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Meningitis Following Otologic Surgeries: A Systematic Review

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ABSTRACT

The review aimed to examine the incidence, etiology, and time course of meningitis as a postoperative sequela of otologic surgeries. A systematic review was performed following PRISMA guidelines using the PubMed, Cochrane, and Web of Science databases for all available published literature between 1960 and 2022. Studies were included if they specified the presence/absence of meningitis for subcategories of otologic surgical procedures, irrespective of the study's primary goal, and provided the number of patients. Additional studies were identified from reference lists. Non-English and non-human studies were excluded. 140 studies were reviewed for a total of 57,108 patients. 49.0% were male, and 57.5% were pediatric patients. There were 215 patients with meningitis, most commonly following cochlear implantation at 72.1% of the total cases. Inner ear malformations were noted in 38.3% of patients with meningitis. Streptococcus pneumoniae was the most common causative agent, followed by Pseudomonas aeruginosa, aseptic, and Haemophilus influenzae. The timing of meningitis ranged from 0 to 180 months post-otologic surgery. Vaccination status was reported in 14.3 to 34.7% of studies. The overall incidence of meningitis following otologic surgeries was 0.38%, from 1951-1999 was 0.35%, and from 2000-2020 was 0.39%. Meningitis post-otologic surgery continues to have an impact on pediatric and adult patients. Meningitis can occur immediately or after many years following otologic surgery, necessitating continual vigilance. S. pneumoniae is the leading causative agent for postoperative meningitis. Inner ear malformations increase susceptibility to postoperative meningitis. While pre- and post-operative vaccinations likely have had an impact on decreasing the number of reported cases, the rates of meningitis remained generally stable with minor increases over time.

Keywords: meningitis, otologic surgeries, postoperative complications, systematic review

INTRODUCTION

Otologic surgeries are procedures of the outer, middle, inner ear, and lateral skull base to address a range of conditions affecting hearing and balance, and can potentially expose structures, including the facial nerve, auditory and vestibular organs, vessels, and temporal lobe dura, to unintended injury.[1,2] However, these post-op complications are uncommon.[2] There are variations in the invasiveness and, thus, associated risks for different otologic surgeries, with complications ranging from tympanic membrane perforation, otorrhea, facial nerve palsy, hearing loss, vertigo, to rare flap breakdown, wound infection, device failure, cerebrospinal fluid leakage, meningitis, and even death.[2-4]

Meningitis, the inflammation of the meninges, is of particular interest given its ability to cause significant morbidity and mortality.[5-7] The causative agents for meningitis can include bacteria, viruses, fungi, and non-infectious etiologies such as medication and neoplasm.[8,9] Causative agents can spread intracranially through the middle and inner ear, directly to the meninges, or hematogenously.[10,11] The risk is potentially increased when the ears and temporal bone structures are operated upon.[11]

Although there have been studies assessing the rate of postoperative meningitis, especially after cochlear implantation,[12] the incidence has not been evaluated systematically for other common otologic surgeries. As such, we conducted a review to examine the incidence, etiology, and time course of meningitis post-otologic surgeries for patients of all ages to provide an overview and assess the impacts of vaccination, surgical technique advancement, and increased awareness of post-op meningitis. These findings could aid in developing post-op monitoring and complication management algorithms and improve awareness in patients and healthcare providers.

METHODS

Conducting the Literature Search

The study was IRB-exempt. A literature search, following PRISMA guidelines (Supplemental Fig. 1), was conducted using PubMed, Cochrane, and Web of Science databases for all available studies published between 1960 and 2022, ending in May 2023. We defined otologic surgeries as those listed under the Pubmed MeSH "Otologic Surgical Procedures" category. We did not include lateral skull base surgeries. The search was implemented using MeSH terms "meningitis" and subcategories of otologic procedures "auditory brain stem implantation", "cochlear implantation", "endolymphatic shunt", "labyrinth fenestration", "mastoidectomy", "middle ear ventilation", "myringoplasty", "ossicular replacement", "stapes surgery", and "tympanoplasty" using "AND". Secondary searches were performed using the "adverse effects" modifier for the surgery type and MeSH term "postoperative complications" in PubMed. Additional studies were identified from the reference lists generated from the original searches.

Inclusion and Exclusion Criteria

Non-English and non-human studies were excluded using automatic database filters. Studies were also excluded if they did not provide the number of patients for inclusion in the trends over time data. Finally, studies were included if they specified the presence/ absence of meningitis as a post-op complication for the otologic procedure. Both reviewers screened and collected data independently; discrepancies were resolved after discussion. The Mixed Methods Appraisal Tool (MMAT) v.2018 was used to assess the methodological quality of the included studies.[13]

Data Abstraction and Analysis

Data for sex, age, timing, etiology, and the number of cases that presented with postoperative meningitis were extracted. The timing of meningitis was converted to the common unit of month, using conversion factors of 1 month equal to 30.5 days, 4.345 weeks, or 730 hours. The reported studies' date ranges were averaged to represent the approximate time frame of occurrences. When not provided, publication years were used as approximate time frames. Incidences of meningitis were determined by dividing the number of patients with meningitis by the total number of patients. The reported causative agents were grouped by gram-positive (Streptococcus pneumoniae, Group A streptococci, Group B streptococci, and Enterococcus), gram-negative (Pseudomonas aeruginosa, Haemophilus influenzae, Serratia marcescens, Pasteurella multocida, Neisseria meningitidis, Acinetobacter baumanii and spp., Eikenella corrodens, and Escherichia coli) bacteria, viral, aseptic/no growth on culture, "bacterial"/ nonspecific meningitis, and fungal. First-episode meningitis data were utilized for those with multiple occurrences. Descriptive analysis of data was performed using Microsoft Excel. Relative risk (RR) was calculated by dividing the risk of meningitis in one type of surgery by the risk of meningitis in a second type of surgery. We could not perform other analyses given the discrepancy in the number and type of studies across the included ear surgeries.

RESULTS

A total of 140 studies were included: 75 for cochlear implantation (CI),[14-88] 25 for stapes surgery (SS),[89-113] 14 for auditory brain stem implantation (ABI),[114-127] 14 for mastoid surgery (MS),[128-141] and 12 for endolymphatic surgery (ES).[142-153] 57,108 patients were included, with 49.0% male and 57.5% pediatric patients (age <18 years). The age range was between 3.6 months–94.9 years.

All included studies are either quantitative non-randomized (MMAT category 3) (21.4% of the total, with 86.7% being cohort studies) or quantitative descriptive (MMAT category 4) (78.6% of the total, with 32.7% being case reports) (Supplemental Figure 2). For SS and MS, most studies were a quantitative descriptive design (96.0% and 78.6%, respectively), with 62.5% and 72.7% being case reports, respectively. CI, ABI, and ES also had primarily quantitative descriptive study designs (70.7%, 85.7%, and 83.3%, respectively), with a smaller proportion of studies being case reports at 22.6%, 8.3%, and 0.0%, respectively.

Most patients received CI as their otologic procedure, at 85.5% of total patients, followed by SS at 9.5%, ABI at 0.7%, MS at 2.1%, and ES at 2.2%. 215 patients experienced postoperative meningitis, most commonly

Otologic Surgery	Number of cases of postop meningitis	% of total	Number of cases of postop meningitis in pediatric and adult patients	% of pediatric patients
Cochlear Implantation	155	72.1	116 | 11	91.3
Stapes Surgery	30	14.0	4 | 18	18.2
Auditory Brain Stem Implantation	12	5.6	3 | 3	50.0
Mastoid Surgery	13	6.0	1 | 8	11.1
Endolymphatic Shunt/Sac Surgery	5	2.3	0 | 3	0.0

Table 1. Number of cases and percent of total of postop meningitis and breakdown by pediatric and adult patients by otologic surgery types.

following CI with 155 cases (72.1%) (Table 1). In addition, 74.3% of the meningitis cases post-ear surgeries were in pediatric patients (Table 1). The distribution of postoperative meningitis in male and female patients was 61.7% and 38.3%, respectively.

Incidence

The overall incidence of postoperative meningitis following otologic surgeries was 0.4%, with an incidence of 0.3% for CI, 0.6% for SS, 3.0% for ABI, 1.1% for MS, and 0.4% for ES (Supplemental Fig. 3). The RR of meningitis between CI and SS is 0.6, between CI and ABI is 0.1, between CI and MS is 0.3, and between CI and ES is 0.8, demonstrating that patients undergoing CI had between 0.1 and 0.8 times the risk of postoperative meningitis compared to other ear surgeries. When grouped by time, the incidence of meningitis for otologic surgeries from 1951-1999 was 0.35%, and from 2000-2020 was 0.4%.

The scatterplot of patients with post-CI meningitis over the years demonstrated a slightly positive trend line, indicating a small increase in reported cases over time (Fig. 1). There was a spike in the number of meningitis cases reported in the early 2000s, which has since seemed to decrease (Fig. 2). The number of reported meningitis post-SS and ABI demonstrated slight decreasing trends over time (Figs. 3 and 4), while the number of reported patients for MS and ES seemed to remain stable (Figs. 5 and 6).

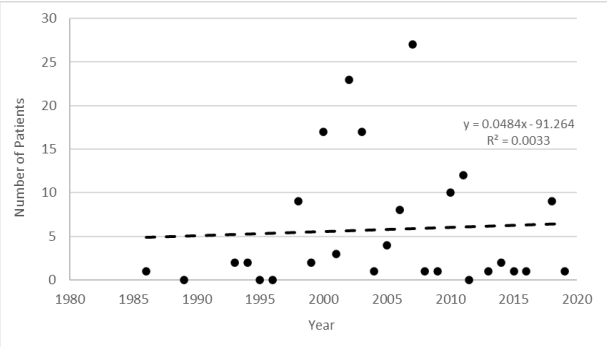

Figure 1. Number of patients with meningitis reported by year for cochlear implantation.

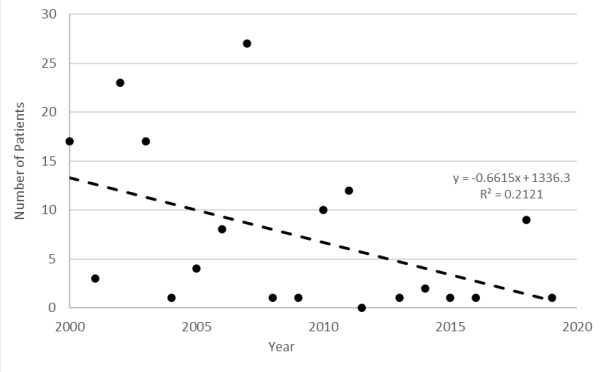

Figure 2. Number of patients with meningitis reported by year since 2000 for cochlear implantation.

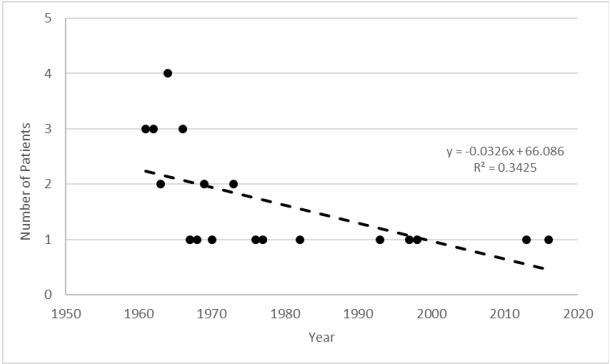

Figure 3. Number of patients with meningitis reported by year for stapes surgery.

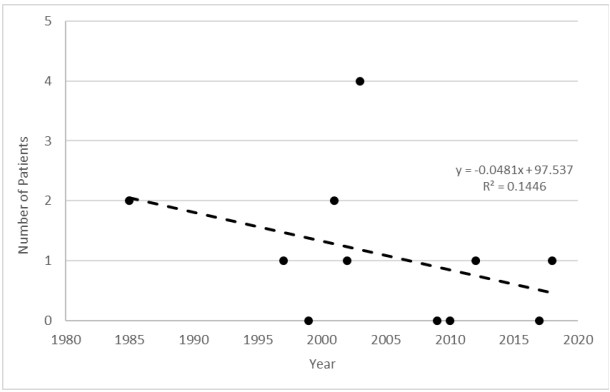

Figure 4. Number of patients with meningitis reported by year for auditory brainstem implantation.

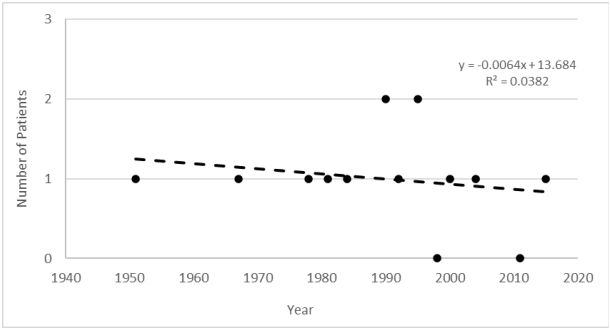

Figure 5. Number of patients with meningitis reported by year for mastoid surgery.

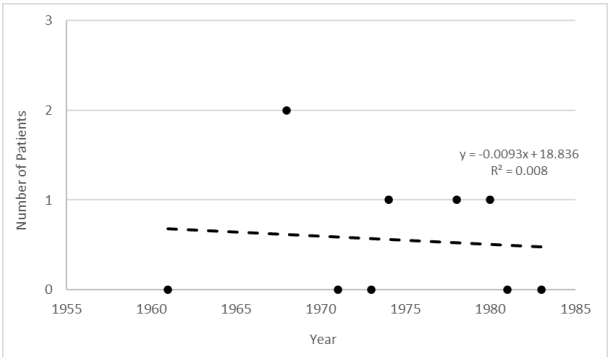

Figure 6. Number of patients with meningitis reported by year for endolymphatic surgery.

Time Course

Timing of meningitis following otologic surgeries ranged from 0-72 months for CI, 0.02-72 months for SS, 0.3-72 months for ABI, and 0.03-180 months for MS. No time data were provided for ES. The median month of post-operative meningitis was 12 for CI, 11.5 for SS, 25 for ABI, and 0.7 for MS (Fig. 7). However, the data for ABI and MS were limited by small sample sizes.

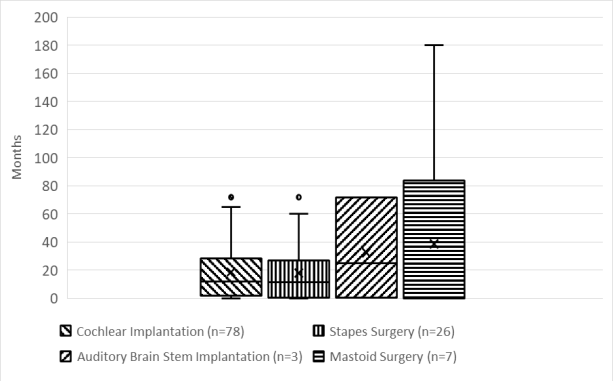

Figure 7. Timing of meningitis following otologic surgeries.

Etiology

The most common pathogen was Streptococcus pneumoniae (56.0%), followed by Pseudomonas aeruginosa (7.2%), aseptic (7.2%), and Haemophilus influenzae (6.4%). Gram-positive bacteria composed 60.8% of the total, followed by gram-negative at 22.4%, "bacterial" meningitis at 8.0%, aseptic at 7.2%, viral and fungal meningitis at 0.8%. Gram-positive bacteria were the major causative agent for CI and SS, with S. pneumoniae being the major contributor (Fig. 8 and Supplemental Figs. 4 and 5). ABI had equal distribution across gram-positive, bacterial, and aseptic meningitis, while gram-negative bacteria were the most common cause of meningitis in MS (Fig. 8 and Supplemental Figs. 6 and 7). However, the strengths of these trends were limited, given the small sample sizes for ABI and MS.

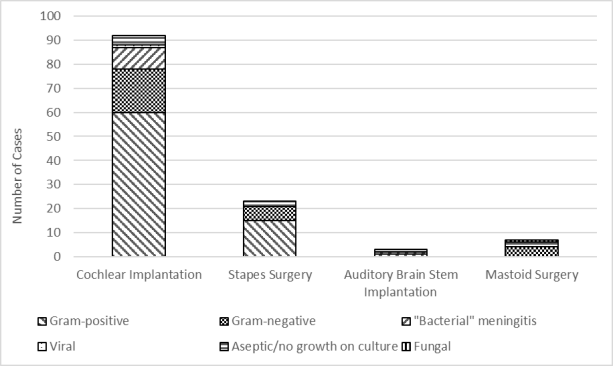

Figure 8. Etiology of post-operative meningitis.

Inner ear malformations were present in 38.3% of patients with meningitis. In addition, abnormal inner ear structures were noted in 49.1% of pediatric and 0.0% of adult CI patients with meningitis. Inner ear malformation data were limited for the remaining otologic surgeries. 50.0% of pediatric SS, 66.7% of adult ABI patients, and 100.0% of pediatric ABI patients with meningitis had inner ear malformations.

Vaccination data were only provided for 34.7% of CI and 14.3% of ABI studies. For the CI group, 31 patients with meningitis received vaccination before implantation, most of whom received the pneumococcal vaccine. Some also received the Hib and/or meningococcal vaccine. 13 of the CI patients with meningitis did not receive vaccinations. For the ABI group, one patient with meningitis was reported to be up to date with their vaccination. The remaining studies did not provide vaccination information.

DISCUSSION

Incidence

Though a rare occurrence following otologic surgery, with an incidence of 0.38%, postoperative meningitis continues to have an impact on pediatric and adult patients. Terry et al. reported the incidence of meningitis post-CI between 2003 and 2013 as 0.2%.[154] However, a review of studies between 1991 and 2020 by Alanazi et al. reported the incidence of meningitis post-CI as 0.7%.[12] Our current review found the incidence of meningitis post-CI between 1982 and 1999 at 0.16% and between 2000 and 2020 at 0.36%, for an overall incidence of 0.32%. Lalwani and Cohen found that meningitis has been decreasing from 1999 to 2010.[155] Overall, there seems to be a consensus that postoperative meningitis is a rare but possible complication.

Our aggregate data indicated that the incidence of meningitis increased over time despite the implementation of vaccination. This could be due to the increased number of surgeries performed (from 17,649 between 1951-1999 to 39,459 between 2000-2020), there is incomplete vaccination data, and implementation as we included studies conducted globally, the methodology of averaging time data, and incomplete reporting of total surgical cases which could skew the calculation. In addition, there were reports around the early 2000s regarding the possible link between CI, specifically those with electrode positioners, and meningitis, resulting in investigations and guidelines from federal and state organizations.[49] These events could have increased vigilance for postoperative meningitis[48] and correlated with the reported spike in post-CI meningitis. Also, during this period (October 2002), the CDC began its vaccination recommendations for CI recipients.[156,157] Vaccines are currently available against bacterial meningitis caused by Hib, N. meningitidis, and S. pneumoniae. Children

receiving CI are advised to follow the childhood immunization schedule for PCV13/PCV15, and those two and older should also receive the PPSV23 vaccine, while adults without previous vaccination are recommended to receive PCV15 plus PPSV23/PCV20 at least 2 weeks before implantation.[158,159] The pneumococcal vaccine was first developed as a killed vaccine, which then transitioned to polysaccharide vaccines.[159-161] These capsular polysaccharide vaccines failed to sufficiently elicit immune responses in children younger than two, necessitating the development of the serotype-specific, conjugated PCV vaccines.[159,160] However, a limitation of the current vaccines is their serotype-specificities. There is continual research to develop vaccines with greater or non-serotype-specific coverage to prevent pneumococcal diseases.[160,161] When post-CI meningitis data were assessed from 2000 to 2020, the number of patients with meningitis and years demonstrated a negative correlation, indicating a decrease in the number of reported patients with meningitis, which could be attributed in part to the increased awareness and implementation of vaccination guidelines.

Few recently published studies have assessed meningitis as a complication of stapes surgeries. Most of the literature was published before 2000, with only two studies identified after 2000. This could reflect the soft surgical techniques and technological advances in stapes surgery, or changes in the number of surgeries performed over time.[162,163] We observed a weak decreasing relationship between the number of patients with meningitis and the year, and a low incidence of meningitis at 0.55%. Recent reviews by Hajiioannou et al. and Bartel et al. reported dizziness, vertigo, and dysgeusia as the most common postoperative complications for microscopic and endoscopic stapes surgery, but did not mention meningitis.[164,165]

We also found a weak negative relationship between the number of meningitis patients and the year for ABI. The study by Sanna et al. reported that complications following ABI included dislocation of electrodes, lower cranial nerve stimulation, and vertigo during the activation process. Their review of 19 studies found postoperative meningitis in NF2 patients reported in two studies.[166] The study by Kim et al. found that CSF leakage was the most common complication of pediatric ABI.[167] A review by Ontario Health found that meningitis following ABI is a rare incident, with frequencies between 2-4% reported in 3/12 studies reviewed for surgical complications,[168] which was similar to our finding of 3.0% incidence.

We observed a relatively unremarkable trend between the number of patients with meningitis over time for mastoid surgery and an overall low incidence of 1.1%. The low number of studies reporting postoperative meningitis and nonsignificant changes over the year could be attributed to the use of mastoidectomy as a second-line treatment for otologic meningitis to eradicate the source of infection after the failure of antibiotics and myringotomy.[169,170]

The studies of endolymphatic surgery are sparse, with all identified studies published before the 2000s. Moreover, our data showed no relationship between the number of patients with meningitis and the year of operation. In addition, the overall incidence of meningitis post-ES was low at 0.41%. Similarly, the Cochrane review on surgeries for Meniere's disease could not reach any conclusion due to a lack of data on adverse effects.[171]

Etiology

Our results indicated that S. pneumoniae remains a major causative agent of meningitis post-otologic surgery. Specifically for CI and SS, S. pneumoniae comprised most reported cases. Cohen et al. and Alanazi et al. reported that S. pneumoniae was the most common, and Cohen et al. mentioned H. influenzae as another common cause.[12,172] Given the availability of pneumococcal vaccines, our findings corroborate with the literature on the importance of improving vaccination rate, documentation, and education to minimize the risk of post-operative meningitis. Unfortunately, we could not fully assess the etiology of meningitis due to the limited data for ABI, MS, and ES.

Time Course

The time frame for meningitis ranges from 0–180 months postop, with median values toward the first-year post-procedure for CI and SS. Alanazi et al. also reported meningitis post-CI occurred between 1 day and 72 months.[12] Despite this broad time frame, meningitis most commonly occurs during the first year following surgery, with infectious complications occurring earlier in pediatric patients.[48,172,173] Similarly, Lalwani and Cohen found that more than two-thirds of cases occurred within two years of implantation.[155] As a result, physicians and healthcare providers should remain vigilant for signs of meningitis in patients with a history of otologic surgery. However, the limited data hindered our understanding of the timeframe of meningitis following ABI, MS, and ES.

Our findings that 38.3% of patients with meningitis had inner ear malformations, increasing up to 49.1% of pediatric CI patients, demonstrated that inner ear malformations increase susceptibility to postoperative meningitis. This observation has been reported across the literature, especially with CI,[12,22,174,175] and warrants patient education, preoperative planning, and careful monitoring. It is important to note that at baseline, patients with inner ear malformations are at increased risk for meningitis.[176,177]

The CDC has recommendations for pneumococcal vaccination for adults and children and Hib vaccination

for younger children, but no specific recommendation for meningococcal vaccination for non-teens CI recipients.[178] While vaccinations likely have had an impact on the decrease in the overall rates of meningitis, per the literature,[174,179,180] the data regarding surgery-related meningitis is limited and complex. Our findings indicated that some vaccinated patients were still at risk, which corresponded with other reports.[155] This finding is unsurprising as the available vaccines do not cover all the serotypes. However, the importance of continual improvement in vaccination rates for risk reduction remains central to patient care.[181] In addition, there are still challenges with achieving high vaccine compliance and with documentation.[182-186] Possible methods to address this issue include the implementation of a vaccine specialist, follow-up reminders, and providing accessible information.[184,187]

Soft surgical techniques and technological advances may have improved the rate of meningitis over time; however, this trend was difficult to ascertain from our data, given the complex relationships among contributing factors and limited sample sizes. For example, the literature reported that many CI surgeons made technique improvements, including smaller cochleostomies with soft tissue seal, and modified placement of the cochleostomy; however, this may be countered by the expanded candidacy for CI to include those with inner ear malformations.[155,172,174]

Limitations included heterogeneity of reported data, a low number of studies for certain otologic procedures, lack of reporting for certain outcomes, the methodology of acquiring and averaging time data, and the inclusion of case reports, case series, and prospective/retrospective studies that vary significantly among types of otologic surgeries. We were constrained in our ability to describe the trends and outcomes for procedures, including ABI, MS, and ES.

Future studies are needed to clarify the incidence, etiology, and time frame of postoperative meningitis to verify the identified trends, especially for ABI, MS, and ES. In addition, large, multicenter studies are required to elucidate the impacts of vaccination, soft surgical techniques, and technological advances on postoperative meningitis.

CONCLUSION

Meningitis post-otologic surgery continues to have an impact on pediatric and adult patients. Inner ear malformations increase susceptibility to postoperative meningitis. Meningitis can occur immediately or after many years following otologic surgery, necessitating continual vigilance. S. pneumoniae is the leading causative agent for postoperative meningitis. While pre- and post-operative vaccinations likely have had an impact on decreasing the number of reported cases, the rates of meningitis remained generally stable with minor increases over time. More data on vaccination rates is needed to evaluate the effect of vaccination on postoperative meningitis.

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CONFLICTS OF INTEREST

All authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Study Design: QL, AJ

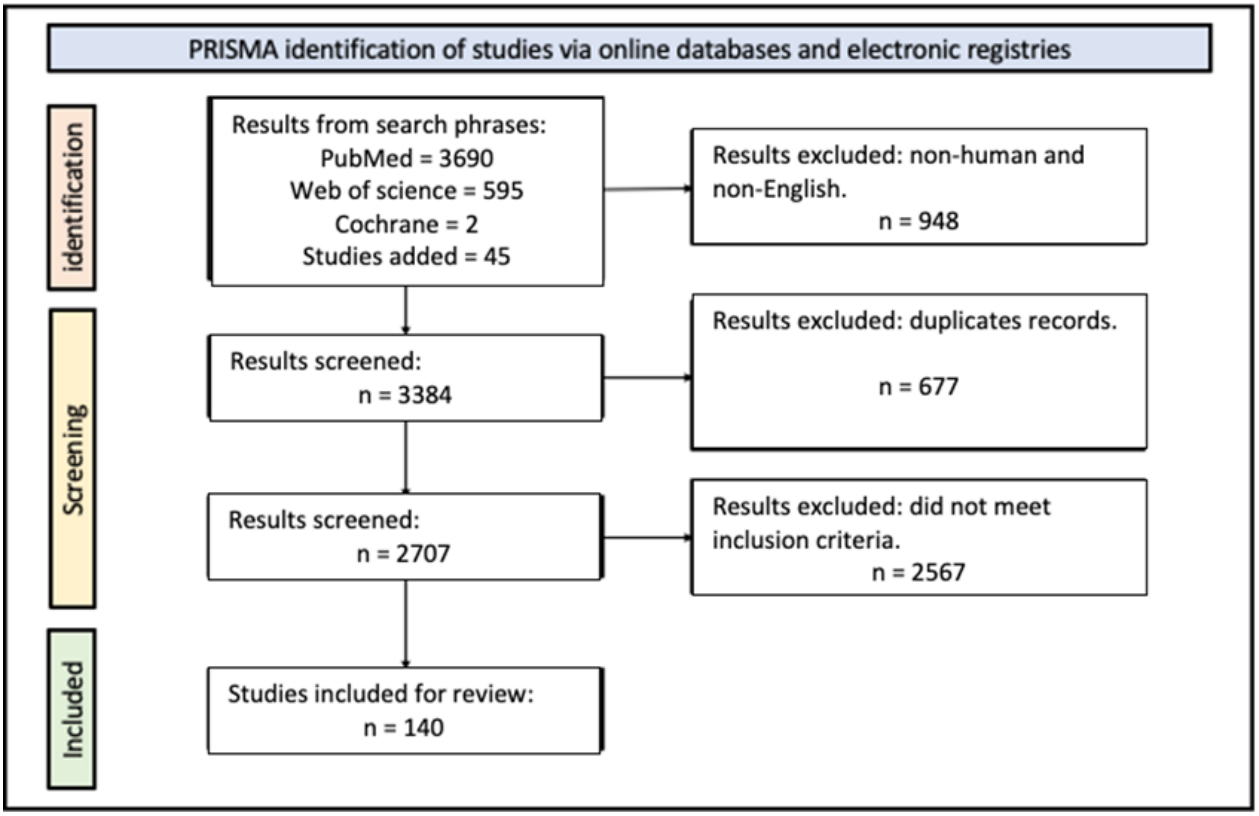
Data Collection: QL, AJ

Data analysis: QL, AJ

Manuscript Preparation: QL, AJ

Manuscript Review: QL, AJ

SUPPLEMENTAL FIGURES



Supplemental Figure 1. PRISMA flow chart.

Type of Otologic Surgery	First author	Year	Sample size	Participants	MMAT Category of Study Designs
CI	Kitano	2021	70	Adults & Pediatric	4
CI	Nisenbaum	2020	246	Pediatric	3
CI	Karltorp	2020	103	Pediatric	3
CI	Yang	2020	89	Pediatric	4
CI	Yan	2020	1	Pediatric	4
CI	Parent	2020	5728	Adults & Pediatric	3
CI	Zernotti	2020	1	Pediatric	4
CI	Halawani	2019	1027	Adults & Pediatric	4
CI	Theunisse	2018	1222	Adults & Pediatric	4
CI	Chiesa Estomba	2017	57	Adults	4
CI	Daneshi	2015	4346	Pediatric	4
CI	Wong	2016	150	Adults	3
CI	Vila	2017	421	Adults & Pediatric	4
CI	Farinetti	2014	403	Adults & Pediatric	3
CI	Ciorba	2012	438	Adults & Pediatric	4
CI	Chen	2013	445	Adults	3
CI	Tarkan	2013	475	Pediatric	4
CI	Roman	2013	1	Pediatric	4
CI	O'Mahony	2011	1	Pediatric	4
CI	Palau	2012	350	Adults & Pediatric	4
CI	Hou	2010	262	Adults & Pediatric	4
CI	McJunkin	2010	136	Pediatric	4
CI	Birman	2009	24	Pediatric	4
CI	Torkos	2009	1	Pediatric	4
CI	Loundon	2010	434	Pediatric	4
CI	Ding	2009	1237	Adults & Pediatric	4
CI	Ovesen	2009	300	Adults & Pediatric	4
CI	Mancini	2008	141	Pediatric	4
CI	Venail	2008	500	Adults & Pediatric	4
CI	Kandogan	2005	205	Pediatric	4
CI	Bhatia	2004	300	Pediatric	4

CI	Cunningham	2004	733	Adults & Pediatric	4
CI	Callanan	2004	30	Pediatric	4
CI	Reefhuis	2010	24	Adults & Pediatric	4
CI	Biernath	2006	4265	Pediatric	4
CI	Reefhuis	2003	4264	Pediatric	3
CI	Arnoldner	2005	292	Adults & Pediatric	4
CI	Summerfield	2005	3630	Adults & Pediatric	3
CI	Green	2004	214	Adults	4
CI	Woolley	1998	4	Pediatric	4
CI	Weber	1995	12	Pediatric	4
CI	Jeppesen	2013	269	Adults & Pediatric	4
CI	Gysin	2000	102	Pediatric	4
CI	Hansen	2010	367	Adults & Pediatric	3
CI	Theunisse	2014	912	Adults & Pediatric	4
CI	Lima	2010	250	Adults & Pediatric	4
CI	Garrada	2021	148	Adults & Pediatric	4
CI	Miyamoto	1996	100	Pediatric	4
CI	Deep	2021	136	Pediatric	3
CI	Glikman	2009	1	Pediatric	4
CI	Pettersen	2005	1	Pediatric	4
CI	Holman	2013	26	Pediatric	3
CI	Chweya	2021	327	Pediatric	3
CI	Page	1997	1	Pediatric	4
CI	Migirov	2006	292	Adults & Pediatric	3
CI	Lavinsky-Wolff	2012	75	Adults & Pediatric	3
CI	Suzuki	1998	1	Pediatric	4
CI	Michel	2016	1	Pediatric	4
CI	Ahn	2011	11	Pediatric	4
CI	Ahn	2008	80	Adults & Pediatric	4
CI	Fakurnejad	2020	3420	Adults & Pediatric	3
CI	Piromchai	2021	458	Adults & Pediatric	3
CI	Dagkiran	2020	1357	Adults & Pediatric	3
CI	Onan	2022	55	Adults & Pediatric	3

CI	Ajallouyean	2011	262	Pediatric	3
CI	Bajin	2018	73	Adults & Pediatric	4
CI	Lander	2020	7449	Adults & Pediatric	3
CI	Brito	2012	550	Adults & Pediatric	4
CI	Afsharpaiman	2014	371	Pediatric	4
CI	Cohen	1993	2908	Adults & Pediatric	4
CI	Daspit	1991	1	Adult	4
CI	Suleiman	2014	2	Pediatric	4
CI	Javia	2016	478	Pediatric	3
CI	Pross	2016	1	Pediatric	4
CI	Mylanus	2004	13	Pediatric	3
SS	Kou	2016	2	Pediatric	4
SS	Nielsen	2000	1	Adult	4
SS	Jablokow	1982	1	Adult	4
SS	Richards	1977	1	Pediatric	4
SS	Munro	1969	1	Not provided	4
SS	Wolff	1964	1	Adult	4
SS	Snyder	1979	1	Adult	4
SS	Benitez	1977	1	Adult	4
SS	Graham	1976	1	Adult	4
SS	Newlands	1960	1	Adult	4
SS	Clairmont	1975	1	Adult	4
SS	Palva	1960	1	Adult	4
SS	Matz	1968	1	Adult	4
SS	Cox	1967	2	Adult	4
SS	Brown	1967	413	Adult	4
SS	Rutledge	1960	1	Adult	4
SS	Stevenson	1993	1	Pediatric	4
SS	Watts	2017	3	Adult	4
SS	Wolferman	1966	1	Not provided	4
SS	Leonard	1967	100	Not provided	3
SS	Goodhill	1967	4	Adults	4
SS	Shea	1963	2021	Not provided	4

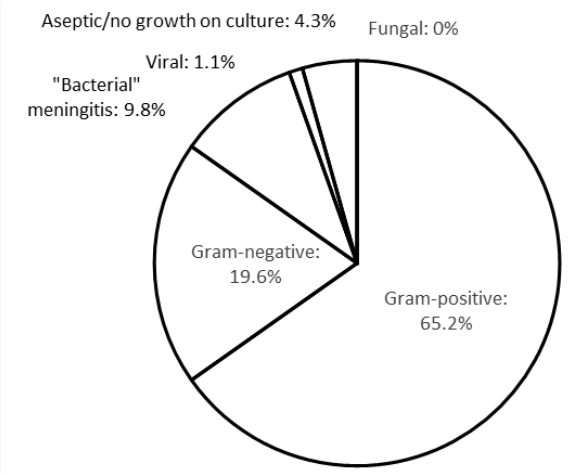
SS	Sheehy	1962	2	Not provided	4
SS	Vincent	2006	2525	Adults & Pediatric	4
SS	Palva	1977	360	Not provided	4
ABI	Kanowitz	2004	18	Adults & Pediatric	4
ABI	Wilkinson	2017	5	Pediatric	4
ABI	Colletti	2002	3	Pediatric	4
ABI	Teagle	2018	5	Pediatric	4
ABI	Choi	2011	11	Adults & Pediatric	4
ABI	Sennaroglu	2016	60	Pediatric	4
ABI	Mandala	2012	1	Pediatric	4
ABI	Grayeli	2008	31	Adults & Pediatric	3
ABI	Otto	2002	61	Adults & Pediatric	4
ABI	Colletti	2010	114	Adults & Pediatric	3
ABI	Ramsden	2016	49	Adults & Pediatric	4
ABI	Brackmann	1993	25	Adults & Pediatric	4
ABI	Colletti	2001	2	Pediatric	4
ABI	Colletti	2002	9	Adults & Pediatric	4
MS	Dammeijer	1991	1	Adult	4
MS	Pond	2015	1	Adult	4
MS	Djouhri	1998	1	Adult	4
MS	Migirov	2010	27	Adults	4
MS	Harbert	1966	1	Adult	4
MS	Moore	1984	1	Adult	4
MS	Emmerson	1978	1	Adult	4
MS	Das	2019	50	Adults & Pediatric	3
MS	Palma	2007	13	Pediatric	3
MS	Morwani	2009	61	Adults & Pediatric	4
MS	Mocanu	2022	200	Adults & Pediatric	3
MS	Van Baarle	1983	864	Adults & Pediatric	4
MS	Chattopadhyay	1981	1	Adult	4
MS	Parry	1991	1	Adult	4
ES	Goldenberg	1983	48	Adults	4
ES	Brackmann	1980	125	Adults	4

ES	Glasscock	1977	109	Adults	4
ES	Brackmann	1987	196	Adults	4
ES	Arenberg	1987	214	Adults & Pediatric	4
ES	Gardner	1975	32	Not provided	4
ES	Pulec	1969	91	Not provided	4
ES	Silverstein	1978	64	Adults & Pediatric	3
ES	Luetje	1988	171	Not provided	3
ES	Brackmann	1980	125	Adults & Pediatric	4
ES	House	1962	7	Adults	4
ES	Paparella	1976	46	Not provided	4

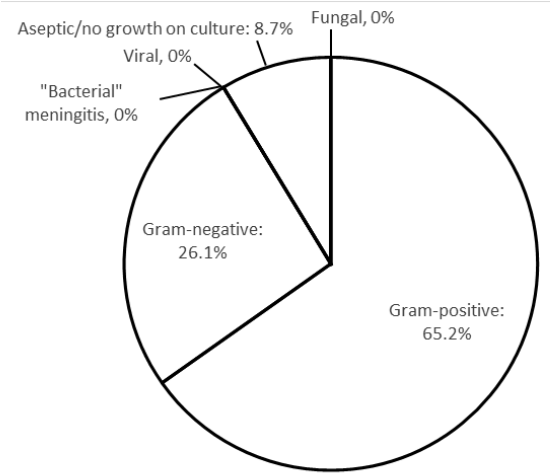
Supplemental Figure 2. Sample size, participant, and MMAT category of study design for studies included in review.

Surgery Type	Total Number of Patients	Number of Meningitis	% Total Number
Cochlear implantation (CI)	48,816	155	0.32
Stapes surgery (SS)	5,447	30	0.55
Auditory brainstem implantation (ABI)	394	12	3.0
Mastoid surgery (MS)	1,223	13	1.1
Endolymphatic surgery (ES)	1,228	5	0.41

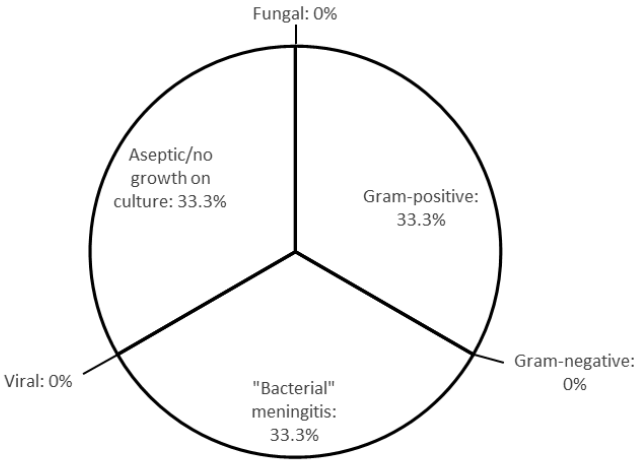
Supplemental Figure 3. Number of meningitis and total number of patients by surgery type.



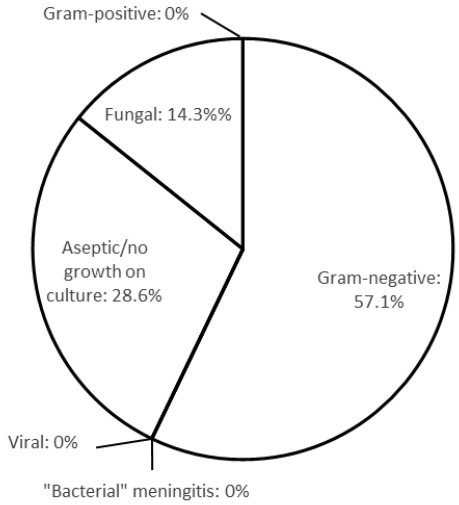
Supplemental Figure 4. Etiology of post-operative meningitis by percentages for cochlear implantation.



Supplemental Figure 5. Etiology of post-operative meningitis by percentages for stapes surgery.



Supplemental Figure 6. Etiology of post-operative meningitis by percentages for auditory brain stem implantation.



Supplemental Figure 7. Etiology of post-operative meningitis by percentages for mastoid surgery.