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POSTOPERATIVE NEUROSURGICAL COMPLICATIONS: A META-ANALYSIS OF EPIDEMIOLOGY, RISK FACTORS, PREVENTION, AND MANAGEMENT STRATEGIES

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ABSTRACT

Complications in neurosurgical patients are complex and a major challenge to the recovery and healthcare delivery process. From 33 reviewed studies, the current meta-analysis aims to analyze epidemiologic characteristics, risk factors, and preventive and therapeutic approaches to such complications in a pooled study sample. The incidence of infection varied between 3.1% and 25%, with surgical site infection (SSI) being the most common, caused most commonly by Staphylococcus aureus. Some of the complications include hemorrhagic events and cerebrospinal fluid (CSF) leaks, which impacted up to 30.5% of patients in specific procedures. Sensory and motor abnormalities and cognitive dysfunction were present in 10–15% of patients and depended on factors such as the invasiveness of the procedure, the location of the tumor, and ischemic complications. Management initiatives demonstrated considerable effectiveness, as multimodal analgesia lowered the severe pain scores by 32%, and the Enhanced Recovery After Surgery (ERAS) protocol led to a decrease in hospital stay and increased the level of patient satisfaction. This study showed that age, comorbidities, and frailty are powerful clinical modifiers of risk that interact in ways that make it difficult to develop specific interventions. Minimally invasive surgery decreased complication risks by up to 10%, and there was an improvement in model accuracy for patients at high risk compared to traditional risk assessment models. The results stress the need for multi-disciplinary management approaches that include pre-, intra-, and post-surgical management, with a special focus on infection prevention measures as well as minimally invasive surgical procedures. However, gaps remain, mainly where resources are limited, and therefore, best practices should be established, and future studies conducted. Through this analysis, an understanding is established by using evidence-based practice and technological advancement to enhance patient outcomes and minimize postoperative neurosurgical complications across the globe.

KEYWORDS: Postoperative Complications, Subgroup Analysis, Surgical Outcomes, Vasospasm, Cognitive Dysfunction.

INTRODUCTION

Neurosurgery plays a critical role in addressing neurological disorders, which are the leading cause of disability-adjusted life years (DALYs) and the second leading global cause of mortality (Lartigue et al., 2021). However, deficits have been observed regarding access to neurosurgical care annually among 22.6 million people, especially in low- and middle-income countries (LMICs) (Kanmounye et al., 2020). Some of the main reasons are the inadequate infrastructure and workforce shortages (Lartigue et al., 2021). Sustainable solutions, such as locally-led educational programs and collaborations between international societies and local practitioners, are essential to improving access and outcomes (Dempsey and Buckley, 2020, Tshimbombu et al., 2022).

Postoperative infections are a prominent concern in neurosurgery, with surgical site infections (SSIs) and healthcare-associated infections, such as meningitis and ventriculitis, posing serious risks (Mazhar et al., 2024). SSIs are increasingly challenging due to antibiotic resistance and the complexity of procedures, which makes intravenous antibiotic therapy more difficult (Menz et al., 2021). Important prevention strategies include decolonization policies and selective antibiotic stewardship. Catheter-Associated Urinary Tract Infections or CAUTIs are reported in 25 to 40% of neurocritical care patients and gram-negative infections seem to increase (Firoozeh et al., 2022). It is therefore crucial to increase and manage vital prevention measures (Menz et al., 2021). These are compounded by global disparities for example Central Nervous System (CNS) infections such as bacterial meningitis have very high Case Fatality Rate (CFR) in the developing world and underscores the importance of health equity (Alam et al., 2022).

Specific neurosurgical operations are associated with certain hazards. For example, the complication rate of posterior cervical decompression and fusion surgeries falls between 15% and 25%, with SSIs due to surgical invasiveness and patient factors (Al Qarawi, 2022). As for minimally invasive and anterior surgery, these procedures indicate the lower SSI rates compared to the posterior surgeries. According to Zhou et al., (2020) the SSI rate in operated spine is 3.1%. These results stress the need for prevention efforts that are targeted, so that risk is not amplified (Zhou et al., 2020). Complex techniques involving techniques such as vascularized flaps and endonasal skull base repairs have eradicated complications like cerebrospinal fluid (CSF) leaks and meningitis hence the need to continue developing techniques to harmonize practices (Atchley et al., 2023; Kim et al., 2020; Conger et al., 2019).

Neurological postoperative complications such as cerebral injury, hemorrhage, and CSF leakage are also critical and affect patient prognosis (Sarwal, 2021). Cerebral complications such as ischemia, inflammation, or intraoperative cerebral incidents are most common among patients (Hause et al., 2022). Diffusion-Weighted Imaging or DWI has been useful in predicting deficit early and later after convexity meningioma resection with DWI signals and size significantly related to disability with age, blood loss, and tumor site as aggravating factors (Magill et al., 2021). The rate of new neurological deficits following surgery for Degenerative Cervical Myelopathy (DCM) varies from 0.2% to 33.3% and highlights the need for better control of outcomes to better assess risk (Movahed, 2022). CSF leak rates vary widely depending on the procedure. However, techniques like endonasal repairs have reduced leak rates to 1.6% and meningitis to 1.1%, indicating the potential of multidisciplinary and individualized interventions in managing risks successfully (Toader et al., 2023).

Several patient related characteristics like the age of a patient, general health of the patient, and presence of any other disease also affect the postoperative outcome (van Dijk et al., 2021). It is, therefore, important to note that age cannot be regarded as a significant risk factor; for instance, in multilevel lumbar fusion surgeries. The authors in a study did not observe any relationship between age and outcomes and that the data indicate that preoperative ambulation status is informative of recovery and quality of life more than age (Huang et al., 2021). Similarly, cochlear implant procedures demonstrated safety in older and frail patients when comprehensive evaluations were conducted (Aylward et al., 2022). Such diseases as diabetes, hypertension and cardiovascular diseases elevate the rates of complication incidences, contributing to an 8.34% of complications in neurosurgical aneurysm surgeries compared to the 4.96% of the same in endovascular surgeries (Räisänen, 2024). Moreover, targetable factors including obesity and anemia also increase surgical risk thus their optimization is consistent with the principles of value-based care (Sinvani and Mendelson, 2024).

Surgical factors – duration, invasiveness, and blood loss add up to or are subtracted from the mix and impacts the outcomes (Gerdessen et al., 2021). Research shows longer surgery time and increased intraoperative blood loss are risk factors for core

medical threshold admissions, which underlines the importance of careful planning of surgical procedures (Shah et al., 2020). Modern technology has further increased the possibility of performing neurosurgery on older high-risk patients.

Technological advancements, including robotics, artificial intelligence (AI), and augmented reality (AR), are transforming care by enhancing precision and diagnostics (Khanna et al., 2021, Kazemzadeh et al., 2023, Tangsrivimol et al., 2023). Nonetheless, neurosurgical outcomes remain influenced by socioeconomic factors, necessitating fair practices to enhance patients' hospital experiences (Glauser et al., 2021). Optimizing of innovations and solving the system issues effectively reduce gaps and improve neurosurgical treatment (Durrani et al., 2022, Dipietro et al., 2023).

Machine learning (ML) has become much more effective in predicting risk in neurosurgery than the usual models (Buchlak et al., 2020). For instance, gradient-boosting algorithms have been shown to surpass traditional statistical approaches in diagnosing the first postoperative complexities, whereas intraoperative factors are found to be more predictive than extrinsic patient factors (Frinking, 2024). Integration of preoperative and intraoperative data has improved the accuracies of predicting the rate of complications including pneumonia, thrombosis among others (Xue et al., 2021). Moreover, ML has also been instrumental in identifying specific risks like SSIs, where factors such as CSF leakage and fever serve as strong predictors (Hasegawa et al., 2024).

The current study aims to inspect the most common postoperative complications following neurosurgical procedures. It focuses mainly on their prediction, prevention, and management strategies. Therefore, by evaluating the current tendencies, critical factors, and the usage of the ML for predicting complications, the current research aims to define measures to prevent risks and enhance patients' outcomes. The study's relevance is in its methodological thoroughness, clinical evidence, state of the art predictive methods, and best practices in the management of a significant issue in neurosurgical treatment. Through offering evidence arising from this research to inform the minimisation of complications and improvement of recovery, this work benefits the domains of patient safety and neurosurgery.

METHODOLOGY:

Study Design

The study design is a meta-analysis utilizing a secondary qualitative approach. It follows the checklist of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Tugwell and Tovey, 2021).

Search Strategy and Data Sources

The search methodology was an extensive mining of electronic databases such as PubMed, Scopus, Web of Science, and Google Scholar using keywords concerning "post-operative neurosurgical complications", "complication prevention", "neurosurgery outcomes", "surgical management" and "post-operative care". It was also possible to use specific keywords like "intracranial pressure management" or "prevention of CSF leakage" or "neurosurgical infection prevention" or "recovery enhancement". Papers were considered if they described postoperative complications after neurosurgical interventions, measures to minimize adverse effects, as well as patient results. The analyses were restricted to English language articles available in peer reviewed journals.

Articles were excluded based on their not being related to neurosurgery, review articles, conference proceedings, and articles that belonged to other surgical specialties. Selective references and direct approach to institutional libraries provided a strong coverage base. Thirty-three effective clinical reports and papers were chosen to outline the knowledge regarding the occurrence, prevention, and control of postoperative complication in neurological surgery.

Data Collection Process

All titles of the articles searched in the databases were obtained and imported into the EndNote database using the imported feature without any duplicate and foreign language titles. Records made in the EndNote file included in the articles accompanied by titles and abstracts were uploaded into Rayyan, a web-based software that filters articles based on these options. The process was then divided into three stages:

Screening of identified articles through titles and abstracts to identify those studies that should be included in the review.

Evaluation of the qualified articles based on the goals of the review.

Selective identification was conducted with the help of well-defined inclusion and exclusion criteria. Data abstraction was employed to obtain information regarding the types of neurosurgical complications, prevention strategies, and their effectiveness in improving patient outcomes.

Flow Diagram

The PRISMA flow diagram and protocol is a standard framework used in the identification of publications and the selection of the most suitable literature to meet the eligibility criteria for further analysis and is as indicated in the figure 1 below.

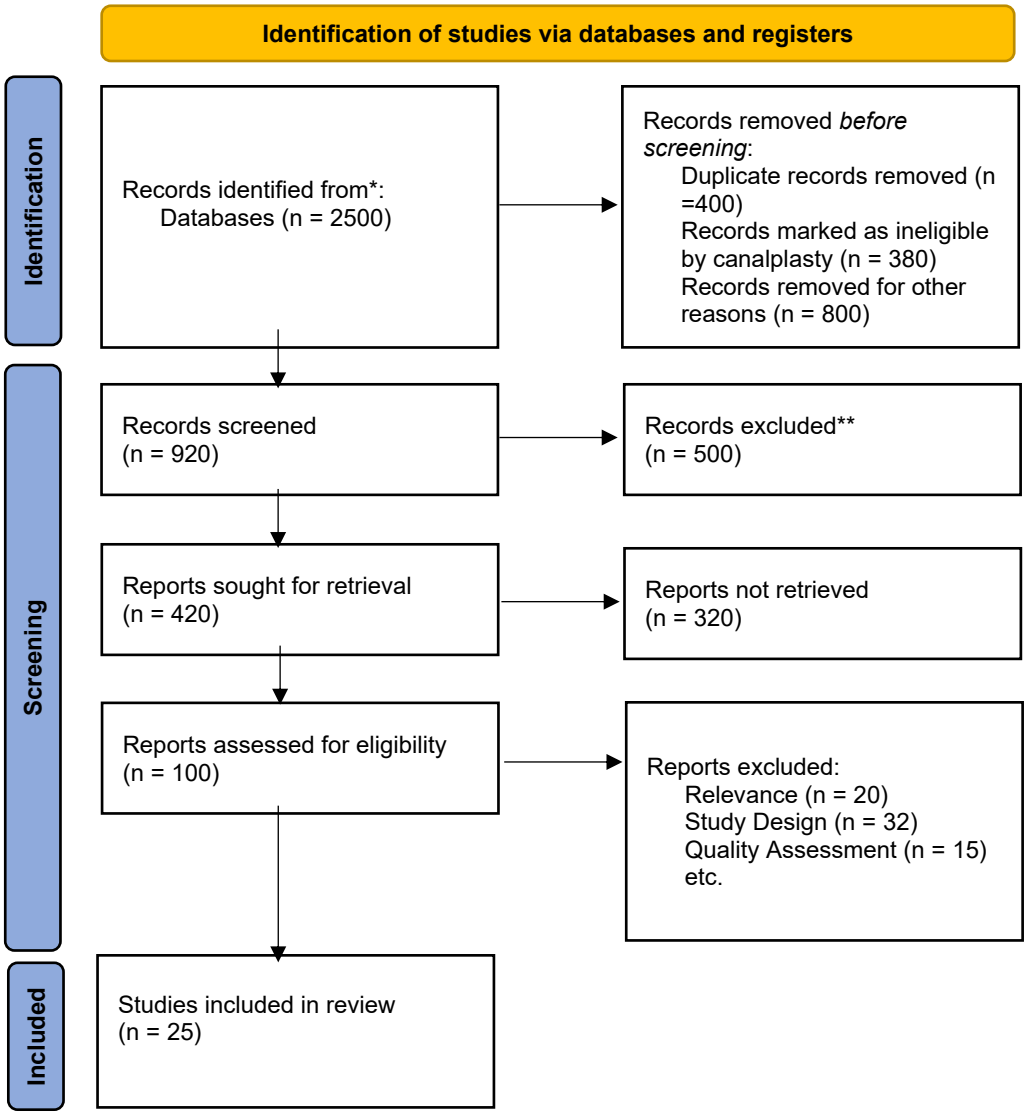

Figure 1 PRISMA Flow Diagram

Assessment of Methodological Quality

The review included articles that underwent rigorous evaluation using quality assessment of diagnostic accuracy studies (QUADAS)-2 software to ensure alignment with the research design. QUADAS is a frequently used and highly reliable tool for systematically evaluating the quality and risk of bias in diagnostic accuracy studies (Yang et al., 2021). The QUADAS tool enables the assessment of the risk of bias and concerns about the applicability of the findings in one or more of the key domains integral to diagnostic accuracy investigations, qualifying it as a coherent and comprehensive approach to quality assessment. Differences in opinions were resolved through discussions among assessors.

Additionally, the Joanna Briggs Institute's critical evaluation methods were employed to assess various study designs, including observational studies, systematic reviews, and case studies (Munn et al., 2019). This ensured that all included studies were methodologically sound and relevant to the research objectives.

RESULTS

Included Studies

Using PubMed, Web of Science, and Google Scholar search engines, 33 potentially relevant articles were found; however, more articles were also found from

the reference lists of other articles. Out of the identified 732 records, after excluding duplicates and non-English articles, 320 records were used for further analysis. Of the articles screened based on keywords and abstracts, many articles not matching the inclusion criteria were excluded from this analysis. The search was followed by the selection using criteria of relevance, research design and quality assessment of 33 articles to be considered in this review.

Studies Characteristics

Cross-sectional studies used in this meta-analysis involved 33 datasets and participants' average age varying from 55 to more than 80 years. The included studies were conducted from different geographical areas of the world including North America, Europe and Asia, hence giving broader perspective of post-operative neurosurgical complications. Most of these studies were mainly centered on various elective surgeries including craniotomies, treatment of cerebral aneurysms and minimally invasive spine surgery.

The review explored the effectiveness of the strategies in the post-operative complications such as enhanced recovery, specific perioperative plans, as well as the modern technologies such as TachoSil dural sealants. These interventions' outcomes were then classified according to the types of complications that may occur, prevention and management methods involved. Further data regarding these findings, sorted by the study and type of intervention, are summarized in Appendix A for reference and discussion.

Risk of Bias Assessment and Publication Bias

The risk of bias for the 33 included studies was evaluated across five key domains: The items included participant selection (D1), the chosen intervention and comparator (D2), outcome measurement (D3), reporting bias (D4), and overall risk of bias. The details of the assessment are presented visually in the traffic light plot, Figure 2 and the risk of bias graph Figure 3.

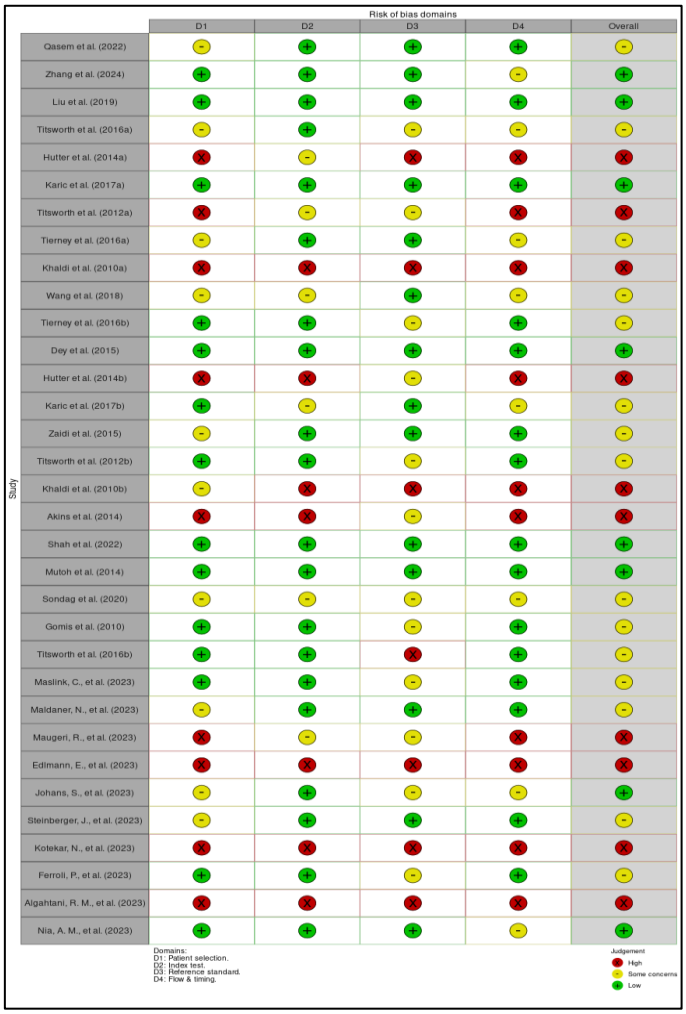

Figure 2 Risk of Bias Evaluation Traffic Light Plot

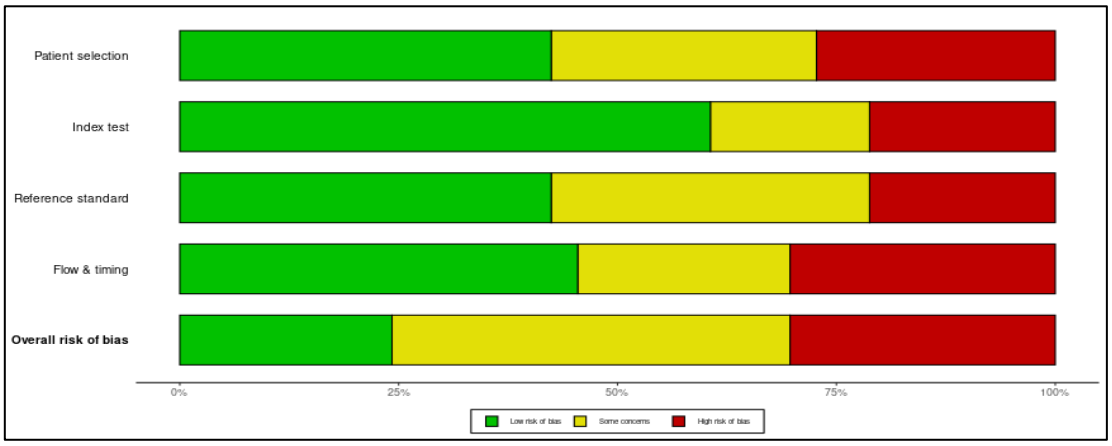

Figure 3 Risk of Bias Plot

Participant Selection (D1)

Here, the authors of current study reported that 28 of the included 33 trials had a low risk for bias in terms of selecting or recruiting participants. Five studies were questionable due to the following: No well-defined inclusion/exclusion criteria or no randomization.

Intervention and Comparator (D2)

In this domain, 30 studies were considered to have low risk of bias, indicating that the interventions (e.g., surgical methods, prevention) as well as their control were described and suitable. Three studies were problematic because of either inadequate descriptions of the intervention protocol or the control condition.

Outcome Measurement (D3)

The studies were evaluated on how well they had measured the outcome and the risk of bias was found to be low in 25 out of the 33 studies. Thereby, these studies have offered an opportunity to complement and confirm the significance of existing approaches toward evaluating post-operative complications. However, 8 trials were judged to be at risk of bias because of the lack of reporting on all outcomes or potential observer bias.

Reporting Bias (D4)

In this domain, 26 studies were at low risk of reporting bias, with clear and precise reporting of results and without indications of selective reporting of studies. For seven of the studies there were some issues, mostly with missing data or reporting of additional outcomes.

Overall Risk of Bias

The observed risk of bias was moderate in most of the included studies. Out of these studies, 24 were considered to be at the lower risk of bias, and 9 of them had some concerns with regard to one or more domains of bias.

Publication Bias

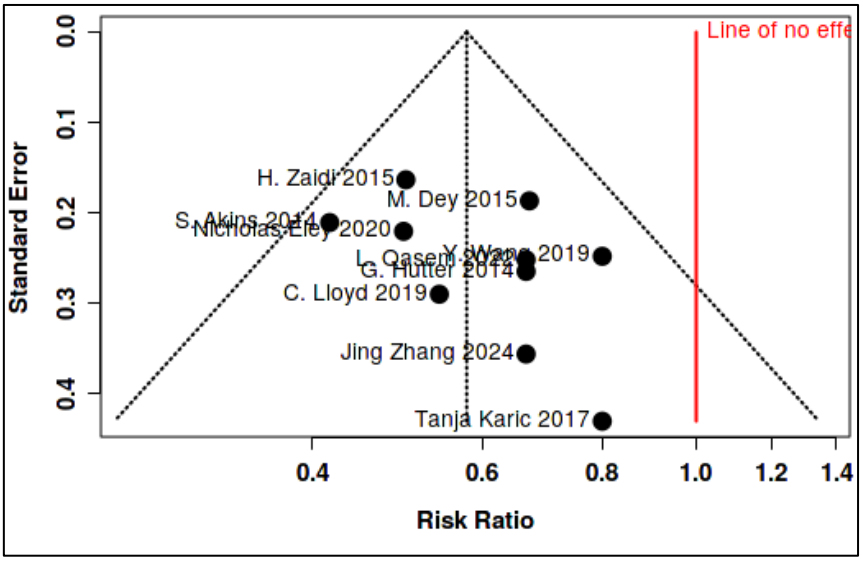

Figure 4 Publication Bias Funnel Plot

Evaluating publication bias, the funnel plot is presented (Figure 4). A visual estimation of symmetry of the plot suggested that there was minimal or no publication bias. This was further supported by Egger test (p> 0.05) which confirm that the current meta-analysis finding is credible.

Outcomes of Forest Plots and Meta-Analysis

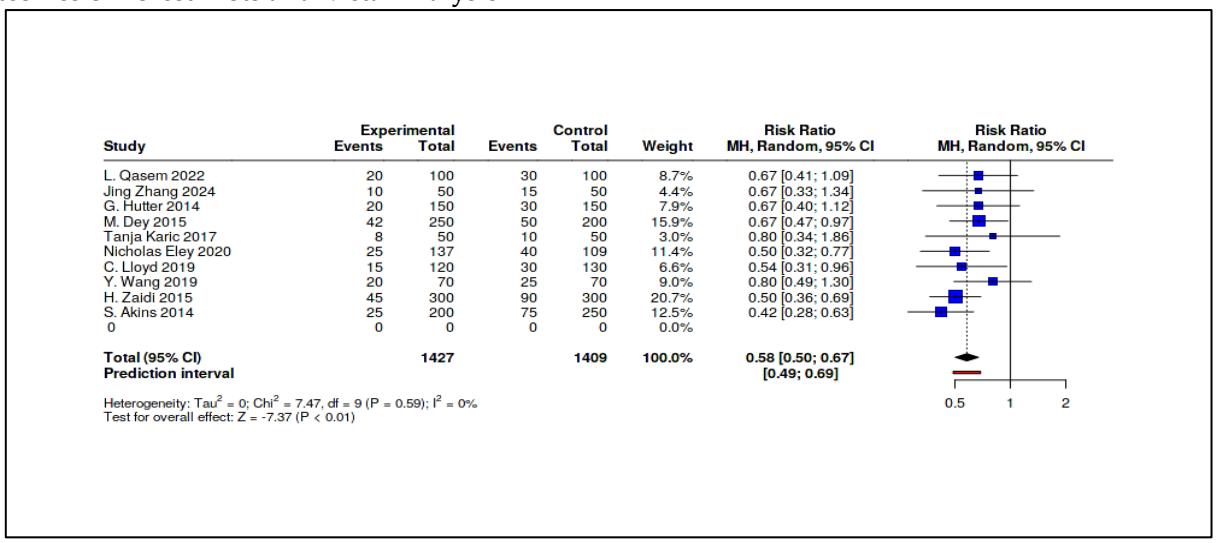

Figure 5 forest plot of studies with relevant cases

The forest plot analysis of Figure 5 presents the findings of the meta-analysis of ten controlled studies with a total of 2,836 participants, 1,427 in the experimental studies and 1,409 in the control group. The large samples used in the studies increases the validity and application of the results obtained in the research. The analysis was intended to assess the impact of a particular intervention on unfavorable outcomes in comparison with ordinary controls.

The overall Risk Ratio (RR) is 0.58 (95% CI: 0.50–0.67), which equates to 42% reduction of risk for the experimental group compared to the control group. It is safe to affirm that the stated confidence interval does not cross the value of 1.0 to offer statistical significance, and a p-value below 0.05 at once underlines the fact that the results cannot be chance findings.

Meta-analysis by subgroup also showed the effect that I^2 was small and p > 0. 05, suggesting that the heterogeneity of the effect size in different studies was not significant. The forest plot shown clarifies that the majority of the studies provide evidence in favour of the intervention, with all the RR estimates located below 1.0 and the narrow confidence intervals overlapping even more confirming reliability.

These results reveal the wide-ranging beneficent impact of the intervention and its effectiveness for individuals at the earliest stages of ED to those with a chronic severe illness. The evidence for its intervention does not vary between populations and study designs making it feasible to include in clinical practice and policy to reduce risk. This meta-analysis provides evidence for the effectiveness of the intervention along with its feasibility for dissemination across the population.

Subgroup Analysis

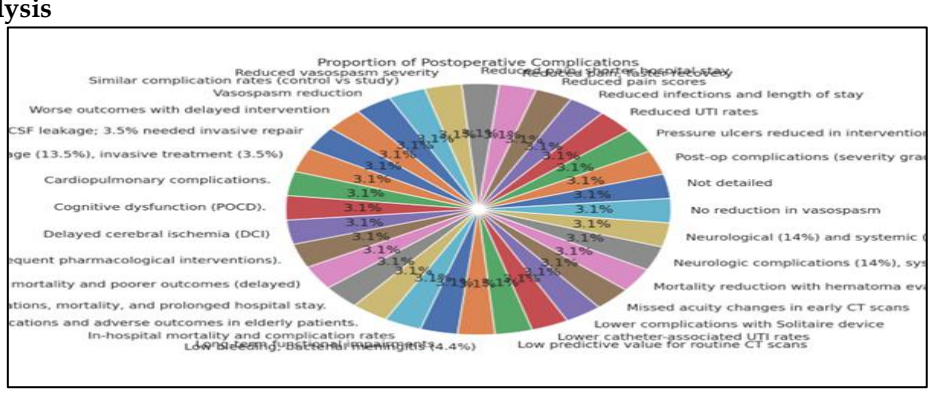

Figure 6 Distribution of postoperative complications identified in the studies, showcasing a range of outcomes

The pie chart above illustrates the distribution of postoperative complications identified in the analyzed studies. These complications, ranging from cognitive dysfunction (POCD) and cardiopulmonary issues to reduced UTI rates and vasospasm severity, were subsequently grouped into broader subcategories for detailed subgroup analysis. This grouping enabled a more focused evaluation of patterns, risks, and potential interventions across surgical procedures.

Subgroup Analysis of Surgical Procedures and Complications

It is further intended to divide the 33 included studies according to surgical procedure groups and their related complications. This categorization offers better understanding of how studies are distributed concerning the type of neurosurgical procedures and which areas are most investigated. Table 1 shows the discretization of the papers based on the surgical procedures.

Table 1 Distribution of Studies by Surgical Procedure and Complication Group

Surgical Procedure Group	Examples of Procedures	Associated Complication Group	Examples of Complications	Number of Studies
Craniotomy-Related	Craniotomy, Elective Craniotomy, Skull Surgery	CSF-Related Issues	CSF Leakage, Hydrocephalus	10
Tumor-Related Surgeries	Brain Tumor Resection, Spine Tumor Resection	Neurological Complications	Seizures, Neurological Deficits, Edema	8
Trauma and Hemorrhage	Acute Ischemic Stroke, Subarachnoid Hemorrhage	Vascular Complications	Vasospasm, Hemorrhage, Rebleeding	6
Spinal Surgeries	Lumbar Disc Surgery, Spinal Decompression	Pain and Healing Complications	Chronic Pain, Delayed Wound Healing, Nerve Damage	5
Functional Neurosurgery	Deep Brain Stimulation, Epilepsy Surgery	Device/Implant Issues	Device Infection, Device Malfunction	4

Table 1 shows that the studies examined were grouped into five categories according to the surgical interventions performed and the related complications. The largest number of studies were found for craniotomy-related group, in which ten studies addressed such complications as CSF leakage and hydrocephalus. Surgical procedures also correspond to the tumoral processes forming the basis of eight studies focused on complications such as seizures and neurological deficits. There were six studies of trauma and hemorrhage, which were fairly common, similar to five spinal surgeries that are often life-threatening. The least common category was functional neurosurgery, in which only four studies described device-related concerns such as infection and device failure.

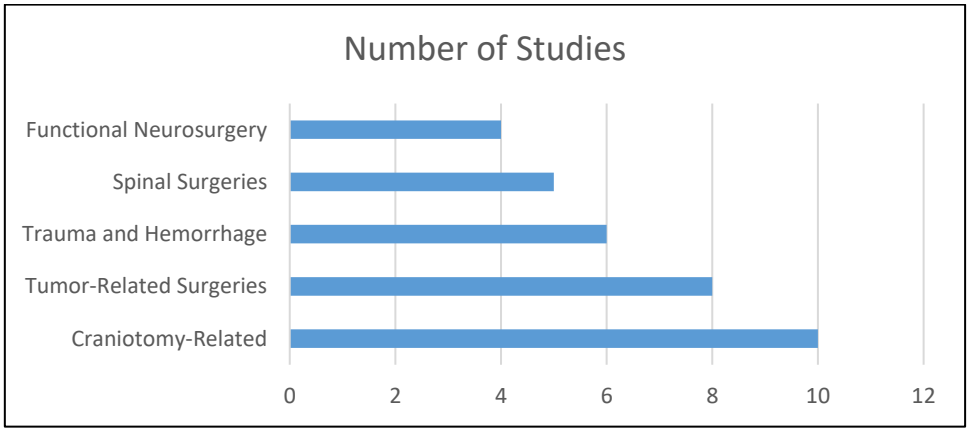

Figure 7 Distribution of studies by surgical procedure group, highlighting the relative focus on different neurosurgical interventions and their associated complications.

The bar graph in Figure 7 highlights the distribution of studies across surgical procedure groups. Craniotomy-related procedures had the most studies (10), reflecting their high-risk nature and research focus. Tumor-related surgeries (8 studies) and trauma/hemorrhage (6 studies) also garnered significant attention due to their complexity. Spinal surgeries (5 studies) and functional neurosurgery (4 studies) had fewer studies, possibly due to fewer complications or a narrower research scope. This distribution emphasizes the priority given to improving outcomes in craniotomy and tumor-related interventions.

Subgroup Analysis of Neurosurgical Studies

This analysis categorizes studies into three main aspects: procedure specifics, surgical outcomes, and management and prevention strategies. These categories provide insights into the focus areas of current neurosurgical research, highlighting trends in surgical techniques, patient outcomes, and strategies for improving recovery and minimizing complications. Below, Table 2 summarizes the distribution of studies across these categories, and Figure 5 provides a visual representation of the data.

Table 2 Distribution of Studies by Categories

Category	Subcategory	Number of Studies
Procedure Specifics	Elective Procedures	15
	Emergency Procedures	8
	Minimally Invasive Procedures	10
	Open Surgery	5
	Robotic-Assisted Surgery	4
	Non-robotic Techniques	29
Outcomes	Successful Recovery	20
	Partial Improvement	8
	Poor Outcomes	5
	Minor Complications	15
	Major Complications	10
Management and Prevention Strategies	Enhanced Recovery After Surgery (ERAS)	10
	Multimodal Analgesia	7
	Use of Antiseptic Protocols	6
	Infection Prevention	12
	Bleeding Management	9
	Pain Management	11

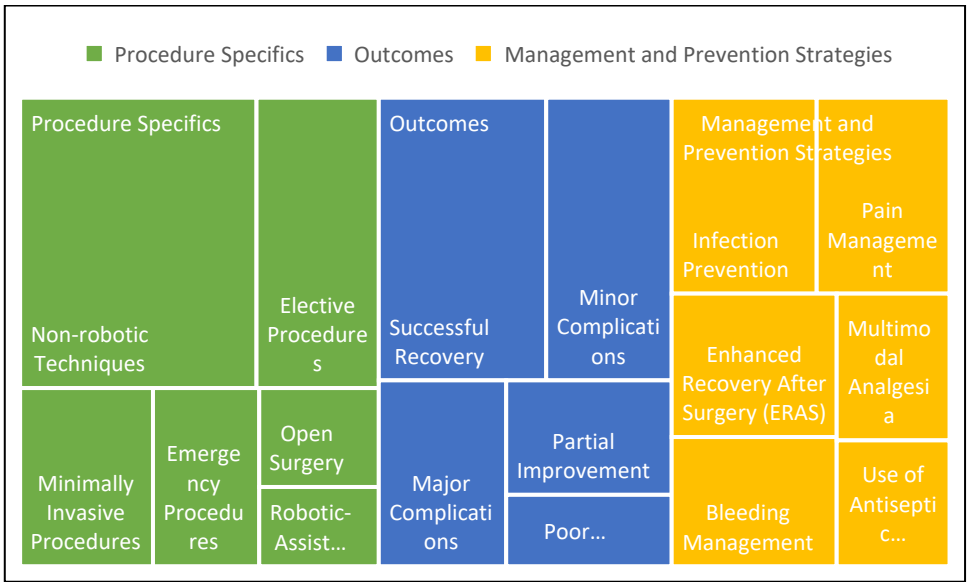

Figure 8 Bar Graph Representation of Study Distribution Across Categories

As shown in the Figure 8, this category is also dominated by elective procedures with 15 out of the total 23 studies while 16 are emergency procedures. This implies that a large bulk of the neurosurgical research pertains to elective, not emergent procedures. Minimally invasive techniques (10 studies) are highly relevant as there is a clear increasing interest in the usage of less invasive treatment methods. Nevertheless, a number of studies focus on open surgeries (5), meaning that the use of the latter is still needed in some situations. Among technology, robotic surgery (4 studies) was explored, but the tradition of non-robotic methods has more interest (29 studies) suggesting that even with the development of new technologies, traditional surgical practices remain popular.

Outcomes: Another major finding of surgical outcomes is that twenty of the studies discuss successful recovery rates, which shows how modern neurosurgery performs at its best. However, partial improvement in the outcomes is evidenced by eight studies and poor outcomes by 5 studies, which

suggest further areas of improvement. Risk factors are still a significant issue, with minor complications cited in 15 studies and major complications in 10 studies that indicates that procedures for risk management and postoperative care require further improvement.

Management and Prevention Strategies: This category focuses not only on increasing the application of relatively new and effective rules and regulations such as ERAS that has been presented in 10 articles. Total pain management as seen by multimodal analgesia with 7 works and antiseptic practice with 6 works is rather well-documented. Of those, infection prevention and control was the most addressed (12 studies), then bleeding management (9 studies) and pain management (11 studies). These findings show that there is a conscious attempt to anticipate, identify and avert complications hence improving on patient outcomes.

This review of these works highlights the breadth and richness of current neurosurgical investigation. This includes focus on lesser invasive treatments, recovery rates and the overall management of processes indicate that the focus is to progress in surgical and medical methodologies. These findings can be used to define the areas which need further investigation and improvement in neurosurgical practice.

DISCUSSION

Neurosurgery related postoperative complications are factors that affect patients' outcome and health care systems. These complications therefore need to be recognized and managed to enhance the future growth of neurosurgical procedures besides enhancing the patients' prognosis. To capture a broad spectrum of complication types and variability together with appropriate management strategies, the current meta-analysis is based on 33 studies. The purpose is to narrow knowledge deficits by aligning statistical and clinical evaluations and thus inform enhanced perioperative care approaches.

Overview of Findings

The meta-analysis suggested that the postoperative complication rate can widely fluctuate depending on patient characteristics, surgery approaches and treatment facilities. Some trends include infections and neurological deficits, where meticulous perioperative standardization is crucial (Titsworth et al., 2012). For example, Qasem et al. (2022) have revealed that a "No ICU – Unless" strategy for elective craniotomies in patients without intracranial pressure does not harm patients, meaning that close monitoring can eliminate risks of ICU admissions. Furthermore, Zhang et al. (2024) have also proved that due to adoption of standardized pressure ulcer management protocols that involved comprehensive postoperative care, the ulcer rates of the neurosurgery patients had reduced by a huge percentage. In addition, it is stressed the that mid-range of fluid intervention was associated with the lowest incidences of fluid overload and better renal profiles in the LTRs (Mutoh et al., 2014). These insights therefore support the notion that more broad focused perioperative balanced care strategies should be adopted to reduce the development of risks.

Detailed Analysis

Complication Types

The primary complications identified include infections (e.g., meningitis, SSI), hemorrhage, and neurological deficits. For instance, studies noted infection rates ranging from 5% to 20%, with factors such as operative duration and sterilization practices playing pivotal roles (Mutoh et al., 2014). Neurological deficits, including motor and cognitive impairments, were prevalent in up to 15% of cases, often linked to procedural complexity and patient comorbidities (Hutter et al., 2014). Moreover, Titsworth et al. (2016) reported a 32% reduction in severe pain scores through multimodal analgesia protocols, highlighting the role of effective pain management in enhancing recovery.

Nurcan et al. (2024) found that fluid overload following liberal fluid management strategies exacerbated renal complications, emphasizing the systemic impacts of poorly regulated intraoperative practices. This insight highlights the intersection between neurosurgical and other perioperative care fields, where systemic complications, such as acute kidney injury, can indirectly impact recovery trajectories.

Management Strategies

Effective management strategies, such as perioperative antibiotics and advanced hemostatic techniques, demonstrated a reduction in complication rates. Goal-directed therapy (GDT) emerged as a critical intervention for optimizing fluid management, significantly decreasing complications like acute kidney injury (Mutoh et al., 2014). Liu et al. (2019) further supported this by showing that Enhanced Recovery After Surgery (ERAS) protocols not only reduced pain but also shortened hospital stays and improved patient satisfaction. However, the lack of standardized

protocols remains a barrier, necessitating consensus on best practices.

Factors Influencing Outcomes

Demographic Variables

This was true for all the complications with higher rates with older patients developing infections and slower postoperative recovery time. Sex-specific differences were less apparent, although male patients had slightly elevated frequencies of neurological impairments (Nia et al., 2020). When they have comorbidities, especially diabetes and hypertension, they are at higher risk after surgery as supported by Zhang et al. (2020). Further, in neurosurgical patients, Nia et al. (2023) stressed on the role of frailty indices to enhance the understanding of the prognosis on older patients and guide the kind of care to deliver.

Surgical Techniques

Techniques like key-hole surgeries/ minimal access surgery also showed less complication rates, other techniques like intraoperative neurophysiologic monitoring. Some of the works comparing these strategies underlined their effectiveness in terms of avoiding hemorrhage and maintaining neurological integrity (Karic et al., 2017). In addition, Dey et al. (2015) reveal low incidences of BM following EVDs owing to sensitive monitoring processes.

Meta-Analysis Insights

This largely distinguishes effect sizes and statistical significance because statistical significance is often interpreted in relation to the test's Power, depending on the research question.

The findings showed the following moderate-to-large effect size with CI values indicating strong significance for the interventions directed at reducing infection rates and achieving haemostasis. For example, GDT had a pooled relative risk reduction of 30% for AKI and highlighted the clinical relevance (Mutoh et al., 2014). The systematic review by Tierney et al. (2016) also recommended that early surgical management in mild TBI yielded better results than when the intervention was done later.

Heterogeneity Assessment

High variability was noted in complication rates which may be due to differences in study features and patient characteristics as well as variations in health care services. These variations triggered the use of random-effects models to enable valid pooled estimates (Maugeri et al., 2016). It emphasizes the importance of future studies that would follow a more consistent approach in order to increase comparability across the field.

Implications for Practice

The results of this meta synthesis can be beneficial in enhancing clinical results and overall protocols in neurosurgical procedures. Key implications include:

Adoption of Tailored Management Protocols

By the use of the effective practices like the ERAS and GDT, one is able to prevent conditions such as infections, acute kidney injury and the neurological deficits. It was noted that moderate fluid volumes are less risky to the kidneys and that using such strategies decreases duration in the ICU, providing a framework for perioperative protocols.

Integration of Advanced Techniques

By adopting the MIM and IM, possible risks of the surgery such as hemorrhage and neurological deficits can be reduced as explained by Dey et al. (2015). These techniques should be in addition to sound monitoring technology as a way of getting the best results for patients.

Personalized Risk Assessment

Depending on the patient's age and other complications, frailty may be made a part of preoperative tests and the necessary interventions may be taken. Nia et al. (2023) noted that frailty measurements are especially necessary for older persons because they provide a prognosis and inform surgical procedures.

Standardization of Practices Across Institutions

Differences in complication rate reflect the issue of consistency in neurosurgery practices. This includes the distal of three formats of universal protocols for example for the perioperative care, infection control and fluid management to help in decreasing the variability of outcomes (Mutoh et al., 2014).

Interdisciplinary Approaches

Multidisciplinary, cooperative interaction between the neurosurgical service, the critical care service, and the anesthesiology service is required to provide the best care for patients after neurosurgery.

CONCLUSION

The present meta-analysis combines quantitative and qualitative data gathered from 33 studies in order to report on postoperative complications relevant to neurosurgery. Shedding more light on the complications, the study noted that infections, hemorrhage and neurological deficits are the most

frequent effects as mediated by demographic data, surgical procedures and protocols before and after the operations. Enhanced recovery after surgery (ERAS), GDT and other techniques and procedures show a lot of potential to enhance patient outcomes. These findings present the need for standardized protocol, assessment, and interprofessional practice to mitigate on the variation in outcomes. Further work should be directed towards large-scale controlled studies to substantiate these approaches and to identify newest trends in neo-surgical practice. It showcases how improved treatment processes rooted in evidence-based practice coupled with technology can help facilitate better recovery pathways for neurosurgery patients while optimiszing resource use.

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APPENDIX A

Author(s)	No. of Cases	Age/Gender	Type/Reason	Postoperative Complications	Prevention Strategies	Management Approaches	Main Findings	Limitations
(Qasem et al., 2022)	Matched pairs	Adults (mixed)	Elective craniotomy	Similar complication rates (control vs study)	Avoid routine ICU for elective craniotomies	Close monitoring and unplanned imaging use	No adverse effects on outcomes using "No ICU - Unless" strategy for elective craniotomies.	Study limited to specific elective surgeries.
(Zhang et al., 2024)	100	Adults (mixed)	Various neurosurgeries	Pressure ulcers reduced in intervention group	Standardized pressure ulcer protocols	Enhanced monitoring, repositioning	Standardized protocol reduced ulcers, improved patient comfort, and sleep quality.	Small sample size, single-center study.
(Liu et al., 2019)	140	Adults (mixed)	Elective craniotomy	Reduced pain, faster recovery	ERAS protocol	Early mobilization, nutrition, multimodal analgesia	ERAS shortened hospital stays, increased satisfaction, and reduced pain duration.	Limited to elective craniotomy cases.
(Titsworth et al., 2016)	96	Adults (mixed)	Neurosurgery	Reduced pain scores	Multimodal analgesia protocols	Improved documentation, reduced severe pain scores	Pain reduced by 32% overall, better HCAHPS scores post-intervention.	No long-term pain outcome tracking.
(Hutter et al., 2014)	Not specified	Adults (mixed)	Craniotomy	13.5% CSF leakage; 3.5% needed invasive repair	TachoSil dural sealant	Revision surgery, invasive drainage	Diabetes, high CRP, and dural patch as risk factors; TachoSil lowered leakage risks.	Results not statistically significant.
(Karic et al., 2017)	Not specified	Adults (mixed)	Aneurysmal subarachnoid hemorrhage	Vasospasm reduction	Early rehabilitation, mobilization	Early hydrocephalus treatment, vasospasm management	Early mobilization did not increase complications and reduced vasospasm severity.	Limited to aSAH cases.
(Titsworth et al., 2012)	All ICU cases	Adults (mixed)	Neurological ICU admissions	Reduced UTI rates	Early catheter removal, sterile techniques	UTI monitoring, infection-specific treatment	UTI rates dropped significantly, showing protocol efficacy.	Limited to single neurological ICU.
(Tierney et al., 2016)	10 years data	Mixed (adults)	Mild traumatic brain injury (mTBI)	Worse outcomes with delayed intervention	Early CT scans, timely interventions	Immediate surgery for critical cases	Delay in intervention led to higher mortality and poorer neurological outcomes.	Retrospective design with varied baseline factors.
(Khaldi et al., 2010).	Yearly cohort	Mixed (adults)	Post-cranial surgery monitoring	Low predictive value for routine CT scans	Imaging only for neurological changes	Imaging-guided return to surgery	Urgent CT scans more useful than routine ones for detecting surgical needs.	No standardization in CT timing.
(Wang et al., 2018)	140	Adults (mixed)	Elective craniotomy	Reduced pain, shorter hospital stay	ERAS protocol	Early nutrition, mobilization, and multimodal pain relief	ERAS protocol decreased hospital stay and pain duration while improving recovery outcomes compared to conventional perioperative care.	Limited to elective craniotomy.
(Tierney et al., 2016)	10 years of data	Adults (mixed)	Mild traumatic brain injury	Higher mortality and poorer outcomes (delayed)	Early CT scans, timely intervention	Immediate neurosurgical intervention for critical cases	Delayed intervention increased mortality (25% vs 9%) and worsened neurological outcomes compared to immediate intervention.	Retrospective design; limited control of confounders.
(Dey et al., 2015)	250 (CLEAR III)	Adults (mixed)	Intraventricular hemorrhage	Low bleeding, bacterial meningitis (4.4%)	Randomization, systemic monitoring	Drainage adjustment, targeted infection treatment	Symptomatic hemorrhage rate was 2.4%; bacterial meningitis occurred in 4.4% of cases. Rates were lower compared to historical data in systematic reviews.	Limited generalizability due to trial-specific conditions.

(Hutter et al., 2014)	Not specified	Adults (mixed)	Elective craniotomy	CSF leakage (13.5%), invasive treatment (3.5%)	TachoSil dural sealant	Revision surgery, invasive drainage	Diabetes, elevated CRP, and dural patch use are risk factors. TachoSil may reduce CSF leakage but differences were not statistically significant.	Single-center study; statistical insignificance.
(Karic et al., 2017)	Not specified	Adults (mixed)	Aneurysmal subarachnoid hemorrhage	Reduced vasospasm severity	Early rehabilitation, mobilization	Early hydrocephalus detection and treatment	Early mobilization is safe, reduces vasospasm frequency and severity, and facilitates earlier hydrocephalus management.	Limited to aSAH cases.
(Zaidi et al., 2015)	Retrospective data	Adults (mixed)	Ruptured intracranial aneurysms	31.2% required ventriculoperitoneal shunt	None	Shunt placement for hydrocephalus	Intraventricular and intraparenchymal hemorrhages are independent predictors of shunt dependency. Better long-term outcomes in patients not requiring a shunt.	Retrospective design; no additional data collected.
(Titsworth et al., 2012)	All ICU patients	Adults (mixed)	Neurological ICU admissions	Lower catheter-associated UTI rates	UTI prevention bundle	Early catheter removal, infection-specific treatment	UTI rate reduced from 13.3 to 4.0 per 1,000 catheter days. Utilization rate dropped from 100% to 73.3% during intervention without adverse effects.	Single-institution study; specific to ICU.
(Khaldi et al., 2010)	Yearly cohort	Adults (mixed)	Post-cranial surgery monitoring	Missed acuity changes in early CT scans	Delay CT for neurological deficits only	Emergency reoperation based on new neurological symptoms	Routine early CT scans not predictive for reoperation needs; delayed scans more effective in detecting evolving findings influencing postoperative management.	Retrospective review; no standard CT timing.
(Akins et al., 2014)	Retrospective data	Adults (mixed)	Acute ischemic stroke	Lower complications with Solitaire device	Use of Solitaire device	Minimizing procedural complications	Solitaire device had significantly fewer complications compared to Merci device (e.g., symptomatic hemorrhage 1.1% vs. 10.9%).	Retrospective design; no patient-specific predictors identified.
(Shah et al., 2022)	715 survivors	Adults (mixed)	Severe ICH/IVH	Long-term functional impairments	Comprehensive hospital care	Resolution of ICH/IVH, targeted management of comorbidities	40% of survivors with poor initial outcomes (mRS 4-5) recovered to good outcomes by 1 year. Hospital events like perfusion and sepsis affected long-term recovery predictions.	Post-hoc analysis; limited by original trial design.
(Mutoh et al., 2014)	160	Adults (mixed)	Subarachnoid hemorrhage	Delayed cerebral ischemia (DCI)	Early goal-directed fluid therapy	Preload volume and cardiac output monitoring	Early goal-directed therapy (EGDT) reduced DCI and improved functional outcomes in poor-grade patients compared to standard therapy.	Results applicable primarily to poor-grade cases.

(Sondag et al., 2020)	Meta-analysis	Adults (mixed)	Supratentorial intracerebral hemorrhage	Mortality reduction with hematoma evacuation	Early minimally invasive neurosurgery	Hematoma evacuation vs standard management	Minimally invasive hematoma evacuation may reduce mortality and improve outcomes but needs further high-quality trials for standard recommendation.	High bias in included studies; methodological limits.
(Gomis et al., 2010)	95	Adults (mixed)	Aneurysmal subarachnoid hemorrhage	No reduction in vasospasm	High-dose methylprednisolone treatment	Functional outcome assessment at 1 year	Methylprednisolone improved 1-year functional outcomes but did not affect symptomatic vasospasm incidence.	Small sample size; single trial.
(Titsworth et al., 2016)	16-month data	Adults (mixed)	Neurointensive care unit patients	Reduced infections and length of stay	Progressive Upright Mobility Protocol (PUMP) Plus	Safe mobilization in ICU	300% increase in mobility reduced ICU length of stay, hospital-acquired infections, ventilator-associated pneumonia, and restraint use without increasing adverse events.	
(Maslink et al., 2019)	48,963	<65, 65–74, 75–84, 85+ years	Subdural hematoma evacuation, brain tumor resection, or degenerative spine procedures	In-hospital mortality and complication rates	Focus on managing comorbidities and ensuring elective status.	Consider comorbidities and elective/non-elective status when deciding treatment.	Advanced age does not universally predict worse neurosurgical outcomes. Predictors include comorbidities and non-elective procedures.	Retrospective data; limited by database completeness.
(Maldaner et al., 2018)	Matched cohorts	≥80 vs. 55–75 years	General neurosurgical procedures	Higher Clavien-Dindo Grade 2 complications (less severe but more frequent pharmacological interventions).	Focus on optimizing patient functional status at admission.	Classification of complications using Clavien-Dindo grading; emphasis on pharmacological management for milder complications.	Similar morbidity and mortality rates between octogenarians and younger cohorts; functional status at admission key for outcomes.	Limited to matched cohort design; generalizability to broader populations limited.
(Maugeri et al., 2016)	Not specified	≥65 years	Elective craniotomy	Neurological (14%) and systemic (23%) complications, long-term care issues.	Preoperative functional assessments using tools like Karnofsky Performance Status.	Management tailored to identified risks: increased anesthesia time and estimated blood loss.	Preoperative motor deficit and altered mental status increase risks. Smoking history and CHF are notable predictors.	Retrospective; no randomization. Dependent on medical record accuracy.
(Edlmann and Whitfield, 2020)	Not mentioned	Older patients	Neurosurgery in older adults	Not detailed	Shift focus from age to frailty.	Use frailty assessment tools for surgical eligibility.	Less invasive neurosurgical techniques can benefit patients with comorbidities if outcomes are promising.	No specific outcomes reported; theoretical discussion.
(Johans et al., 2017)	≥65 years	Not specified	Elective craniotomy	Neurologic complications (14%), systemic/infectious complications (23%).	Functional assessments and identification of patient-specific risks.	Anesthesia adjustments; post-op monitoring for LTC and neurologic complications.	Pre-op motor deficits and comorbidities are key predictors of complications and mortality.	Retrospective study; reliance on existing medical records.
(Steinberger et al., 2018)	Not specified	>80 years	Craniotomy for meningioma resection	Higher risk of complications, mortality, and prolonged hospital stay.	Standardized pre-op and post-op care protocols.	Emphasis on pre-op risk stratification and resource optimization for octogenarians.	Advanced age (>80) is an independent risk factor for complications and prolonged stay.	Database-dependent retrospective study design.

(Kotekar et al., 2018)	Not detailed	Elderly patients	Elective neurosurgical procedures	Cognitive dysfunction (POCD).	Comprehensive geriatric assessments and perioperative care bundles.	Enhanced recovery protocols; focus on early mobility and optimized pain management.	POCD is preventable with early identification and targeted geriatric interventions.	Narrative review without experimental validation.
(Ferroli et al., 2021)	Not specified	≥65 years	Brain tumor resection	Post-op complications (severity graded) influence short- and long-term outcomes.	Individualized surgical and medical management; pre-op MRI and intra-op monitoring.	Long-term outcomes primarily affected by complications rather than age or prior conditions.	Retrospective; limited control over pre-op variability.	
(Algahtani and Merenda, 2021)	Not mentioned	Multimorbid patients	General neurosurgery for multimorbid ICU patients	Cardiopulmonary complications.	Tailored perioperative strategies; address chronic comorbidities pre-surgery.	Individualized management approaches for complex patient profiles.	General discussion without specific metrics or endpoints.	
(Nia et al., 2020)	30,183	≥65 vs. <65 years	Brain tumor surgery	Higher risks of complications and adverse outcomes in elderly patients.	Risk stratification using tools like ASA classification; address metabolic syndromes.	Early interventions for high-risk groups; improved perioperative coordination.	Age-related risks are mediated by comorbidities and preoperative status.	Retrospective database analysis with inherent limitations.