-Neuroendoscopic Technique (INET) and laser-guided soft-channel approaches represent refinements that may further improve precision and safety (Ai Chen et al., 2025; Bo Du et al., 2018).

- **Acute Subdural Hematoma (ASDH):** The choice between craniotomy (bone flap replaced) and decompressive craniectomy (bone flap removed) for ASDH involves a critical trade-off. While DC is often performed for severe cases with significant brain swelling, meta-analyses indicate it is associated with higher mortality and worse functional outcomes compared to craniotomy in propensity-matched analyses (Phan et al., 2017; Shafique et al., 2024; Ali et al., 2024). This is likely due to the more severe initial injury in DC patients, but the data suggest craniotomy should be the preferred approach when feasible. Techniques that preserve the bone flap while achieving decompression, such as hinge craniotomy or four-quadrant osteoplastic decompressive craniotomy (FoQOsD), offer a promising middle ground, eliminating the need for subsequent cranioplasty and its associated risks and costs (Panchal et al., 2025; Vankipuram et al., 2019).
- **Emerging Techniques: Cisternostomy and Stepwise Decompression:** Cisternostomy, which involves opening the basal cisterns to enhance cerebrospinal fluid (CSF) drainage and relax the brain, shows great promise as an adjunct or alternative to DC. Evidence suggests it may provide additional ICP control and is associated with particularly low mortality rates (OR 0.348) (Kumarasamy et al., 2024; Satyarsa et al., 2023). Similarly, stepwise or controlled decompression techniques aim to mitigate the rapid pressure shifts and complications like encephalocele or contralateral hemorrhage associated with standard DC, leading to improved safety profiles (Shi et al., 2015; Zhijie et al., 2017; Huang et al., 2025).
- **Spinal Trauma (Thoracolumbar Fractures):** The evidence for MIS in spinal trauma is compelling for fractures not requiring direct canal decompression. Percutaneous pedicle screw fixation and minimally invasive corpectomy techniques achieve equivalent radiological outcomes in terms of kyphosis correction and vertebral height restoration compared to open surgery (McAnany et al., 2015; Podet et al., 2020). Their advantages are predominantly perioperative: significantly reduced blood loss (150-200 mL less), lower postoperative pain scores, shorter time to ambulation, and reduced hospital length of stay (mean 3.34 days shorter) (Wei Zhang et al., 2016; Mohammad Daher et al., 2025; Carazzo et al., 2021). However, for fractures with severe canal compromise requiring direct neural decompression, traditional open surgery may still be necessary to achieve optimal canal clearance, as the MIS visualization for decompression can be more limited (Bin Zhang et al., 2022).

Safety and Complication Profiles: A Balanced View

The safety profiles of MIS techniques are distinct from, not universally superior to, open approaches. DC, while life-saving, carries a higher overall complication rate (RR 1.94), including subdural effusions, hydrocephalus, and infections related to the external ventricular drain (EVD) or cranioplasty (Danfeng Zhang et al., 2017). In contrast, endoscopic and puncture techniques for ICH demonstrate lower rates of serious infections compared to craniotomy or EVD placement but have a higher incidence of benign intracranial air (Yujuan Zhang et al., 2019; Jian Xu et al., 2015). In spinal surgery, MIS approaches have comparable or lower overall complication rates but introduce specific risks such as pneumothorax in lateral approaches, guidewire or screw malposition, and increased radiation exposure to the surgical team (Podet et al., 2020; Barbagallo et al., 2012).

Limitations of the Evidence and Future Directions

The synthesized evidence, while robust, has limitations. A significant portion of the primary literature consists of retrospective cohort studies susceptible to selection and confounding biases. Heterogeneity in patient populations, surgical techniques, outcome definitions, and follow-up durations is considerable, complicating direct comparisons and pooled analyses. The focus often remains on short- to medium-term outcomes; long-term data on functional status, quality of life, and socioeconomic reintegration are scarce.

Future research must address these gaps. There is a pressing need for large, pragmatic, multicenter randomized controlled trials (RCTs) that compare modern MIS techniques against contemporary standards of care in well-defined patient subgroups. Standardized core outcome sets for neurotrauma research should be employed to facilitate meta-analyses. Long-term follow-up studies are essential. Furthermore, research should explore not just clinical efficacy but also cost-effectiveness, operational impacts on healthcare systems, and the integration of advanced technologies like robotics, augmented reality, and advanced intraoperative imaging to refine MIS further (Andrews et al., 2020).

Overall Synthesis and Clinical Integration

The paradigm of neurotrauma surgery is steadily shifting towards minimally invasive approaches. The evidence confirms that reduced surgical invasiveness reliably translates to decreased perioperative morbidity—less blood loss, less pain, fewer infections, and shorter hospital stays—without compromising, and often enhancing, survival and functional recovery. However, "minimally invasive" is not a single entity but a toolbox. The optimal tool must be selected based on a nuanced understanding of the specific pathology (ICH vs. ASDH vs. spinal fracture), the patient's characteristics (especially age and neurology), the surgeon’s expertise, and the available resources. DC remains a cornerstone for saving lives in refractory intracranial hypertension, particularly in the young, while endoscopic evacuation is becoming the preferred method for ICH. In spinal trauma, MIS fixation is the standard for stabilization, reserving open techniques for cases requiring extensive decompression. As techniques continue to evolve and evidence matures, the goal remains steadfast: to maximize survival while minimizing morbidity, guiding patients on the best possible path to neurological and functional recovery.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This comprehensive systematic review demonstrates that minimally invasive surgical techniques have a definitive and valuable role in the management of neurotrauma, offering significant benefits over traditional open approaches in many clinical scenarios. Key conclusions are:

1. **Mortality Reduction:** Decompressive craniectomy is a life-saving intervention for severe TBI with refractory intracranial hypertension, reducing mortality by 34-41%. Cisternostomy and endoscopic hematoma evacuation also show significant mortality benefits for specific pathologies.
2. **Functional Outcomes:** The impact on functional recovery is technique- and context-specific. Endoscopic and stereotactic evacuation for ICH consistently lead to better functional independence. The functional benefit of DC is most pronounced in younger patients (<40 years) and may manifest over a longer recovery period (≥12 months).
3. **Perioperative Advantages:** Across both cranial and spinal trauma, MIS techniques are consistently associated with reduced surgical trauma, evidenced by significantly less blood loss, lower postoperative pain, shorter operative times in experienced hands, and reduced hospital length of stay.
4. **Pathology-Guided Selection:** No single MIS technique is optimal for all neurotrauma. Endoscopic surgery is superior for ICH evacuation. For ASDH, craniotomy is preferred when feasible, with hinge techniques offering a bone-preserving alternative. In thoracolumbar fractures without severe canal stenosis, percutaneous MIS fixation is the standard due to its perioperative benefits.

The adoption of MIS represents a positive evolution in neurotrauma care, aligning with the broader surgical goal of achieving therapeutic efficacy with minimal collateral damage.

Recommendations

- **For Clinical Practice:**
  - **Severe TBI/Refractory ICP:** Consider early decompressive craniectomy, especially in patients ≤50 years with GCS >5. Adjuncts like cisternostomy or stepwise decompression may improve safety and outcomes.
  - **Spontaneous ICH:** Prioritize minimally invasive evacuation (endoscopic or stereotactic puncture) over conventional craniotomy for eligible patients with supratentorial hematomas.
  - **Acute SDH:** Favor craniotomy over decompressive craniectomy as the initial approach. Consider hinge craniotomy to avoid secondary cranioplasty.
  - **Thoracolumbar Fractures:** Utilize percutaneous MIS fixation for stabilization, especially in AOSpine type A and B injuries without neurological deficit requiring direct decompression.
  - **Chronic SDH:** Minimally invasive techniques (twist-drill craniostomy, bedside evacuation) are effective first-line treatments, acknowledging potentially higher recurrence rates that may require close follow-up.
- **For Future Research:**
  - Conduct large, multicenter RCTs with long-term follow-up to compare advanced MIS techniques (e.g., neuroendoscopy, robot-guided) against current standards.
  - Develop and implement core outcome sets to standardize the measurement of functional recovery, quality of life, and cost-effectiveness in neurotrauma trials.
  - Investigate the integration of advanced intraoperative imaging and navigation to enhance the precision, safety, and efficacy of MIS procedures.
  - Explore the economic impact and resource utilization associated with the shift towards MIS pathways in neurotrauma care.

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