

REVIEW

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Detection of hearing loss by formal audiological testing after acute infectious meningitis: a global systematic review and meta-analysis

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Abstract

Background Acute community-acquired bacterial meningitis remains a significant global health concern with significant mortality and morbidity, including neurological sequelae such as sensorineural hearing loss (SNHL). Early detection of meningitis-associated SNHL mitigates permanent deafness and poor outcomes, including cognitive decline, social isolation, and mental health disorders. This systematic review evaluates the optimal time point(s) to perform formal audiological diagnostic testing and follow-up in adult and pediatric meningitis patients to effectively detect hearing loss (HL) outcomes.

Methods A literature search was conducted across Medline, Embase, and Cochrane databases. Studies reporting the time frames for HL detection secondary to acute meningitis using formal audiological tests were included. Data were analyzed descriptively for continuous and categorical variables. A meta-analysis calculated the pooled prevalence of outcomes, with subgroup analyses stratified by the time frame of audiological diagnostic assessment.

Results A total of 41 studies were included, with $n = 8105$ meningitis patients comprising $n = 1397$ (17.2%) adults and 6708 (82.8%) children. In adults, most audiological testing occurred post-discharge ($n = 530$ vs. $n = 145$), yet the proportion of hearing loss diagnoses was higher before discharge than after (45.5% vs. 42.5%). Similarly, more audiological assessments were administered post-discharge compared to pre-discharge ($n = 3340$ vs. $n = 1975$) in children, but HL diagnoses were more frequent before discharge (33.9% vs. 25.3%). The pooled prevalence of HL diagnoses during hospitalization or at discharge was 30.4% (95% CI 22.9–38%), compared to 22.9% (95% CI 12.6–33.1%) within 1 month post-discharge, 20.3% (95% CI 8.8–31.9%) between 30 and 60 days post-discharge, 22.7% (95% CI 12.1–33.4%) between 60 and 180 days post-discharge, and 10.8% (95% CI 5.9–15.7%) more than 180 days after discharge.

Conclusions The considerable variability in the time frame of audiological test administration following an acute meningitis episode highlights the need for standardized auditory evaluations after meningitis diagnosis. Our findings

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emphasize that as hearing loss may occur and recover at different stages after an infectious meningitis episode, coordinated hearing assessments at discharge and during follow-up are important to ensure adequate detection and care.

Keywords Audiological test, Acute meningitis, Hearing impairment, Sensorineural hearing loss

Background

The global burden of community-acquired bacterial meningitis (CABM) continues to be a significant public health burden with high morbidity and mortality [1]. The Global Burden of Disease Study estimated a global incidence of 2 million meningitis cases, 236,000 meningitis-related deaths, and 571,000 years lived with a disability (YLDs) in 2019 [2].

Sensorineural hearing loss (SNHL) is one of the most prevalent neurological sequelae of bacterial meningitis, affecting over 50% of survivors of acute bacterial meningitis (ABM) [3]. Hearing loss significantly diminishes the quality of life of adults, by limiting education and employment opportunities and increasing the risk of cognitive decline, social isolation, and mental health disorders [4, 5]. As the most common childhood sensory impairment, hearing loss sustained during early development contributes to socialization difficulties, behavioral disturbances, and language delay [6, 7].

Given the substantial morbidity and mortality associated with bacterial meningitis, its prevention and control remain a critical public health priority. Yet, several challenges persist in vaccination coverage, novel vaccine development, prevention and control strategies, and epidemic response efforts [8–10]. Mitigating this burden requires increased affordability and accessibility of vaccines in high-burden regions, and expansion of access to low-cost diagnostics and therapeutics for prompt management of infection and potential long-term sequelae, such as hearing impairment. In recognition of these complexities, the World Health Organization (WHO) and global partners initiated the development of a comprehensive strategy to address meningitis, culminating in *Defeating Meningitis by 2030: A Global Road Map* [11]. This roadmap aims to eliminate meningitis epidemics, reduce meningitis morbidity and mortality, and alleviate the impact on quality of life caused by meningitis-related sequelae [11].

Hearing impairment is one of the most common long-term sequelae as a consequence of meningitis [12] with as many as 14% of survivors experiencing bilateral hearing loss of 25 dB or higher [13]. When hearing loss remains unaddressed, it has far reaching consequences on the person's speech, communication, education, and cognitive development [14]. These adverse effects can be mitigated through prompt detection of hearing loss followed by appropriate patient-centered hearing rehabilitation.

In line with the meningitis global road map, the WHO aimed to develop evidence-based guidelines on the diagnosis, treatment, and care of meningitis, encompassing both the acute phase and long-term follow-up after diagnosis [15]. These guidelines are primarily directed toward healthcare professionals, policymakers, and organizations, with the broader goal of informing research priorities and improving outcomes in persons with ABM. Accordingly, as part of a WHO guideline development initiative, we conducted a systematic review and meta-analysis to identify the optimal time(s) before and/or after hospital discharge for formal audiological testing and follow-up in adults and children with meningitis.

Methods

Study selection

This systematic review was performed in adherence to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) and Meta-Analysis of Observational studies in Epidemiology (MOOSE) guidelines [16, 17]. The review addresses the following question: among cases of acute meningitis from any cause, should a formal audiological diagnostic assessment be conducted before discharge or within 4 weeks of discharge? The question followed the PICO (Population, Intervention, Comparator, and Outcome) framework, detailed in Supplemental Additional file 1: Table S1.

The literature search was conducted using electronic databases (Ovid Medline, Elsevier Embase, and the Cochrane Library) with results limited to articles published in the last 20 years. Indexed search terms and free text terms were constructed by a trained information specialist (J.U.), based on main concepts of acute infectious meningitis of all causes and formal audiological test terms (search strategy detailed in Additional file 1: Tables S2–S4). The searches were run on the 9th of February 2024. The search strategy included a list of pathogens per etiologic category (bacterial, viral, fungal, and parasitic) and focused on community-acquired acute meningitis in adults and children (> 1 month). Given the scope of the WHO clinical guidelines, this systematic review did not address meningitis in neonates (0–28 days), rehabilitation or management after hearing loss detection, subacute or chronic meningitis, hospital-acquired meningitis, or non-infectious meningitis. The complete list of microorganisms can be viewed in Additional file 1: Table S5.

Duplicates were removed using the tool Deduplick [18], and studies were uploaded to the online Covidence platform [19], where pairs of authors (L.F.A., C.Y.K., A.C.B., J.A.R., L.E.M., C.E.H., F.J.V., S.A.H., B.M.G., and P.B.) screened each publication independently by title and abstract, and by full-text review. Discrepancies were resolved in group consensus meetings. Studies that documented the time frames of hearing loss detection secondary to acute meningitis of any cause and reported using formal audiological test(s) for hearing loss detection were included. Embedded observational studies in randomized controlled trials were included to assess the outcomes in the non-intervention group, and systematic reviews and meta-analysis studies were included to identify key primary references.

Case reports, experimental studies (excluding RCTs), animal model studies, etiologic investigations, histopathologic or physiologic studies, non-peer-reviewed articles, and disease modeling studies were excluded. Studies without accessible full texts or those primarily focused on subacute, chronic, or non-infectious causes of meningitis (e.g., chemical or inflammatory) were also excluded.

Eligibility criteria and diagnostic parameters

In accordance with WHO guidelines, the age threshold for children were defined as 1 month to 18 years. Persons older than 18 years were classified as adults [20]. Pediatric cases were stratified by age (30 days to 1 year, 1–5 years, 5–18 years).

The diagnosis of meningitis was defined by the presence of compatible clinical signs and symptoms in combination with positive confirmatory laboratory findings. These studies included the detection of microorganisms in cerebrospinal fluid (CSF) or blood samples through culture or nucleic acid amplification (e.g., polymerase chain reaction (PCR)), or through a positive antigen detection test or Gram stain on CSF samples, in the presence of additional CSF findings considered compatible with meningitis. Possible meningitis etiologies considered for this analysis included bacterial, viral, fungal, and parasitic pathogens. An unspecified etiology was defined as the absence of a pathogen isolated in CSF culture/PCR/antigen testing or when the causative agent was not reported in the study.

The included studies implemented both screening and diagnostic assessments. Studies relying on screening measures reported the presence of hearing impairment; however, these tests did not specify the degree of hearing loss. In contrast, studies using diagnostic assessments reported hearing loss by degree of severity, including mild, moderate, moderately severe, severe, profound, or complete, with some variability depending on the

audiological test applied. For the purposes of this review, and to identify the time points at which hearing loss was evaluated, data were extracted and analyzed using hearing impairment as a dichotomous variable, defined as the presence or absence of hearing loss. Hearing impairment was considered present when thresholds were ≥ 20 dB based on the World Report on Hearing by the WHO [14]. Sensorineural hearing loss (SNHL) was the only type of hearing loss assessed across all included studies.

Timing of hearing impairment detection was cataloged with hospital discharge as the reference point. Audiological tests administered at admission, during hospitalization, or at discharge were categorized as before discharge. Screening for hearing loss after discharge included follow-up periods of within 1 month, short-term follow-up (1–3 months), and long-term follow-up (>3 months). Some studies used meningitis diagnosis, onset of treatment, or initial lumbar puncture as reference point, which were treated as surrogate timepoints for time of admission in our analysis.

Data extraction

For each included study, data extraction was performed independently by a pair of authors (L.F.A., C.Y.K., A.C.B., J.A.R., L.E.M., C.E.H., F.J.V., S.A.H., B.M.G., and P.B.) using the Covidence platform [19]. Consensus was performed by a third author (L.F.A., C.Y.K., K.T.T.) for each eligible publication. Data variables of interest included general study characteristics (e.g., the type of study, the country in which the study was conducted, and the study period); number of reported meningitis cases; number of patients who received appropriate audiological testing after meningitis diagnosis; number of patients with hearing loss; timing of hearing loss detection; infectious etiology of meningitis; and the type of test used for hearing loss detection. This information was extracted separately for adult and pediatric populations.

Assessment of risk of bias

A pair of authors (L.F.A., C.Y.K., A.C.B., J.A.R., L.E.M., C.E.H., F.J.V., S.A.H., B.M.G., and P.B.) independently assessed the risk of bias for each included study in an Excel spreadsheet. Any discrepancies were resolved by a third author (L.F.A., C.Y.K.), and any remaining questions or doubts were discussed during periodic review team meetings.

To assess the risk of bias for embedded observational studies in randomized control trials, the CLARITY tool was used [21]. For the included observational studies, the tools used to assess the risk of bias were Newcastle–Ottawa Cohort for cohort studies [22]; Newcastle–Ottawa CC for case–control studies [23]; JBI Checklist

for case series studies [24]; and AXIS tool for cross-sectional studies [25].

Statistical analysis

Descriptive analysis was performed; continuous data with means and standard deviations, and categorical data with counts and proportions. The weighted average time to hearing loss detection was calculated and categorized into before and after discharge groups. The proportion of persons with infectious meningitis diagnosis over the total number of those tested with a formal audiological test was calculated per time point. This descriptive analysis was primarily conducted by using Excel and R programming software version 4.3.3.

Meta-analyses were performed if data on the frequency of the hearing loss were available from two or more studies. Pooled prevalence for outcome along with its corresponding 95% confidence interval (CI) was calculated using a random-effects model. For pooling, prevalence estimates were transformed using the Freeman-Tukey double arcsine transformation [26] for better approximation to normal distribution as required by the assumption of conventional meta-analytic model. Subgroup analyses were conducted after stratification by timing of screening testing conducted. The proportion of patients with screening results reflecting any degree of hearing loss over the total patients tested with a formal audiological test was used for meta-analysis per time point: at admission, during hospitalization/at discharge, short-term follow-up, and long-term follow-up.

GRADE evidence profile

Due to the lack of studies with a comparator group, a GRADE evidence profile could not be constructed.

Results

Included studies

A total of $n=371$ studies were identified through the search strategy. After removing $n=89$ duplicates, $n=282$ studies were screened based on title and abstract, and $n=103$ were assessed in full-text review. Studies were excluded due to reporting outcomes beyond our scope, falling outside the stipulated timeframe, or lacking information on the timeframe of hearing impairment detection. A total of $n=41$ studies were included for analysis (Fig. 1 and Table 1). Of these, $n=25$ studies (60.9%) were conducted in high-income countries (as per World Bank income classification), four studies (9.8%) in upper-middle income countries, $n=14$ studies (34.1%) in lower-middle income countries, and two studies (4.9%) in low-income countries. Most studies were from North America and Europe (Fig. 2), with seven of these studies (17.1%) conducted in the USA. The study designs

of the articles included in the review were cohort studies ($n=24$, 58.3%), randomized controlled trials ($n=8$, 19.5%), case series ($n=5$, 12.2%), case-control studies ($n=3$, 7.3%), and one (2.4%) cross-sectional study (Table 1).

Four studies assessed audiological examinations in adult populations only, $n=35$ in pediatric populations only, and two in both populations. There was a total of $n=8105$ patients with meningitis, including 1397 adults (17.2%) and 6708 children (82.8%). All audiological tests, designed to diagnose hearing loss in these patients, are outlined in Table 2.

Risk of bias assessment

When assessing the risk of bias among the $n=24$ included cohort studies, three (12.5%) were rated as poor quality, five (20.8%) as fair quality, and 16 (66.7%) as good quality. Among the eight observational studies embedded in RCTs, three (37.5%) showed some concerns for risk of bias, while five (62.5%) were considered to have a low risk of bias. Among the five case series, one (20%) was of fair quality, and the remaining four (80%) were of good quality. For the three case-control studies, one (33.3%) was assessed as fair quality, and two (66.7%) as good quality. Lastly, the single cross-sectional study included in the analysis was found to be of fair quality (Table 1).

Adult population

All $n=1397$ adults had bacterial meningitis, with *Streptococcus pneumoniae* ($n=1046$, 74.9%) as the most common etiology, followed by *Neisseria meningitidis* ($n=264$, 18.9%) and *Haemophilus influenzae* ($n=60$, 4.3%). Among adults with a meningitis diagnosis, 48.3% ($n=675/1397$) were reported to have a formal audiological test, with 43.1% ($n=291/675$) confirmed to have some degree of hearing impairment. Five of the six studies assessing hearing loss in the adult population used a pure-tone audiometry test, and two used auditory brainstem response (ABR) or distortion product otoacoustic emissions tests (DPOAEs) (Table 2). In those with meningitis-related hearing loss, *S. pneumoniae* was the most common isolated etiology ($n=234$, 80.4%), followed by *N. meningitidis* ($n=19$, 6.5%) and *H. influenzae* ($n=8$, 2.7%) (Table 3).

Of the patients with meningitis-related hearing impairment who underwent audiological testing with specified timing, a higher proportion (45.5%, $n=66/145$) was diagnosed before hospital discharge compared to 42.5% ($n=225/530$) post-discharge. Before discharge, 64.3% of the patients tested at admission ($n=36/56$) had hearing impairment, compared to 25.8% of those tested during hospitalization ($n=17/66$) and 19.7% of those tested at discharge ($n=13/23$). The three studies reporting

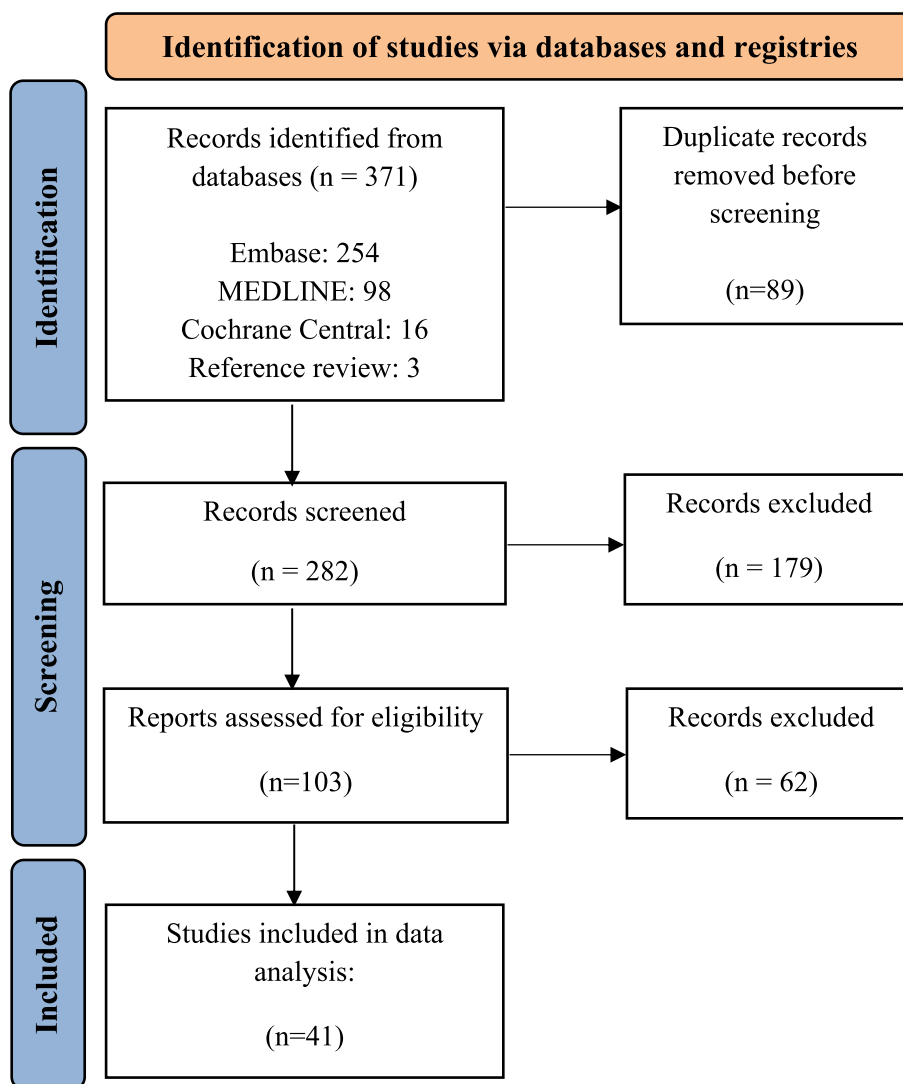


Fig. 1 PRISMA flow diagram for systematic review

diagnosis of hearing impairment before discharge did not specify days to diagnosis of hearing loss with reference to admission or discharge dates (Table 4).

Among adults diagnosed with hearing impairment after discharge, 62.5% ($n=15/24$) were diagnosed within the first month, with an average of 24 days until detection. Of those tested 1–3 months post-discharge, 13.6% ($n=38/280$) patients were diagnosed with hearing impairment, with a mean time to diagnosis of 57 days. Lastly, for those tested after more than 3 months after discharge, 76.1% ($n=172/226$) were diagnosed with hearing impairment, with a mean time to diagnosis of 365 days (Table 4).

From the included studies, only two (Jensen et al. [3] and de Gans and van de Beek [50]) evaluated

meningitis-related hearing loss both before or at discharge and post-discharge. Jensen et al. focused on adult patients with bacterial meningitis, evaluating patients with pure-tone audiometry and DPOEs at the moment of discharge and 60 days post-discharge. Not all patients in the study underwent audiological testing due to limitations in patient recruitment and the challenges associated with conducting the test in a clinical setting.

Of note, de Gans and van de Beek [50] exclusively analyzed adult patients with bacterial meningitis, conducting audiological examinations only on those with clinically evident hearing loss. Hearing was evaluated in 28 patients upon admission and then 27 patients had hearing loss diagnosis at 8 weeks during follow-up. In both studies, there was no evaluation of the progression of hearing loss

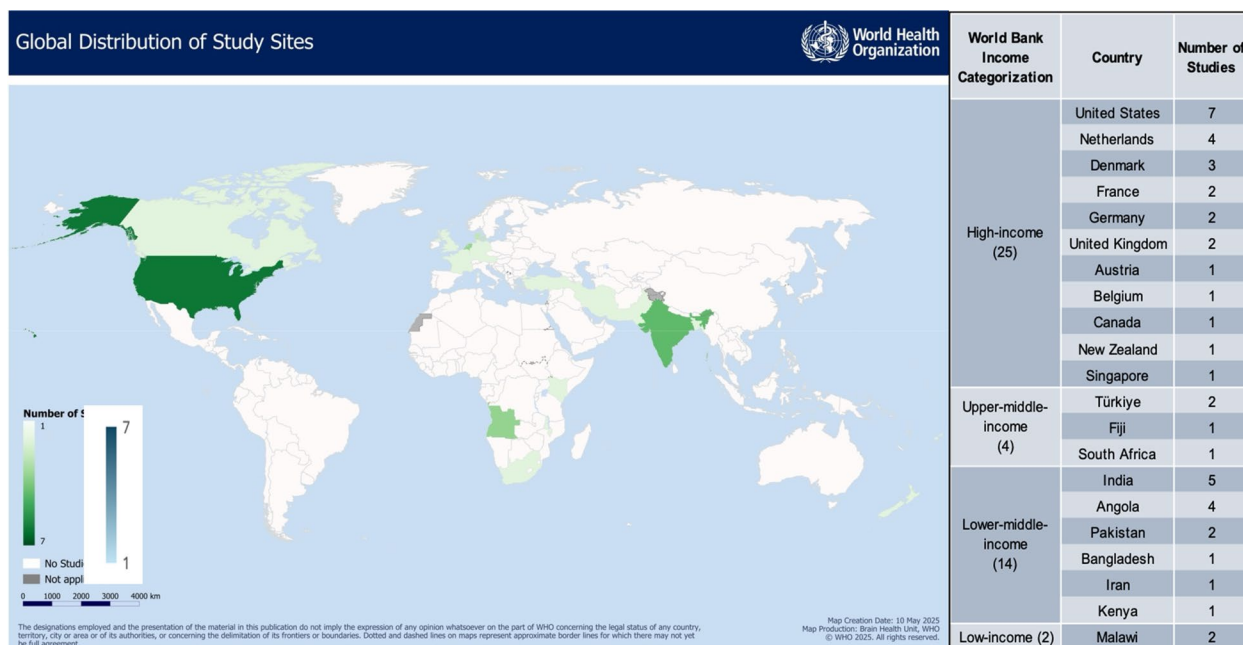


Fig. 2 Global distribution of study sites. Distribution of study sites from included references according to the World Bank income classification

over time, nor was it clear whether the patients tested before discharge were the same individuals tested after discharge.

Pediatric population

Of the 6708 children diagnosed with acute meningitis, 90.4% ($n=6064/6708$) were caused by a bacterial etiology, 2.8% ($n=191/6708$) viral etiology, and 6.8% ($n=453/6708$) with unspecified etiologies. A majority of pediatric meningitis patients, 79.8% ($n=5351/6708$) were tested with audiological exams, and from the tested patients, 22.4% ($n=1198/5351$) had meningitis-related hearing loss diagnosis. Hearing loss diagnosis was attributable to bacterial meningitis in 94.7% ($n=1135/1198$) of the children, 2.0% ($n=24/1198$) to viral meningitis, and 3.3% ($n=39/1198$) to unknown etiologies. In those with bacterial meningitis-related hearing loss, 32.2% ($n=366/1135$) had *S. pneumoniae*, 9.3% ($n=105/1135$) *N. meningitidis*, 9.2% ($n=104/1135$) *H. influenzae*, and 0.5% ($n=6/1135$) *S. agalactiae*. The remaining 48.8% of bacterial pathogens included enterobacteria, such as *Escherichia coli*, *Enterococcus* sp., and *Salmonella* sp. (Table 3).

The range of formal audiological tests implemented in the pediatric population was broad. ABR was the most utilized test, followed by pure-tone audiometry and transient-evoked otoacoustic emission tests (TEOAEs). Other audiological tests are reported in Table 2. The number of studies that reported hearing loss diagnosis before and after discharge was $n=18$ and $n=24$, respectively. Out of

the patients with documented audiological testing before discharge, 30.9% ($n=611/1975$) had a hearing loss diagnosis. Of those tested at admission, 22.8% ($n=59/258$) were diagnosed with meningitis-related hearing loss; of those tested during hospitalization, 25.6% ($n=249/973$) were diagnosed; and of those tested within discharge, 33.6% ($n=441/1312$) were diagnosed with meningitis-related hearing loss. Of the patients tested during hospitalization, the mean time from admission to hearing loss diagnosis was 8 days. Those diagnosed at discharge had a mean length of hospitalization of 14.2 days (Table 4).

Among the patients with documented timing of post-discharge testing, 25.3% ($n=384/1518$) were diagnosed within 1 month, with a mean time to diagnosis of 28 days. Of those tested between 1 and 3 months, 17.9% ($n=123/688$) were diagnosed, with an average time to diagnosis of 35.9 days. Among those tested more than 3 months after discharge, 21.4% ($n=270/1259$) were diagnosed, with a mean time to diagnosis of 284.9 days (Table 4).

From the included studies, only five reported audiological assessments both before and after discharge (De Barros et al. [62], Lempinen et al. [56], Richardson et al. [29], Singhi et al. [53], and Wellman et al. [32]). The timing of pre-discharge assessments varied across these studies: at admission (Richardson et al. [29]), during hospitalization (De Barros et al. [62], Lempinen et al. [56], Wellman et al. [32]), and/or at discharge (Richardson et al. [29], Lempinen et al. [56], Singhi et al. [53]).

Table 1 Included studies. Included references and their corresponding study type

Author and year	Country of conduct	World Bank income classification	Risk of bias
Cohort studies			
Arditi 1998 [27]	United States	High-income	Good quality
Francois 1997 [28]	France	High-income	Fair quality
Richardson 1997 [29]	United Kingdom	High-income	Good quality
Zeeshan 2018 [30]	Pakistan	Lower-middle-income	Good quality
Worsoe 2010 [31]	Denmark	High-income	Good quality
Wellman 2003 [32]	Canada	High-income	Good quality
Turel 2013 [33]	Turkey	Upper-middle-income	Fair quality
Singhi 2007 [34]	India	Lower-middle-income	Fair quality
Shi 2021 [35]	United States	High-income	Good quality
Roine 2013 [36]	Angola	Lower-middle-income	Good quality
Rodenburg-Vlot 2018 [37]	Netherlands	High-income	Good quality
McCulloch 2003 [38]	United Kingdom	High-income	Poor quality
Kutz 2006 [39]	United States	High-income	Fair quality
Kuschke 2018 [40]	South Africa	Upper-middle-income	Good quality
Kopelovich 2011 [41]	United States	High-income	Good quality
Koomen 2003 [42]	Netherlands	High-income	Good quality
Karanja 2014 [43]	Kenya	Lower-middle-income	Good quality
Jensen 2023 [3]	Denmark	High-income	Good quality
Heckenberg 2012 [44]	Netherlands	High-income	Good quality
Choong 2021 [45]	Singapore	High-income	Good quality
Chandrashekar 2015 [46]	India	Lower-middle-income	Poor quality
Buckingham 2006 [47]	United States	High-income	Poor quality
Biaukula 2012 [48]	Fiji	Upper-middle-income	Good quality
Asadi-Pooyaa 2008 [49]	Iran	Lower-middle-income	Fair quality
Observational Studies Embedded in Randomized Control Trials			
deGans 2002 [50]	Germany; Denmark, Netherlands, Belgium, Austria	High-income	Low risk of bias
Molyneux 2003 [51]	Malawi	Low-income	Some concerns
Pelkonen 2011 [52]	Angola	Lower-middle-income	Low risk of bias
Singhi 2002 [53]	India	Lower-middle-income	Low risk of bias
Sankar 2007 [54]	India	Lower-middle-income	Some concerns
Molyneux 2002 [55]	Malawi	Low-income	Some concerns
Lempinen 2022 [56]	Angola	Lower-middle-income	Low risk of bias
Karppinen 2015 [57]	Angola	Lower-middle-income	Low risk of bias
Case series (>5 cases)			
Drake 2000 [58]	New Zealand	High-income	Good quality
Kastenbauer 2003 [59]	Germany	High-income	Good quality
Cherian 2002 [60]	India	Lower-middle-income	Good quality
Herrmann 2024 [61]	United States	High-income	Good quality
DeBarros 2014 [62]	France	High-income	Fair quality
Case-control			
Saha 2009 [63]	Bangladesh	Lower-middle-income	Good quality
Ozen 2008 [64]	Turkey	Upper-middle-income	Fair quality
Orman 2020 [65]	United States	High-income	Good quality
Cross-sectional studies			
Gohar 2021 [66]	Pakistan	Lower-middle-income	Fair quality

Table 2 Reported audiological tests to detect hearing loss. The included studies reported various audiological tests used in both pediatric and adult populations to properly assess hearing loss following acute meningitis

Formal audiological tests	No. of articles	
	Adult	Children
Acoustic impedance test	0	5
Audiometry (pure-tone audiometry)	5	16
Auditory brainstem response (ABR)	2	22
Auditory steady-state response	0	1
Behavioral observation audiometry	0	9
Conditioned play audiometry	0	2
Cortical electrical response audiometry	0	1
Distortion product otoacoustic emissions (DPOAEs)	2	0
Evoked response audiometry	0	5
Formal audiological testing (unspecified)	0	1
Spontaneous otoacoustic emissions (SOAEs)	0	6
Transient-evoked otoacoustic emissions (TEOAEs)	0	12
Tympanometry	0	2
Visual reinforcement audiometry	0	5

De Barros et al. conducted a case series study where hearing loss was detected in three (60%) of the five patients during hospitalization, while the remaining two (40%) patients experienced hearing loss 92 and 210 days after their meningitis diagnosis. Lempinen et al. conducted a study on 512 patients with confirmed meningitis. Among 391 patients tested during hospitalization, 136 (34.8%) had hearing impairment. At discharge, 92 out of 310 tested patients (29.7%) had hearing loss. This number decreased to 43 of 168 (25.6%) at 30 days of follow-up, 6 of 78 (7.7%) at 90 days, and 15 of 47 (31.9%) at 180 days.

Richardson et al., followed 83 patients who were tested for hearing loss upon admission, at discharge, and 270 days post-discharge. The study reported that out of the 83 patients, hearing impairments were found in 21 (25.3%) at admission, 8 (9.6%) at discharge, and 3 (3.6%) at the 270-day follow-up. Singhi et al. assessed 69 patients with meningitis, testing 67 (97.1%) of them at discharge and again at 1 month post-discharge. Initially, 15 (22.4%) patients were diagnosed with hearing loss, which decreased to 14 (20.9%) at follow-up. Wellman et al. reported on 79 confirmed cases of meningitis. During hospitalization, hearing loss was detected in 22 out of 42 tested patients (52.4%). Of these, five children did not undergo subsequent follow-up. Among the 17 children with follow-up, a total of 11 were diagnosed with mild-to-moderate to profound hearing impairment at an average of 2.4 months post-discharge.

Table 3 Meningitis-associated hearing loss: etiology and detection time

	Adults	Children
Studies	6 ^a	37 ^a
Meningitis patients	1397	6708
Bacterial ^b	1397 (100%)	6064 (90.4%)
<i>Streptococcus pneumoniae</i>	1046 (74.9%)	–
<i>Neisseria meningitidis</i>	264 (18.9%)	–
<i>Haemophilus influenzae</i>	60 (4.3%)	–
<i>Streptococcus agalactiae</i> (GBS)	NR	–
Viral	NR	191 (2.8%)
Unspecified/not reported	NR	453 (6.8%)
Meningitis patients tested for hearing loss	675	5351
Bacterial ^b	675 (100%)	–
<i>Streptococcus pneumoniae</i>	374 (55.4%)	–
<i>Neisseria meningitidis</i>	90 (13.3%)	–
<i>Haemophilus influenzae</i>	NR	–
<i>Streptococcus agalactiae</i> (GBS)	0	–
Viral	0	–
Unspecified/not reported	0	–
Patients with meningitis-related hearing loss	291	1198
Bacterial ^b	291 (100%)	1135 (94.7%)
<i>Streptococcus pneumoniae</i>	234 (80.4%)	366 (32.2%)
<i>Neisseria meningitidis</i>	19 (6.5%)	105 (9.3%)
<i>Haemophilus influenzae</i>	8 (2.7%)	104 (9.2%)
<i>Streptococcus agalactiae</i> (GBS)	0	6 (0.5%)
Viral	0	24 (2.0%)
Unspecified/not reported	0	39 (3.3%)

^a Two studies had both adult and pediatric populations

^b Only the most commonly reported bacterial pathogens are listed. Several articles also described other etiologies (e.g., enterobacteria such as *Salmonella* and *E. coli*), so the percentages do not add up to 100% of bacterial cases

Meta-analysis

For adults, the pooled proportion of participants diagnosed before discharge were 32.1% (10.6–53.6%).

In children, the pooled prevalence of hearing loss diagnoses during hospitalization or at discharge was 30.4% (95% CI 22.9–38%). After discharge, diagnoses were reported in 22.9% (95% CI 12.6–33.1%) of children within 1 month, 20.3% (95% CI 8.8–31.9%) between 30 and 60 days, 22.7% (95% CI 12.1–33.4%) between 60 and 180 days, and 10.8% (95% CI 5.9–15.7%) beyond 180 days post-discharge (Fig. 3A–E).

Discussion

This systematic review included a total of 8105 meningitis patients, with *S. pneumoniae* as the most common infectious etiology, followed by *N. meningitidis*, in both pediatric and adult populations, which is consistent with prior literature [67]. Of the adult patients

Table 4 Time of hearing loss detection. Children and adult populations had hearing loss detection at different times after meningitis diagnosis. Timepoints were divided into before and after discharge. Before discharge, audiological testing was performed at admission, during hospitalization, and at discharge. After discharge, audiological testing was performed within 1 month, 1–3 months, and > 3 months of follow-up

	Studies	Adults detection/tested (%)	Mean time to hearing loss detection in days (months)
Before discharge	3 ^a	66/145 (45.5%)	^b
At admission	2	36/56 (64.3%)	1
During hospitalization	1	17/66 (25.8%)	NR
At discharge	1	13/23 (19.7%)	NR
After discharge	5	225/530 (42.5%)	188 (6.2)
Within 1 month	1	15/24 (62.5%)	24 (0.8)
Short-term follow-up (1–3 months)	2	38/280 (13.6%)	57 (1.9)
Long-term follow-up (> 3 months)	2	172/226 (76.1%)	365 (12)
	Studies	Children detection/tested (%)	Mean time to hearing loss detection in days (months)
Before discharge	18	611/1975 (30.9%)	4.9
At admission	2	59/258 (22.8%)	1
During hospitalization	7	249/973 (25.6%)	8
At discharge	9	441/1312 (33.6%)	14.2
After discharge	24*	756/3340 (22.6%)	94.3 (3.1)
Within 1 month	6	322/1499 (21.5%)	28 (0.9)
Short-term follow-up (1–3 months)	9	123/688 (17.9%)	35.9 (1.2)
Long-term follow-up (> 3 months)	9	270/1259 (21.4%)	284.9 (9.5)

^a The discrepancy between total number of studies per broad timeframe and subcategories of timeframe is due to studies that report multiple hearing loss detection timepoints

^b The three studies reporting detection of hearing impairment before discharge did not specify days to screening of hearing loss with reference to admission or discharge dates

tested for hearing loss, 43% were diagnosed with some degree of impairment, with pure-tone audiometry as the most commonly used testing method. A few studies reported the use of ABR or DPOAEs tests, particularly for adult patients who were unresponsive or non-cooperative. While more patients were tested after discharge ($n=530$ vs. $n=145$), the proportion of diagnosed patients was higher before discharge (45.5% vs. 42.5%). Furthermore, among those tested post-discharge, a greater proportion of patients were diagnosed during long-term follow-up beyond 3 months compared to those tested within 1 to 3 months (76.1% vs. 13.5%).

There was a significant proportion of adult patients (52%) that did not undergo formal audiological testing after meningitis diagnosis, which may be attributed to loss to follow-up or mortality during or after hospitalization. Some studies specified that only patients reporting auditory symptoms during the hospitalization were referred for audiological testing later at follow-up. This selective referral process, along with loss to follow-up

and case fatality, contributes to a heterogenous implementation of audiological diagnostic assessment.

Considerably more children with meningitis underwent formal audiological testing compared to adults (79.8% vs. 48.3%). The audiological tests used in children varied significantly across studies, as these must correspond to age-appropriate developmental and behavioral characteristics to ensure accurate assessment of hearing. Factors such as limited attention spans, difficulty following instructions, and developmental differences contribute to the challenge of standardizing audiological testing in this population.

Similar to adults, a greater number of children were tested for hearing loss after discharge compared to before discharge ($n=3340$ vs. $n=1975$), with a higher proportion of hearing loss diagnoses before discharge than post-discharge. The pooled prevalence of hearing loss diagnoses during hospitalization or at discharge was higher than post-discharge, with 30.4% (95% CI 22.9–38%), compared to 22.9% (95% CI 12.6–33.1%)

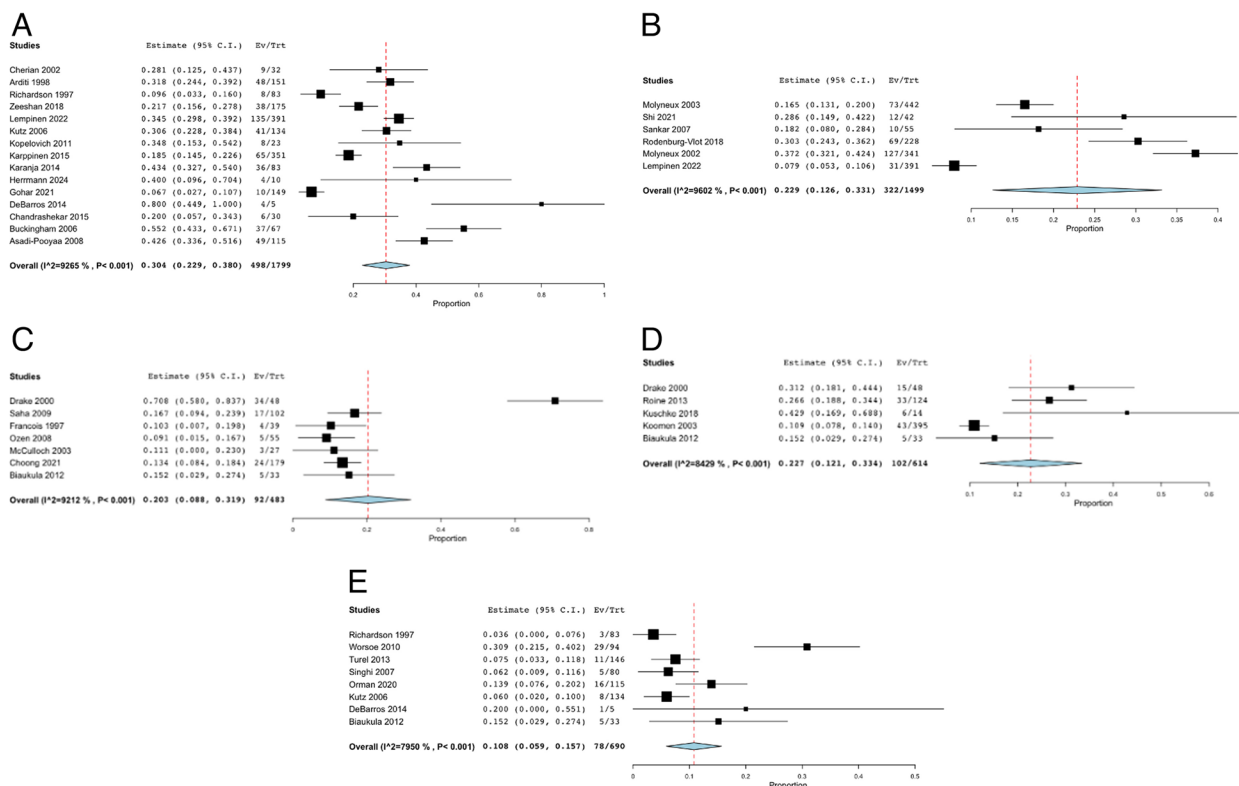


Fig. 3 **A** Meta-analysis of hearing loss detection in children during hospitalization or at discharge. Forest plot showing the proportion of pediatric patients diagnosed with hearing loss over the total patients tested with a formal audiological test during hospitalization or at discharge. **B** Meta-analysis of hearing loss detection in children within 1 month of discharge. Forest plot showing the proportion of children patients diagnosed with hearing loss over the total patients tested with a formal audiological test within 30 days of discharge. **C** Meta-analysis of hearing loss detection in children after 30–60 days of discharge. Forest plot showing the proportion of pediatric patients diagnosed with hearing loss over the total patients tested with a formal audiological test between 30 and 60 days of discharge. **D** Meta-analysis of hearing loss detection in children diagnosed after 60–180 days of discharge. Forest plot showing the proportion of pediatric patients diagnosed with hearing loss over the total patients tested with a formal audiological test between 60 and 180 days of discharge. **E** Meta-analysis of hearing loss detection in children after 180 days of discharge. Forest plot showing the proportion of pediatric patients diagnosed with hearing loss over the total patients tested with a formal audiological test after > 180 days of discharge

of children diagnosed within 1 month, 20.3% (95% CI 8.8–31.9%) between 30 and 60 days, 22.7% (95% CI 12.1–33.4%) between 60 and 180 days, and 10.8% (95% CI 5.9–15.7%) beyond 180 days after discharge. Among those tested after discharge, the highest proportion of diagnoses occurred within the first month, with an average time to diagnosis of 28 days post-discharge.

This observed pattern in both children and adults, where more hearing loss diagnoses were made shortly after the meningitis episode and fewer over time, has been documented in long-term follow-up studies of pneumococcal meningitis [68]. Saha et al. reported that 33% of children were diagnosed with hearing loss during short-term follow-up (30 days), but only 18% had persistent hearing loss at long-term follow-up (6–24 months), noting that more diagnoses could be done earlier after the acute meningitis episode [69].

Sensorineural hearing loss due to meningitis can arise from several mechanisms, including direct microbial invasion of the inner ear and inflammatory response, or meningeal inflammation directly affecting the vestibulo-cochlear nerve through neuritis, ischemic injury, or compression [68, 70]. Depending on the specific mechanism, the extent and location of injury within the auditory system, and the type and timing of treatment, partial or complete recovery of hearing can occur. Therefore, some patients initially diagnosed with hearing loss may show improvement over time, which could explain the higher frequency of diagnoses in the early phase after infection [3, 68]. These findings highlight the importance of performing early hearing assessments following infectious meningitis, as many patients develop this sequela during the acute phase. However, continued follow-up remains crucial to monitor potential recovery and to identify

those with persistent deficits who may benefit from further interventions.

The variability in hearing loss detection over time is expected and may also be attributed to delayed diagnosis, which can occur when patients do not initially report symptoms or when hearing impairment is not clinically evident during the acute phase. Once the patient stabilizes, auditory manifestations may become more noticeable, prompting further evaluation and diagnosis through appropriate testing [71–73]. Additional contributing factors include logistical challenges during hospitalization and the limited availability of trained personnel to conduct age-appropriate audiological assessments [71–73]. However, a notable finding of this systematic review is that most included studies did not evaluate hearing loss longitudinally. Only two studies in adults and five in children consistently documented assessments both before and after discharge. Furthermore, some studies reported that audiological evaluations were conducted only in symptomatic patients, further contributing to the inconsistency in hearing assessment administration across studies [74].

As this review demonstrates, a greater proportion of patients were diagnosed with hearing loss before discharge than post-discharge, underscoring the importance of implementing hearing diagnostic assessment protocols after the acute meningitis episode to ensure prompt HL diagnosis and treatment, along with appropriate follow-up care after discharge. If not appropriately treated, persistent inflammation following a meningitis episode can lead to cochlear fibrosis and ossification, potentially limiting the effectiveness of therapeutic interventions such as cochlear implant electrode insertion [11, 74]. This approach is consistent with the recommendations outlined in the recently published WHO guidelines on the diagnosis, treatment, and care of meningitis [15].

This systematic review has multiple limitations, mainly due to the observational nature of the included studies. Most were conducted in high-income countries, with less representation from middle- to low-income regions, and none from South America. This reflects the observed disparities in global clinical research, where limited resources, funding, and research culture hinders evidence-based findings from these areas [72, 73]. As a result, many prevalent diseases rely on guidelines based on high-income settings, which may not always be suitable for other regions [75].

Few studies evaluated hearing impairment sequentially across multiple time points to assess its progression. In the few studies that reported longitudinal data, it was often unclear whether the same individuals were tested before and after discharge. Loss to follow-up or failure to attend to evaluations was not consistently reported

across the included studies. Additionally, there was significant heterogeneity in assessment patterns and testing methods, along with inconsistent reporting of outcomes. Altogether, these inconsistencies limit direct comparisons across timeframes, as different studies contributing to each time point assessed distinct populations. The protocol for this review was not registered in PROSPERO. Although the study followed the WHO methodological framework, we acknowledge that this does not replace prospective protocol registration and that it is a limitation.

Conclusions

This systematic review underscores the importance of implementing standardized auditory evaluation protocols for hearing loss detection and follow-up of auditory sequelae after an infectious meningitis diagnosis. Although there may be variability in the timing of hearing loss onset and recovery, as observed in this review, a greater proportion of both adult and pediatric patients were diagnosed with hearing loss before or at hospital discharge compared to post-discharge after the acute meningitis episode. These findings highlight the need to conduct auditory assessments both prior to discharge and during follow-up visits to accurately evaluate hearing outcomes and monitor the progression or resolution of meningitis-associated SNHL.

Abbreviations

ABR	Auditory brainstem response
CI	Confidence interval
DPOEs	Distortion product otoacoustic emissions
GBS	<i>Streptococcus agalactiae</i>
NR	Not reported
PICO	Population, Intervention, Comparison, and Outcomes
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SOAEs	Spontaneous otoacoustic emissions
TEOEs	Transient-evoked otoacoustic emissions
WHO	World Health Organization

Supplementary Information

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Additional file 1.

Authors' contributions

LFA participated in all phases of the systematic review, from its inception, including the development of the search strategy and organization of the systematic review software, to data analysis and manuscript writing. LFA was involved in screening, full-text review, data extraction, and consensus performance. CYK provided essential support in data analysis and manuscript writing, and also participated in screening, extraction, and consensus processes. LM, CEH, ACBT, JAR, FJV, SAH, BMG, and PB assisted with screening, data extraction, and manuscript writing. MP performed specific data analyses, including meta-analyses, and contributed to the supervision and writing of the manuscript. JU and KUK contributed to the development of the search strategy and reviewed the manuscript. FV, NS, YG, NB, SC and TD supported

the conceptualization and construction of the article. KTT, as the principal investigator, led the project, oversaw the entire execution of the systematic review, participated in consensus discussions, and contributed to the supervision, conceptualization, and writing of the manuscript. All authors read and approved the final manuscript.

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Data availability

All data generated and/or analyzed during this study are included in this published article, its tables and figures document, and its supplementary information file.

Declarations

The authors are responsible for the views expressed in this article. Those views do not necessarily represent the views, decisions, or policies of the institutions with which they are affiliated.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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