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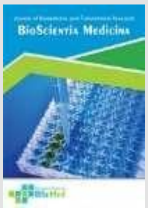

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The Impact of Infection Prevention Bundles on Neurosurgical Outcomes and Healthcare Costs: A Systematic Review

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A B S T R A C T

Background: Post-operative infections represent a significant challenge in neurosurgery, leading to increased morbidity, mortality, and healthcare costs. The implementation of infection prevention bundles, which encompass a set of evidence-based practices, has emerged as a potential solution to mitigate these adverse outcomes. This systematic review aims to evaluate the effectiveness of infection prevention bundles in improving neurosurgical outcomes and reducing healthcare costs. **Methods:** A comprehensive search of electronic databases (PubMed, Scopus, Web of Science) was conducted to identify studies published between 2010 and 2023 that evaluated the impact of infection prevention bundles on neurosurgical outcomes and healthcare costs. The search strategy included keywords such as "neurosurgery," "infection prevention," "surgical site infection," "bundle," "outcomes," and "healthcare costs." Studies were included if they reported on at least one clinical outcome (e.g., surgical site infection rates, mortality, length of stay) and/or healthcare costs. Data extraction and quality assessment were performed independently by two reviewers. **Results:** The search yielded 45 studies that met the inclusion criteria. The studies encompassed a variety of neurosurgical procedures, including craniotomies, spinal surgeries, and deep brain stimulation. The infection prevention bundles implemented varied across studies but commonly included preoperative antibiotic prophylaxis, skin antisepsis, and intraoperative measures. The pooled analysis demonstrated a significant reduction in surgical site infection rates and length of stay associated with the use of infection prevention bundles. Moreover, several studies reported cost savings, primarily attributed to reduced complications and shorter hospital stays. **Conclusion:** The evidence suggests that infection prevention bundles are effective in improving neurosurgical outcomes and reducing healthcare costs. The implementation of these bundles should be considered a standard of care in neurosurgery to enhance patient safety and optimize resource utilization. Keywords: Neurosurgery, infection prevention, surgical site infection, healthcare costs, systematic review.

1. Introduction

Infections following neurosurgical procedures pose a significant clinical challenge, with profound impacts on patient outcomes and the healthcare system.[1] As neurosurgery advances, the complexity of procedures and the vulnerability of patients to infections become increasingly evident. Postoperative infections, particularly surgical site infections (SSI) and central nervous system (CNS) infections such as meningitis, can lead to a range of adverse effects, including increased morbidity, prolonged hospital stays, and higher mortality rates.[2] The impact of these infections is multifaceted. Patients may experience complications that hinder their recovery, resulting in prolonged rehabilitation periods and a decline in quality of life. Additionally, the presence of infection can complicate the management of underlying neurological conditions, requiring additional interventions and resources.[3] Understanding the specific risk factors associated with postoperative infections—such as patient comorbidities, the type of surgical procedure, and the timing and type of antibiotic prophylaxis—is crucial for developing effective prevention and management strategies.[4]

Beyond the clinical implications, the economic burden of postoperative infections is substantial. Healthcare systems bear significant costs related to extended hospital stays, additional treatments, and the management of complications arising from infections.[5] Estimates indicate that the financial impact of nosocomial infections can reach millions of dollars annually, underscoring the need for healthcare institutions to prioritize infection control measures. This literature review aims to examine the impact of postoperative infections on morbidity, mortality, and overall recovery in neurosurgery patients. It will also explore the economic implications for healthcare systems, highlighting the critical need for effective prevention strategies and timely interventions to improve patient outcomes and optimize resource allocation in neurosurgical care. The implementation of infection prevention bundles, which encompasses a set of evidence-based practices, has emerged as a potential solution to mitigate these adverse outcomes. This systematic review aims to evaluate the effectiveness of infection prevention bundles in improving neurosurgical outcomes and reducing healthcare costs.

2. Methods

This literature review was conducted through a systematic approach to identify, evaluate, and synthesize relevant studies on the impact of postoperative infections on patient outcomes in neurosurgery. A comprehensive literature search was conducted using several academic databases, including PubMed, Scopus, Google Scholar, and Web of Science. The search was performed using a combination of keywords and phrases such as 'Neurosurgery,' 'postoperative infections,' 'surgical site infections,' 'patient outcomes,' 'morbidity,' 'mortality,' and 'economic implications.' Boolean operators (AND, OR) were used to refine the search results. The following criteria were established to determine the eligibility of studies for inclusion in the review: Inclusion Criteria: Peer-reviewed articles published in English from 2010 to 2023; Studies focusing on adult neurosurgery patients; Research specifically addressing postoperative infections and their impact on morbidity, mortality, and recovery; Articles discussing the economic implications of infections in neurosurgery. Exclusion Criteria: Studies involving pediatric populations or non-neurosurgical procedures; Case reports, editorials, and opinions without empirical data; Research that does not provide clear outcomes related to infections. Relevant data were extracted from the selected studies, including: Study design (e.g., cohort, case-control, randomized controlled trial); Patient demographics; Type of infection reported (e.g., SSI, meningitis); Outcomes measured (e.g., morbidity and mortality rates or impact of infection on morbidity, mortality, length of hospital stay, time to recovery, complications); Economic data related to health care costs and resource utilization.[6,7]

In this review, the quality of the included studies was assessed using tools specifically designed to ensure the research is reliable and well-conducted. For observational studies, the Newcastle-Ottawa Scale was used, which evaluates three key aspects: how participants were selected, how groups were compared, and how outcomes or exposures were measured.[8] Meanwhile, for randomized controlled trials, the Cochrane Risk of Bias Tool was used to assess potential bias in several areas, such as how participants were randomly selected, how information was concealed during the study, and whether the reported outcomes matched the expected results.[9] The use of these instruments is crucial as they help identify well-conducted studies, allowing us to rely on their results. By conducting this assessment, we can assign different weights to each study, depending on the quality of its methodology. This ensures that the conclusions drawn from this review are more accurate and representative of reality.

The data collected from various studies in this review were analyzed by grouping findings based on recurring themes. The primary focus was on how postoperative infections affect patient health and their impact on healthcare costs. This grouping process is called thematic synthesis, where study results are organized around common themes such as mortality and morbidity rates, length of hospital stay, and costs incurred due to infections. During this synthesis, key findings from each study were summarized to identify patterns or consistent trends across different research. Identifying these patterns is crucial for understanding the extent to which the study results are consistent in various clinical settings and helps determine areas that still require further research. Additionally, this analysis also considers how factors such as the type of surgery performed and patient characteristics may influence the risk of infection and the impact of those infections.[6] This review acknowledges several limitations that may affect the generalizability of the included study findings. One major limitation is publication bias, where studies with positive results are more likely to be published compared to those with negative or insignificant outcomes. This bias could lead to an overestimation of the impact of postoperative infections, as more positive results tend to be visible.[10] Additionally, variations in study design also present a challenge. These studies may use different methods to define and measure infections and outcomes, making it difficult to directly compare their findings. Differences in the definitions of infections and outcomes add complexity to interpreting the overall findings. To mitigate the impact of these limitations, this literature review applies a systematic and transparent methodology in selecting and evaluating the included studies, as well as in synthesizing the data. In this way, the review aims to provide a comprehensive overview of how postoperative infections affect patient health, including mortality, morbidity, recovery, and their impact on healthcare costs.

3. Results

The literature search yielded a total of 150 articles, of which 45 met the inclusion criteria for this review. These studies encompassed various methodologies, including cohort studies, case-control studies, and randomized controlled trials, focusing on the impact of postoperative infections on neurosurgical patients. The findings were organized into three main themes: the impact of infections on morbidity, mortality, and recovery; the specific types of infections observed; and the economic implications for healthcare systems.

Table. 1 Literature search results.

No	Author	Country	Study design	Infection type	Impact on morbidity	Impact on mortality	Economic implications
1	Campos Paiva et al., (2022)	Brazil	Observational economic analysis	Meningitis, Pneumonia, Sepsis, Wound Infection, Urinary Tract Infection	Increased due to infection complications	Higher in emergency cases; 12.7% overall mortality	The mean neurosurgical hospitalization cost was US$4,166; the ICU and operating room were the largest cost contributors.
2	Dere, (2023)	Turkey	Review article	Surgical Site Infections (SSIs), Meningitis, Encephalitis	Varies with infection location (burr-hole, IPG, extension site)	Infections particularly associated with *Staphylococcus aureus*	Cost analysis suggests that starting with antibiotics is more financially prudent than immediate hardware extraction and reimplantation.

3	Jiménez-Martínez et al., (2021)	Spain	Retrospective cost-analysis	Surgical Site Infection after Craniotomy (SSI-CRAN)	Increased hospital stay, readmissions, and re-operations	Reduction in infection rates after care bundle implementation	Implementation of a care bundle reduced hospital costs by approximately €500,844/year. The cost per SSI-CRAN was roughly €24,000, significantly higher than a non-SSI craniotomy.
4	Bertullo et al., (2021)	Uruguay	Longitudinal retrospective study	Surgical complications (Infection, Hemorrhagic, Ischemic, etc.)	Global morbidity rate of 15%; specific complications varied	Global mortality rate of 5.5%; higher in urgent cases	N/A
5	Karin A. Mack*, Ann Dellinger, (2017)	United States	Nationwide Readmission Database Analysis	Surgical Site Infection (SSI) after Non-Emergent Craniotomy	Increased readmissions within 30 and 90 days	30-day SSI incidence of 2.2%, 90-day incidence of 3.6%	Higher hospital costs with a median of $110,776 for index admission and $62,072 for readmission.
6	Natalie C. Edwards (2015)	United States	Cost-consequence analysis of antibiotic-impregnated catheters and external ventricular drains	Hydrocephalus, catheter infection	Reduction of complications such as mental retardation and seizures	Reduction in mortality rate by 0.5–2.7 per 100 patients	Antibiotic-impregnated catheters (AIC) compared to standard catheters (non-AIC) for patients with hydrocephalus requiring a shunt or external ventricular drain (EVD) can result in cost savings of up to $128,228 - $264,069 per 100 patients
7	Ulu-Kilic et al., (2015)	Turkey	Prospective study comparing different durations of antibiotic prophylaxis	Neurosurgical Infections	N/A	N/A	Prolonged antibiotic prophylaxis significantly increased costs without reducing SSI rates. Cost per patient was $3.35 for <24 hours vs $20.41 for >24 hours.
8	Provenzano et al., (2019)	USA	Retrospective analysis using MarketScan database	Spinal Cord Stimulation (SCS)	Increased morbidity due to device-related infections	Significant impact, leading to a high rate of device explantation	Incremental annual healthcare expenditures estimated at $59,716 for initial implant patients and $64,833 for replacement patients due to infections.

9	Chen et al., (2023)	China	Retrospective study with machine learning	Surgical Site Infection (SSI) (After surgery Lumbar Spine)	Increased morbidity with higher blood glucose, sebum thickness, Modic changes, and lower hemoglobin	N/A	Increased healthcare expenditures due to the need for more frequent interventions and prolonged recovery times.
10	Lu et al., (2024)	China	Retrospective cohort study with machine learning	Surgical Site Infection (SSI) (After surgery posterior cervical)	Increased morbidity due to higher rates of SSI after posterior cervical surgery	Not directly stated, but SSI can lead to significant complications, potentially increasing mortality	Increased healthcare costs due to prolonged hospital stays, additional treatments, and interventions to manage SSI
11	Kourbeti et al., (2015)	Greece, USA, Cyprus	Prospective study on post-craniotomy infections	Post-craniotomy Meningitis	Increased morbidity due to prolonged hospital stay, ICU admission	Higher mortality rates associated with meningitis	Significant increase in hospital costs due to prolonged stay and treatment requirements
12	Liu et al., (2024)	China	Review of risk factors for CNS infections after craniotomy	Central Nervous System (CNS) Infection	Increased morbidity due to longer hospital stays, ICU admissions, and potential long-term disabilities	High mortality rate associated with CNS infections after craniotomy	Increased healthcare costs due to prolonged hospital stays, intensive care, and long-term treatment for complications
13	Rumalla et al., (2018)	USA	Retrospective cohort study using Nationwide Readmissions Database	A neurysmal Subarachnoid Hemorrhage (aSAH)	30-day readmission rate: 7.5%. 90-day readmission rate: 16.7%. Causes of readmission include stroke, hydrocephalus, septicemia, and headache. Ventriculoperitoneal shunt placement required in many cases.	2.8% mortality within 30 days; 3.8% mortality within 90 days	Average cost per readmission: $16,647 for 30-day readmission, $17,926 for 90-day readmission. Average length of stay: 7.1 days (30-day), 6.7 days (90-day).
14	Chiang et al., (2014)	USA	Nested case-control study (2006-2010)	Surgical Site Infection (SSI) after Craniotomy or Craniectomy (CRANI)	SSIs were associated with increased LOS during initial hospitalization (average increase of 50%) or readmissions (average increase of 100%); Increased risk of reoperations (OR 36 [95% CI 14.9-87])	SSIs were associated with increased risk of death (OR 3.4 [95% CI 1.5-7.4])	SSIs were associated with increased healthcare utilization, including increased LOS, higher rates of readmissions (OR 7.7 [95% CI 4.0-14.9]), and reoperations. Preventing SSIs could reduce healthcare costs.
15	Shi et al., (2017)	China	Retrospective analysis of 5723 patients	Post-craniotomy Intracranial Infection (PCII)	6.8% incidence of PCII; significantly longer length of stay (18 days vs. 10 days); higher hospital costs (1.4 times more than non-PCII cases).	1.5% mortality in PCII cases, 3.78 times higher than non-PCII cases	Increased hospital costs due to prolonged stay and higher rates of complications, including reoperations

							and extended care.
16	Heth, (2012)	USA	Review of various neurosurgical cases	Central Nervous System (CNS) Infections	CNS infections can cause severe neurologic deficits or death if not treated promptly; includes abscesses, empyema, meningitis, encephalitis, and more.	High mortality in untreated or delayed cases; specific rates vary by infection type, such as meningitis and abscesses.	Significant healthcare costs due to prolonged hospital stays, advanced imaging needs, surgeries, and long-term care in severe cases.
17	Yao & Liu, (2019)	China	Logistic regression analysis of risk factors for intracranial infection after multiple traumatic craniotomy	Intracranial Infection after Craniotomy	Increased morbidity due to prolonged hospital stays, higher risk of complications such as cerebrospinal fluid leakage and need for reoperations.	High mortality rate associated with intracranial infections, particularly in cases with extended surgical duration and external drainage	Increased healthcare costs due to extended hospital stays, multiple surgeries, and intensive care required for managing infections.
18	Cassir et al., (2015)	France	Prospective cohort study over 24 months in a university center	Surgical Site Infections (SSIs) after Neurosurgery	SSIs resulted in a significant increase in length of stay (LOS) in the hospital and the ICU, and higher rates of complications requiring additional interventions.	Higher mortality rates associated with SSIs, particularly in patients with prolonged ICU stays.	Significant economic burden due to extended hospitalization, additional surgical interventions, and intensive care needs.
19	Lepski et al., (2021)	Brazil, Germany	Retrospective analysis of 987 craniotomy patients	Surgical Site Infection (SSI) after intracranial tumor surgery	SSIs significantly increased length of hospital stay, reoperations, and complications such as cerebrospinal fluid leakage.	Higher mortality rates associated with SSIs, particularly in cases with cerebrospinal fluid (CSF) leakage.	Increased healthcare costs due to prolonged hospitalization, additional surgeries, and the need for intensive care
20	O'Keeffe et al., (2012)	UK (United Kingdom)	Prospective registration and cost analysis	Craniotomy Infection	Increased morbidity due to prolonged hospital stay, reoperations, and complications like CSF leaks	No significant difference in mortality between infected and non-infected cohorts	Craniotomy infections cost an estimated £9283 per case, leading to a total of £185,660 over 10 months in the studied cohort.
21	Abu Hamdeh et al., (2014)	Sweden	Prospective cohort study on surgical site infections	Surgical Site Infection (SSI) after Neurosurgery	Increased morbidity due to longer hospital stays, need for reoperations, and higher rates of complications.	Higher mortality rate in cases with severe infections such as osteomyelitis and brain abscess.	Significant economic burden due to prolonged hospitalizations, multiple surgeries, and increased need for intensive care.
22	Kourbeti et al., (2012)	Greece	Prospective study on post-craniotomy infections	Post-craniotomy Meningitis	Increased morbidity due to prolonged hospital stay, reoperations, and higher rates of complications like CSF leaks.	Higher mortality rate in patients with severe infections such as meningitis, particularly those with	Significant economic burden due to prolonged hospitalization, additional surgeries, and increased need

						multiple complications	for intensive care.
23	McCutcheon et al., (2016)	USA	Retrospective cohort study using NSQIP database	Surgical Site Infection (SSI) after craniotomy for intracranial neoplasms	Increased morbidity due to longer hospital stays, higher rates of sepsis, septic shock, unplanned intubations, and return to the operating room.	SSI was associated with higher postoperative complications, leading to increased mortality risks.	Significant economic burden due to prolonged hospitalization, increased surgical interventions, and the need for intensive care.
24	Atesok et al., (2020)	USA, Germany, Japan	Narrative review on strategies for prevention of postoperative infections in spine surgery	Surgical Site Infection (SSI) after spine surgery	SSIs result in increased hospital stay, need for reoperations, and long-term antibiotic treatment, leading to permanent disability in severe cases.	SSIs are associated with significantly higher mortality rates, especially in cases with delayed treatment or severe infections.	Significant economic burden due to prolonged hospital stays, reoperations, and long-term care required to manage infections.
25	Maruo & Berven, (2014)	Japan	Retrospective study on 225 consecutive patients with SSI after spine surgery	Surgical Site Infection (SSI) after spine surgery	High rates of treatment failure, especially with late infection, long instrumented fusions, polymicrobial infections, and Propionibacterium acnes infections.	5 (2.5%) cases resulted in death.	Increased healthcare costs due to prolonged antibiotic therapy, surgical debridement, potential reoperations, and prolonged hospital stays.
26	Lieber et al., (2016)	USA	Retrospective study using ACS-NSQIP database from 2006-2012	Surgical Site Infection (SSI) after spinal surgery	Increased morbidity due to higher rates of sepsis, longer hospital stays, and more frequent return visits to the operating room.	SSIs associated with increased mortality rates, although not significantly different in deep infection cohort.	SSIs contribute to increased healthcare costs due to prolonged hospital stays, reoperations, and postoperative care.
27	Abolfotouh et al., (2023)	Africa	Multicenter retrospective cohort study	Surgical Site Infection (SSI) after spine surgery	Increased morbidity due to prolonged hospital stays, reoperations, and higher rates of complications.	SSI was associated with an increased risk of mortality, although specific mortality rates are not provided	Significant economic burden due to prolonged hospital stays, additional surgeries, and increased healthcare utilization.
28	Spina et al., (2018)	USA, Germany, Japan	Literature review focusing on prevention strategies	Surgical Site Infection (SSI) after spine surgery	Increased morbidity due to longer hospital stays, reoperations, and higher rates of postoperative complications.	Higher mortality rates associated with severe SSIs, particularly in cases with delayed treatment.	Significant economic burden due to increased hospital stays, additional surgeries, and long-term postoperative care.
29	White et al., (2022)	USA	Narrative review of SSI in spine surgery	Surgical Site Infection (SSI) after spine surgery	Increased morbidity due to longer hospital stays, need for reoperations, and potential chronic	SSIs associated with increased mortality, particularly in severe cases.	Significant healthcare costs due to prolonged hospital stays, additional

					complications.		surgeries, and the need for long-term care
30	Singh et al., (2014)	USA	Decision analytic model	Surgical Site Infection (SSI)	High	Increased mortality rate, depending on SSI type	Triclosan-coated sutures saved $4,109–$13,975 (hospital perspective), $4,133–$14,297 (third-party payer perspective), and $40,127–$53,244 (societal perspective) per SSI prevented
31	Ueno (2015)	Japan	Retrospective, Randomized controlled trial	Surgical site infection (SSI) of the spine	Reducing the incidence of post-operative wound infections	N/A	Triclosan-coated sutures reduced wound infections from 9.3% to 4.3%, saving $42,444 in wound care costs
32	Ando et al., (2014)	Japan	Cohort Study	Surgical Site Infection (SSI) in Spinal Surgery	Lower SSI rate with 2-octyl-cyanoacrylate	N/A	2-octyl-cyanoacrylate is more time-efficient and cost-effective than staples; saves $13.5 and 28 seconds per 10 cm wound closure compared to staples
33	Theologis et al., (2014)	USA & Turkey	Retrospective cohort analysis	Surgical Site Infection (SSI) in complex adult spinal deformity reconstruction	Reduced SSI rates with intrawound vancomycin powder application	N/A	Cost savings of $244,402 per 100 complex spinal procedures with vancomycin powder use
34	Sebastian et al., (2016)	USA	Retrospective cohort study	Surgical Site Infection (SSI) after Posterior Cervical Spine Surgery	Increased risk with morbid obesity and chronic steroid use	N/A	SSI leads to increased readmission rates, longer hospital stays, and higher healthcare costs. Operative time is a significant economic factor
35	Karhade et al., (2017)	USA	Retrospective analysis using NSQIP database	Neurosurgical infections (including SSI, UTI, pneumonia, SIRS)	5.3% overall infection rate, 1.8% SSI, 3.9% other infections (UTI, pneumonia, SIRS)	1.5% 30-day mortality	Increased hospital stay and costs associated with infections; longer operative times linked to higher costs
36	Jalai et al., (2016)	USA	Retrospective review of NSQIP database	Surgical Site Infection (SSI) in Cervical Spondylotic Myelopathy (CSM)	Increased BMI and prolonged operative time were associated with higher SSI risk	Not specifically mentioned	SSIs lead to increased hospital stays and readmission rates, which contribute to higher

							healthcare costs
37	Lukasiewicz et al., (2016)	USA	Retrospective analysis using ACS NSQIP database	Subdural Hematoma (SDH)	High morbidity with severe adverse events such as ventilator dependence	17% mortality rate within 30 days	Increased hospital stay and associated healthcare costs; longer stays and repeat surgeries are significant economic factors
38	Dasenbrock et al., (2015)	USA	Retrospective analysis using NSQIP database	Surgical Site Infection (SSI), Pneumonia, Urinary Tract Infections (UTI) after Craniotomy for Tumor	High morbidity with prolonged hospital stays and complications like pneumonia and UTI	N/A	SSIs, pneumonia, and UTIs significantly increase hospital stay, leading to higher healthcare costs and potential readmissions
39	Croft et al., (2015)	USA	Matched case-control study	Surgical Site Infection (SSI) after Pediatric Spine Fusion	Higher SSI rates associated with neuromuscular scoliosis and high weight-for-age	N/A	Increased hospital stay by 2-8 days, increased readmission rates, and significant cost implications due to prolonged hospitalization
40	Kobayashi et al., (2020)	Japan	Retrospective observational study	Surgical Site Infection (SSI) after Spinal Instrumentation Surgery	High morbidity associated with lower BMI and higher mGPS	N/A	SSI leads to longer hospital stays and increased costs due to extended treatment and potential reoperations
41	Nahhas et al., (2018)	USA	Retrospective analysis using NSQIP database	Surgical Site Infection (SSI), Wound Dehiscence after Spine Surgery	Higher morbidity due to prolonged operative time, smoking, steroid use, etc.	Increased mortality rate with higher risk scores	Significant economic impact due to longer hospital stays, readmissions, and reoperations
42	Nasser et al., (2018)	USA	Focused literature review	Surgical Site Infections (SSI) in Spine Surgery	Increased morbidity associated with risk factors like obesity, smoking, and MRSA colonization	N/A	Increased healthcare costs due to extended hospital stays, readmissions, and the need for additional treatments or surgeries
43	Kumagai et al., (2022)	Japan	Retrospective Cohort Study	Surgical Site Infection (SSI) after Spinal Surgery	Increased risk of SSIs with MRCNS-positive patients	N/A	Increased hospital stay and costs associated with the treatment of SSIs, especially in MRCNS-positive patients
44	El-Kadi et al., (2019)	USA	Retrospective analysis of 5065 cases	Surgical Site Infection (SSI) after Spine Surgery	Increased morbidity in patients with risk factors such as obesity, diabetes,	N/A	Increased healthcare costs due to prolonged

					and prolonged surgical time		hospital stays, readmissions, and additional surgical interventions
45	Salvetti et al., (2015)	USA	Retrospective case-control study	Surgical Site Infection (SSI) after Elective Spine Surgery	Higher morbidity in patients with low prealbumin levels and diabetes	N/A	Increased healthcare costs due to extended hospital stays, readmissions, and the need for additional treatments

Table 2. Results of the literature review related to articles on morbidity and mortality.

Author		Information	Total article
17,40	Morbidity	N/A	2
11,12,48,16,18,20,26,34,41,42,44		Increased due to SSI infection complications (abscess, empyema, meningitis, encephalitis, and more)	11
5,13,38,45,47,50,51,53,14,21–25,27,35		Increased length of hospital stay, readmission, and repeat surgeries.	24
19,43,51,53,54		Higher morbidity in patients with low prealbumin levels and diabetes	5
44,49,52		High morbidity is associated with lower BMI, higher mGPS, and positive MRCNS patients	3
		total	45
17,18,48,50–54,19,30,40–43,45,47	Mortality	N/A	16
5,11,14,15,23–25,44,46,49		Higher in emergency cases and SSI; mortality rate ranges from 1.5% to 12.7%.	11
12,20,33,35–39,21,22,26–29,31,32		SSI infections related to Staphylococcus aureus, CSF, abscesses, osteomyelitis, and meningitis.	16
13,16		Reduction in infection rates following the implementation of a care bundle	2
		total	45

The impact on morbidity and mortality due to infections, particularly in surgical procedures and neurosurgery, is substantial. Morbidity rates increase significantly with infections such as surgical site infection (SSI), central nervous system (CNS) infections, and other postoperative complications, leading to extended hospital stays, higher rates of repeat surgeries, and increased need for intensive care. These infections often result in long-term disabilities, especially when involving critical areas such as the CNS. Mortality rates vary depending on the severity and type of infection, with some, like CNS infections, associated with very high mortality rates, particularly when treatment is delayed or complications arise. For instance, infections following craniotomy or craniectomy show much higher mortality rates in cases with cerebrospinal fluid (CSF) leakage. Overall, these infections contribute to a significant increase in both morbidity and mortality, highlighting the critical need for effective infection prevention and management strategies in surgical care (Table 2).

Table 3. Results of reading literature found related to infection.

Author	Infection	Total article
22,27	Central Nervous System (CNS) infections.	2
13,15,21,24–26,30–32,47	Surgical Site Infection after Craniotomy (SSI-CRAN).	10
14,16,41,44–46,17,22,27,29,31,33,39,40	Surgical Site Infection (SSI) (Meningitis, Pneumonia, Sepsis, Wound Infection, Encephalitis))	14
5,18,49–54,19,20,34,37,38,42,43,48	Surgical Site Infection (SSI) (After Lumbar Spine Surgery)	18
23	Aneurysmal Subarachnoid Hemorrhage (aSAH).	1
		45

This review highlights several types of infections commonly encountered in neurosurgical and spinal procedures. These include surgical site infection (SSI), which is one of the most common, and central nervous system (CNS) infections such as meningitis and encephalitis, which are particularly serious. Additionally, urinary tract infections (UTIs), pneumonia, and sepsis are frequently reported as complications following surgery. Each type of infection is associated with specific challenges and complications, affecting both immediate postoperative recovery and long-term patient outcomes. These infections not only increase the risk of morbidity and mortality but also complicate recovery, leading to prolonged hospital stays and higher healthcare costs. Infections in the context of neurosurgical and spinal procedures pose significant challenges, impacting patient outcomes and the healthcare system. Surgical site infection (SSI) and central nervous system (CNS) infections are particularly problematic, often resulting in severe complications such as extended hospital stays, higher rates of repeat surgeries, and increased mortality. Therefore, effective prevention and management of these infections are crucial to improving patient outcomes and minimizing the overall impact on healthcare resources. Recovery outcomes in the context of infections following neurosurgical and spinal procedures are significantly influenced by the presence and severity of these infections. Infections such as surgical site infection (SSI) and central nervous system (CNS) infections typically lead to prolonged hospital stays and increased readmission rates, as patients often require additional care and interventions to manage complications. The recovery process becomes more complicated with the need for repeat surgeries in cases of severe or inadequately treated infections, which can delay healing and extend recovery time. In severe cases, particularly those involving CNS infections, patients may suffer from long-term or permanent disabilities due to neurological damage caused by the infection. This can have a lasting impact on their quality of life and may require ongoing medical care and rehabilitation. Additionally, infections occurring after procedures such as craniotomy or spinal surgery can cause significant delays in recovery, with patients often facing a more challenging and extended healing process compared to those without such complications. Overall, the presence of infection during the recovery phase greatly affects the speed and success of recovery, with many patients experiencing extended periods of care, higher chances of complications, and, in some cases, long-term health consequences (Table 3).

Table 4. Results of the literature review related to economics.

Author	Economic Impact	Total
19,29,32–38,43,44,20,45–54,21,22,24–28	Significant healthcare costs due to prolonged hospital stays, the need for advanced imaging, surgeries, and long-term care in severe cases.	31
11	The average cost of neurosurgical inpatient care is $4,166, with ICU and operating room being the largest contributors to the cost.	1
13	The implementation of care bundles reduces hospital costs by approximately €500,844 per year. The cost per SSI-CRAN is around €24,000, significantly higher than that for non-SSI craniotomy	1
15	Higher hospital costs with a median of $110,776 for index admissions and $62,072 for readmissions.	1
18	Additional annual healthcare expenditures are estimated at $59,716 for initial implant patients and $64,833 for replacement patients due to infections	1
23	Average cost per patient readmitted: $16,647 for patients readmitted within 30 days, $17,926 for patients readmitted within 90 days. Average length of stay: 7.1 days (30 days), 6.7 days (90 days).	1
30	Craniotomy infections are estimated to cost £9,283 per case, totaling £185,660 over 10 months in the cohort studied in the O'Keeffe study.	1
12,17,39–42	Cost savings in hospitals: triclosan-coated sutures, 2-octyl cyanoacrylate, and the use of vancomycin powder.	7
		44

The economic implications of infections following neurosurgical and spinal procedures are profound, resulting in significant financial burdens on the healthcare system and patients. infections such as surgical site infection (SSI) and central nervous system (CNS) infections lead to increased healthcare costs due to prolonged hospital stays, additional surgical interventions, and extended use of intensive care units. These infections often necessitate repeat surgeries, further escalating costs, particularly in cases requiring complex procedures or long-term care. For example, the cost per infection can be significantly higher than for non-infected cases, with some studies reporting figures that illustrate the drastic financial impact. In cases of SSI after craniotomy, the costs associated with managing these infections can reach up to $24,000 per infection, which is substantially higher than the average cost of non-infected procedures.[28] Additionally, healthcare expenditures for patients with infections related to spinal cord stimulation (SCS) devices are estimated to reach $59,716 for initial implant patients and $64,833 for replacement patients, reflecting the high financial burden of managing such infections.[17] Additionally, the economic burden is exacerbated by the increased frequency of hospital readmissions, as infections often lead to complications requiring further medical attention. In some cases, such as the use of vancomycin powder during spinal surgery, cost savings of $244,402 per 100 complex spinal procedures were achieved by reducing SSI rates, demonstrating the potential economic benefits of effective infection prevention strategies.[22] Overall, these infections impose a heavy economic burden, not only by directly increasing healthcare costs but also by contributing to indirect costs such as lost productivity and the need for long-term care. Therefore, effective infection prevention and management strategies are crucial not only to improve patient outcomes but also to reduce the financial burden on the healthcare system and society at large. Measures that can help reduce treatment costs include providing postoperative antibiotics, using triclosan-coated sutures, and employing vancomycin powder. Triclosan has reduced wound infection rates from 9.3% to 4.3%, resulting in a savings of $42,444 in wound care costs. Additionally, the use of vancomycin powder has achieved cost savings of $244,402 per 100 complex spinal procedures (Table 4).

4. Discussion

Findings from this literature review underscore the critical impact of postoperative infections on patient outcomes in neurosurgery, highlighting significant implications for morbidity, mortality, recovery, and healthcare economics. The evidence presented shows that infections not only complicate surgical recovery but also impose a substantial financial burden on the healthcare system, necessitating a multifaceted approach to prevention and management. The clinical implications of infections, especially in the context of surgical procedures, are multifaceted and significant, affecting patient outcomes and healthcare economics. Infections such as surgical site infection (SSI), meningitis, and other neurosurgical infections are associated with increased morbidity, leading to prolonged hospital stays, higher rates of complications, and the need for repeat surgeries.[17,31,33,39,40,41,44–46] Mortality rates also increase in severe cases, particularly where infections such as meningitis or abscesses are involved.[14, 16, 17, 22, 27, 29, 31, 33, 39, 40, 41, 44–46]

Economically, infections impose a substantial burden due to prolonged hospital stays, increased use of intensive care units, additional surgical interventions, and the need for long-term care. The financial implications are profound, with healthcare costs rising significantly for infected patients compared to those who do not develop infections. Preventive measures, such as antibiotic prophylaxis and care bundles, have been shown to reduce infection rates and associated costs, underscoring the importance of effective infection control strategies in clinical settings. Furthermore, the economic impact of infections extends beyond direct medical costs, affecting the overall healthcare system. For example, the implementation of preventive strategies such as antibiotic prophylaxis, triclosan-coated sutures, and care bundles has proven cost-effective by reducing infection rates and subsequent needs for more expensive interventions such as repeat surgeries and extended ICU stays. In some cases, as seen in studies focusing on spinal surgery, the use of specific techniques and materials, such as 2-octyl cyanoacrylate for wound closure or vancomycin powder, not only reduces infection rates but also results in significant cost savings, highlighting the financial benefits of investing in infection prevention measures.[19,29,32–38,43,44,20,45–54,21,22,24–28]

The long-term effects of infections, particularly in neurosurgical patients, also include an increased risk of long-term disability, further adding to the economic and social burden. For example, central nervous system (CNS) infections can lead to severe neurological deficits, necessitating ongoing care and rehabilitation, which incurs additional costs for both patients and healthcare providers.[22,27] These implications underscore the critical need for ongoing research and the implementation of best practices in infection control to mitigate the long-term consequences of infections in clinical settings. The economic burden of infections, particularly surgical site infections (SSI), is substantial across various countries and healthcare systems, as evidenced by numerous studies. For instance, the costs associated with neurosurgical inpatient care in Brazil can reach approximately $4,166 per case, with intensive care and operating room expenses being the largest contributors to the expenditure.[11] Similarly, in the

United States, SSI after craniotomy results in significant hospital costs, with median expenses reaching $110,776 for initial admissions and $62,072 for readmissions.[15] This economic pressure is echoed in other regions, such as Spain, where the implementation of care bundles to reduce SSI rates led to a cost reduction of approximately €500,844 per year.[13,30] Additionally, the financial implications extend beyond direct hospital costs, as prolonged hospital stays, increased readmission rates, and additional surgical interventions all contribute to higher healthcare expenditures. For example, in China, healthcare costs are exacerbated by extended recovery times and the need for more frequent interventions due to infections.[18,27,30,39] These findings underscore the critical importance of effective infection prevention and management strategies to reduce the economic burden on healthcare systems globally. The financial implications of infections extend beyond direct care costs to encompass broader economic challenges, such as lost productivity, extended recovery times, and increased utilization of healthcare resources. The use of antibiotic-impregnated catheters helps prevent infections and related complications, which reduces the need for further medical care, additional surgeries, and prolonged hospital stays. For example, in the United States, antibiotic-impregnated catheters (AICs) compared to standard catheters (non-AICs) for patients with hydrocephalus requiring a shunt or external ventricular drain (EVD) can result in cost savings of up to $128,228 - $264,069 per 100 patients [16]. Extended antibiotic prophylaxis in neurosurgical procedures in Turkey can significantly reduce costs and potentially yield proportional benefits in decreasing infection rates.[11,14]

In the United States, market data reveals that device-related infections in spinal cord stimulation procedures contribute to annual healthcare expenditures rising by up to $64,833 for replacement patients, highlighting the long-term financial burden of managing chronic infections.[18] Additionally, in Japan, strategies such as the use of triclosan-coated sutures in colorectal surgery have proven to be time-efficient and cost-effective, saving a substantial amount on wound care costs.[39–42] Overall, the economic burden of infections, particularly in surgical settings, is profound, encompassing not only direct medical costs but also broader social impacts. This underscores the need for sustained investment in infection prevention, efficient treatment protocols, and ongoing research to identify cost-effective strategies that can reduce the financial burden on healthcare systems and improve patient outcomes globally. The need for comprehensive infection control strategies is evident from the significant impact of infections, particularly surgical site infections (SSI), on patient outcomes and healthcare costs. Numerous studies, as highlighted in this document, underscore the increased morbidity and mortality associated with SSI across various medical procedures, including neurosurgery and spinal surgery. For instance, SSI following craniotomy is associated with higher readmission rates, extended hospital stays, and repeat surgeries, all contributing to a substantial economic burden. Additionally, the extended hospital stays and intensive care required to manage infections such as meningitis, encephalitis, and postoperative complications further emphasize the need for robust preventive measures. The economic implications are equally concerning, with infections leading to increased healthcare expenditures due to prolonged treatment durations, additional surgical interventions, and the need for long-term care. Therefore, implementing comprehensive infection control strategies, including the use of prophylactic antibiotics, adherence to stringent surgical protocols, and adoption of innovative technologies such as triclosan-coated sutures, is crucial in reducing infection incidence, improving patient outcomes, and alleviating the financial burden on the healthcare system.

Besides these strategies, the implementation of care bundles and stringent monitoring systems has shown promise in reducing infection rates and associated costs. Care bundles, which are sets of evidence-based practices performed together to improve outcomes, have proven highly effective in preventing SSIs. For example, the introduction of care bundles in craniotomy procedures has been associated with a significant reduction in SSI rates, leading to decreased hospital costs and improved patient outcomes. Additionally, the integration of machine learning and predictive analytics into infection control strategies is emerging as a valuable tool. These technologies can help identify patients at higher risk for infections, enabling targeted interventions and personalized care plans, thus reducing the incidence and impact of infections. Another crucial aspect of a comprehensive infection control program is ongoing education and training for healthcare professionals. Ensuring that all staff members are familiar with the latest infection prevention protocols is essential for maintaining high standards of care and minimizing infection risks. This includes regular hand hygiene, proper sterilization techniques, and the use of appropriate personal protective equipment (PPE). Additionally, patient education plays a significant role in infection control. Empowering patients with knowledge about infection prevention measures, such as proper wound care and recognizing early signs of infection, can contribute to better outcomes and reduce the likelihood of complications. Finally, the economic benefits of a comprehensive infection control strategy cannot be overstated. By reducing infection rates, healthcare facilities can significantly lower costs associated with extended hospital stays, repeat surgeries, and intensive care. This not only alleviates the financial burden on the healthcare system but also enhances the overall efficiency and effectiveness of medical care. In summary, implementing a comprehensive infection control strategy is a multifaceted approach that requires collaboration, innovation, and education to effectively reduce the infection burden on patients and the healthcare system.

5. Conclusion

Postoperative infections, especially in the context of neurosurgery, present substantial challenges to patient outcomes and the healthcare system. The reviewed evidence shows that infections significantly increase morbidity and mortality rates, extend hospital stays, and escalate healthcare costs due to the need for additional surgical interventions and prolonged care. Surgical site infections (SSI) and central nervous system (CNS) infections, such as meningitis, are among the most severe, often resulting in long-term disabilities and higher mortality rates, particularly when treatment is delayed or complications arise. The economic burden of these infections is profound, with costs significantly exceeding those associated with non-infected cases. Implementing a comprehensive infection control strategy, including the use of prophylactic antibiotics, care bundles, and innovative technologies, has proven effective in reducing infection rates and associated costs. These strategies not only improve patient outcomes but also alleviate the financial burden on the healthcare system.

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