Global, regional, and national burden of meningitis, its risk factors, and aetiologies, 1990–2023: a systematic analysis for the Global Burden of Disease Study 2023

*GBD 2023 Meningitis & Antimicrobial Resistance Collaborators**

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Summary

Background Meningitis remains the leading infectious cause of neurological disabilities globally, disproportionately affecting children younger than 5 years and populations in the African meningitis belt. Whereas previous global estimates focused on ten pathogen categories, this study presents the most comprehensive analysis to date, assessing the meningitis burden attributable to 17 causative pathogens based on the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2023 framework.

Methods GBD is a systematic, scientific effort aimed at quantifying the comparative magnitude of health loss caused by diseases, injuries, and risk factors across age groups, sexes, and geographical locations over time. We estimated meningitis mortality using the Cause of Death Ensemble model (CODEm) and morbidity using DisMod-MR 2.1, incorporating data from vital registration, verbal autopsy, surveillance, hospital data, and systematic reviews. Aetiology-specific estimates were generated with pathogen-linked case-fatality ratios and splined binomial regression models. Risk factor attribution was based on established risk–outcome pairs and population attributable fractions.

Findings In 2023, there were 259 000 (95% uncertainty interval 202 000–335 000) global deaths and 2·54 million (2·20–2·93) incident cases of meningitis. Children younger than 5 years accounted for more than a third of deaths (86 600 [53 300–149 000]). *Streptococcus pneumoniae*, *Neisseria meningitidis*, non-polio enteroviruses, and other viruses were the leading causes of death, while non-polio enteroviruses caused the most cases. The four WHO-defined preventable meningitis pathogens of interest (*S pneumoniae*, *N meningitidis*, *Haemophilus influenzae*, and Group B streptococcus) contributed to 98 700 deaths (77 000–127 000) and 594 000 cases (514 000–686 000). Low birthweight, short gestation, and household air pollution were the top risk factors for meningitis-related mortality.

Interpretation Although mortality and incidence have declined significantly since 1990, progress is insufficient to meet WHO 2030 targets. Despite marked progress in reducing bacterial meningitis via global vaccination campaigns, a substantial meningitis burden persists, attributable both to common pathogens such as *S pneumoniae* and *N meningitidis* and to emerging non-bacterial pathogens such as *Candida* spp and drug-resistant fungi. Achieving WHO goals will require sustained investment in surveillance, vaccination, maternal screening, and health-system strengthening, especially in high-burden settings.

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Introduction

Meningitis, or inflammation of the meninges, is the leading infectious cause of neurological disability-adjusted life-years (DALYs) globally.[1,2] It is a heterogeneous infectious syndrome with numerous causative pathogens, including bacteria, viruses, and fungi. Compared with viral meningitis, bacterial meningitis has a higher fatality rate and a higher proportion of survivors with permanent disability.[3,4] A systematic review published in 2024 estimated a worldwide bacterial meningitis case-fatality ratio (CFR) of 18% (95% CI 16–19), or 15% (12–19) when only including study observations after 2010.[5] Another global systematic review published in 2010 estimated that a fifth of people who recover from bacterial meningitis have lasting major sequelae, with the risk of sequelae being twice as high in the African and southeast Asian regions compared with the European region.[6] The most common meningitis sequela is hearing loss, with others including cognitive impairment, motor impairment, and seizures.[6] These disabilities can affect a patient's quality of life through impacts on their education, the burden of care-giving on their family, and their economic abilities.[7]

Since 2000, widespread global vaccine rollout, first against *Haemophilus influenzae* type b (Hib) and later against *Streptococcus pneumoniae* and *Neisseria meningitidis*, has greatly reduced the incidence and mortality due to these infections in both high-income and low-income settings.[8,9] Despite these advances in vaccination, progress against meningitis lags behind

Research in context

Evidence before this study

The global burden of meningitis and its aetiologies has been quantified by different groups, including WHO, the Maternal and Child Epidemiology Estimation Group (WHO-MCEE), and the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD). We conducted a PubMed search using the terms "meningitis" [MeSH] AND ("mortality" OR "incidence") AND "risk factors" AND "global" for studies published from database inception to Feb 3, 2026. Of the 47 resulting studies, seven reported on one meningitis-causing pathogen, three reported on two pathogens, one study examined three pathogens, and the previous GBD 2019 paper included ten pathogen categories. None of these studies quantified the burden of meningitis attributable to *Acinetobacter baumanni*, *Candida* spp, coagulase-negative staphylococci, or non-polio enteroviruses. The most comprehensive study to date has been the GBD 2019 meningitis report, which estimated 2·51 million (95% uncertainty interval 2·11–2·99) cases of meningitis and 236 000 deaths (204 000–277 000) attributable to meningitis globally in 2019.

Added value of this study

This study is based on data and modelled results from GBD 2023 and thus provides the most comprehensive global assessment of meningitis to date, expanding pathogen coverage from ten to 17 categories, including the first global quantification for non-polio enteroviruses (the leading cause of meningitis incidence), *A baumanni*, *Candida* spp, coagulase-negative staphylococci, the aggregate categories of other fungi, and other *Streptococcus* species. For the first time, we assessed meningitis-related deaths attributable to risk factors, including low birthweight, short gestation, and household air pollution, providing evidence to inform prevention strategies in maternal, child, and environmental health. The study also assesses progress towards the WHO global roadmap by quantifying the combined burden of the WHO priority preventable pathogens (*Streptococcus pneumoniae*, *Neisseria meningitidis*, *Haemophilus influenzae*, Group B streptococcus) from 2015 onwards, showing that current rates of decline are insufficient to meet global targets.

Implications of all the available evidence

WHO has set a goal to reduce the global incidence of vaccine-preventable bacterial meningitis by 50% and deaths by 70% by 2030, compared to the baseline year of 2015. Although there have been substantial improvements in reducing the morbidity and mortality of meningitis, the pace of progress is not currently on track to meet these goals by 2030. The two leading causes of meningitis mortality globally, *S pneumoniae* and *N meningitidis*, are both vaccine-preventable bacterial species and serve as notable examples of the need for more comprehensive vaccine coverage programmes. Additionally, viral meningitis poses a rising relative burden in the post-*H influenzae type b*, pneumococcal, and meningococcal vaccine era. We found that non-polio enteroviruses, which generally cause less severe disease and have a lower likelihood of mortality than bacteria, are the number one cause of meningitis incidence and the third leading cause of meningitis-related deaths worldwide. Additionally, we have characterised the burden attributable to the rare *Candida* meningitis, emphasising the growing threat of health-care-associated infections, which pose an increased risk of antimicrobial resistance. Continued efforts focused on vaccination, antibiotic stewardship, and advances in treatment access and equity can promote the continued prevention of disability and deaths due to meningitis.

when compared with other vaccine-preventable diseases.[10] The incidence of meningitis remains high, particularly in low-income countries where access to health care and vaccination coverage are scarce.[11] The African meningitis belt, spanning from Senegal to Ethiopia,[12] has the highest incidence rates, with seasonal outbreaks exacerbating the burden.[13] Additionally, no licensed vaccine exists for key pathogens, including the leading causes of neonatal meningitis, Group B streptococcus and *Escherichia coli*.[5]

Beyond these well known pathogens, dozens more contribute to the global burden of meningitis. Non-polio enteroviruses (NPEVs), a family of more than 100 serotypes that includes coxsackieviruses and echoviruses, comprise the most common cause of viral meningitis. In some populations, particularly among very young children in industrialised settings, enteroviral meningitis cases outnumber bacterial meningitis cases.[14,15] Gram-negative bacteria such as *Klebsiella pneumoniae* and *Acinetobacter baumanii* are particularly associated with populations admitted to the hospital, including neonates, in low-income settings.[16] Some commensal skin flora, such as *Candida* species and coagulase-negative *Staphylococcus*, can cause health-care-associated meningitis in certain populations, with high morbidity and mortality. *Candida* meningitis occurs particularly in neurosurgical patients, immunocompromised patients, or critically ill neonates with disseminated disease.[17,18] Similarly, coagulase-negative *Staphylococcus*, although a rare source of meningitis in the general population, is also a leading cause of meningitis in neurosurgical patients, especially those with implanted devices such as ventricular shunts.[19,20]

In 2021, WHO launched a global roadmap to eliminate meningitis by 2030.[21] The roadmap aims to reduce the incidence of vaccine-preventable bacterial meningitis by 50% and deaths by 70% compared to a baseline year of 2015, as well as eliminate epidemics and reduce meningitis-attributable disability. In its roadmap, WHO

defines vaccine-preventable meningitis as that caused by *S pneumoniae, N meningitidis, H influenzae*, and Group B streptococcus. Although no licensed vaccine currently exists for the prevention of Group B streptococcus, several candidates are in advanced stages of development; furthermore, mother-to-child transmission of Group B streptococcus is considered partially preventable through interventions such as screening and antibiotic administration. In this study, we follow the WHO convention, using the term vaccine-preventable to refer to these four pathogens of great public health interest. The roadmap includes 18 strategic goals within five key pillars: prevention and epidemic control, diagnosis and treatment, disease surveillance, support for people affected by meningitis, and advocacy and engagement. To assess progress towards the goals of the roadmap, a comprehensive assessment of meningitis incidence, mortality, and pathogen distribution is key. These country-specific and regional estimates are fundamental for evidence-based regional planning, allowing policy makers to identify the countries with the highest-burden that require immediate intervention and allocate scarce resources most effectively.[22]

This study leverages results from the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2023 to assess the incidence, mortality, and pathogen distribution of acute infectious meningitis in 204 countries and territories from 1990 to 2023. Notable improvements in GBD 2023 include the pathogen modelling of seven new meningitis aetiology categories: *A baumanni*, *Candida* spp, coagulase-negative staphylococci, and NPEVs, plus the splitting of the previous "other pathogen" category into other *Streptococcus* species, other fungi, other bacteria, and other viruses. This manuscript was produced as part of the GBD Collaborator Network and in accordance with the GBD Protocol.

Methods

Overview

GBD is a systematic, scientific effort aimed at quantifying the comparative magnitude of health loss caused by diseases, injuries, and risk factors across age groups, sexes, and geographical locations over time. The GBD geographical hierarchy encompasses 204 countries and territories, organised into 21 regions based on epidemiological similarities and geographical proximity. These regions are further consolidated into seven super-regions according to patterns of cause-specific mortality. Detailed methods for GBD have been published previously.[23–25] Morbidity and mortality attributable to pathogen aetiologies were estimated through the antimicrobial resistance study by the GBD 2021 Antimicrobial Resistance Collaborators.[26] In this study, we outline the methods and estimation strategies used for meningitis, including its associated risk factors and pathogens.

In this study, meningitis is defined as a disease caused by inflammation of the meninges as a result of bacterial, viral, or fungal agents. The ICD-9 and ICD-10 codes that correspond to meningitis within the GBD framework are listed within appendix 1 (p 4). Age-standardised estimates were calculated with age weights from the GBD standard reference population.[27]

See Online for appendix 1

For information on input data and sources, the GBD Sources tool on the Global Health Data Exchange (GHDx) provides all metadata to identify which sources were used for any of the GBD estimates. This research complies with the GATHER statement (appendix 1 p 72).

For more on the **Global Health Data Exchange** see https://ghdx.healthdata.org/

Mortality estimation process

Meningitis mortality was estimated with the Cause of Death Ensemble model (CODEm) using data from vital registration, verbal autopsy, surveillance, and minimally invasive tissue sampling. CODEm creates an array of sub-models utilising combinations of different predictor covariates to estimate mortality rates or cause fractions.[28] The array of sub-models includes linear mixed-effects models with random intercepts at the super-region, region, and country levels, and spatiotemporal Gaussian process regression models. CODEm selects from the ensemble of models that perform best in out-of-sample predictive validity tests to use as our mortality estimates. Due to the large differences between mortality trends for children younger than 5 years versus those aged 5 years and older, mortality in children younger than 5 years was modelled separately from that in people aged 5 years and older to capture trends adequately. For a complete list of the covariates used in the meningitis model, see appendix 1 (pp 5–6).

Morbidity estimation process

Data used in the estimation processes of meningitis morbidity came from a systematic review of published studies, surveillance data, cause-specific mortality estimates, claims, and inpatient data (appendix 1 pp 8–10). This systematic review was conducted in the online tool DistillerSR and used the software's "DistillerSR Artificial Intelligence System" (DAISY). We used an initial training set of manually screened records to set up DAISY. The tool then prioritised remaining citations for inclusion or exclusion. We worked with the error prediction tool and audit function of DistillerSR to run various checkpoints throughout the process. This allowed our data extraction team members to focus their time on discussing critical decisions and identify potential errors in screening and extractions. These data went through a standardised adjustment to make claims and surveillance data comparable with inpatient data (appendix 1 pp 10–11). Overall morbidity was estimated for meningitis with the Bayesian meta-regression tool DisMod-MR 2.1. A more detailed explanation of DisMod-MR 2.1 can be found in previous studies.[25]

	1990		2015		2023		Percentage change in mortality rates between 1990 and 2023	Percentage change in mortality rates between 2015 and 2023
	Deaths	Mortality rate per 100 000	Deaths	Mortality rate per 100 000	Deaths	Mortality rate per 100 000		
All ages	469 000 (362 000 to 580 000)	8·8 (6·8 to 10·9)	319 000 (252 000 to 404 000)	4·3 (3·4 to 5·5)	259 000 (202 000 to 335 000)	3·2 (2·5 to 4·1)	−63·5 (−72·8 to −51·0)	−25·4 (−40·4 to −5·9)
<5 years	277 000 (186 000 to 373 000)	45·1 (30·2 to 60·8)	129 000 (83 600 to 196 000)	19·0 (12·3 to 28·9)	86 600 (53 300 to 149 000)	13·5 (8·3 to 23·2)	−70·1 (−81·5 to −42·1)	−29·2 (−56·4 to 2·2)
5–14 years	66 800 (50 500 to 84 800)	6·0 (4·5 to 7·6)	50 800 (37 200 to 69 400)	4·0 (2·9 to 5·4)	43 700 (31 200 to 57 700)	3·2 (2·3 to 4·2)	−47·0 (−63·6 to −18·0)	−20·4 (−40·5 to 5·8)
15–49 years	73 000 (57 100 to 88 800)	2·7 (2·1 to 3·3)	78 000 (60 500 to 101 000)	2·1 (1·6 to 2·7)	73 600 (55 100 to 95 000)	1·8 (1·4 to 2·4)	−31·6 (−50·7 to 0·3)	−10·4 (−29·3 to 13·0)
50–69 years	30 600 (24 400 to 36 300)	4·5 (3·6 to 5·3)	31 400 (24 800 to 39 500)	2·5 (2·0 to 3·2)	27 900 (21 700 to 36 200)	1·9 (1·5 to 2·4)	−58·3 (−69·6 to −38·7)	−26·0 (−41·4 to −5·8)
≥70 years	21 500 (17 000 to 26 500)	10·6 (8·4 to 13·0)	29 400 (22 800 to 37 400)	7·1 (5·5 to 9·1)	212 000 (171 000 to 265 000)	39·4 (31·7 to 49·2)	−52·7 (−65·8 to −31·8)	−30·1 (−44·2 to −11·7)

Estimates are presented as rounded values and therefore might not sum to estimated aggregates. Data in parentheses are 95% uncertainty intervals.

Table 1: **Estimates of fatality caused by meningitis globally by age in 1990, 2015, and 2023**

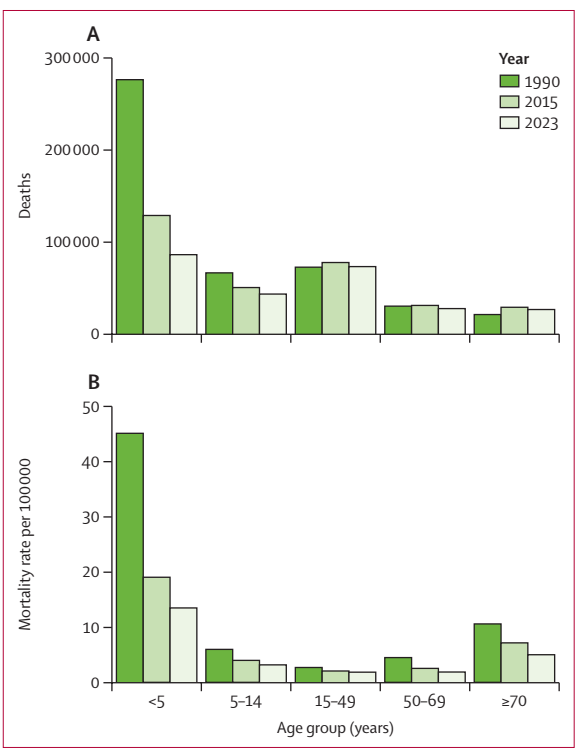

Figure 1: **Mortality counts (A) and rates (B) by age group in 1990, 2015, and 2023, globally**

Aetiology estimation process

We estimated mortality and incidence attributable to the following pathogen categories: *A baumannii*, *Candida* spp, coagulase-negative staphylococci, *E coli*, Group B streptococcus, *H influenzae*, *K pneumoniae*, *Listeria monocytogenes*, *N meningitidis*, NPEVs, other *Streptococcus* species, other fungi, other bacteria, other viruses, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *S pneumoniae*. "Other" categories are defined as residual, aggregate pathogen categories not otherwise modelled with more granularity; for example, "other *Streptococcus* spp" refers to *Streptococcus* spp other than Group B streptococcus or *S pneumoniae*. Data used in the aetiology estimation process included multiple causes of death, hospital discharge, linkage, microbial data, literature studies, and mortality surveillance (Child Health and Mortality Prevention Surveillance [CHAMPS]; appendix 1 pp 16–17). All data were extracted at the most granular pathogen level available; pathogens with fewer than 300 cases were not estimated individually and were modelled in aggregate categories, such as other fungi. The opportunistic fungi genera *Cryptococcus* and *Toxoplasma* were excluded from the other fungi category and from the current study, as deaths due to these pathogens are considered attributable to HIV. *Mycobacterium tuberculosis* was also excluded, as these deaths are attributed to tuberculosis. A more detailed explanation of the aetiology estimation process has been published previously,[26] and is also described in full in appendix 1 (pp 15–39). It should be noted that the GBD and antimicrobial resistance teams' research methods and results describe pathogen distributions for multiple infectious syndromes, of which meningitis is one. Although the different models share the same estimation methodologies, the data and results are independent for each syndrome.

In summary, once data were extracted and processed, pathogen distributions were estimated with the multinomial estimation with partial and composite observations modelling environment, allowing for the inclusion of covariates in the network analysis[26] and for Bayesian priors to be incorporated (appendix 1 pp 30–39). We estimated the incidence proportions attributable to

viral, fungal, parasitic, and bacterial pathogens with this model, and we used modelled CFRs, as described below, to maximally leverage mortality-only data sources to estimate implied cases for incidence estimation. Data that showed clear linkage between pathogen-specific disease incidence and deaths were used to create models for pathogen-specific CFRs for each age group and syndrome. A splined binomial regression was implemented with the RegMod modelling environment to estimate pathogen-specific CFRs as a function of the Healthcare Access and Quality (HAQ) Index and other covariates, as described in appendix 1 (pp 16–21). Finally, the estimated CFR was used to calculate mortality proportions from incidence proportions, as modelled above. More detailed methods are provided in appendix 1 (pp 15–39). To estimate the progress towards the WHO 2030 global roadmap, we computed the totals of what WHO considers to be vaccine-preventable diseases: *S pneumoniae, N meningitidis, H influenzae,* and Group B streptococcus.[21]

Risk attribution estimation process

Risk attribution for meningitis was calculated with risk–outcome pairs that were selected on the basis of their convincing or probably causal relationship to meningitis. Relative risks for each risk–outcome pair were derived from published systematic reviews. Exposure levels for each risk factor were estimated with spatiotemporal Gaussian process regression, a Bayesian meta-regression tool (DisMod-MR 2.1), or other methods when applicable (appendix 1 pp 39–74). Exposure levels that equate to the theoretical minimum risk were calculated through relevant data sources (appendix 1 pp 41–42). We calculated the number of meningitis-related deaths attributable to each risk factor by applying the population attributable fractions (PAFs) for each risk factor to the total number of meningitis-related deaths for each specific risk–outcome pair.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Overall meningitis mortality and morbidity estimates

Globally, meningitis was responsible for 259 000 (95% uncertainty interval [UI] 202 000–335 000) all-age deaths and an all-age mortality rate of 3·2 (2·5–4·1) per 100 000 in 2023 (table 1). This represents a decline in all-age mortality rates of 25·4% (5·9–40·4) since 2015 (4·3 [3·4–5·5] per 100 000), and 63·5% (51·0–72·8) between 1990 and 2023 (8·8 [6·8–10·9] per 100 000 in 1990; table 1). Across age groups, the largest burden was in children younger than 5 years, with 86 600 (53 300–149 000) deaths and a mortality rate of 13·5 (8·3–23·2) per 100 000 (table 1; figure 1). For all ages globally in 2023, meningitis caused around the same number of deaths in females (130 000 [91 300–173 000]) and males (129 000 [95 300–187 000]); mortality rates between males (3·2 [2·4–4·6] per 100 000) and females (3·2 [2·3–4·3] per 100 000) were also nearly the same (appendix 2 table S7).

See Online for appendix 2

Globally, in 2023, there were 2·54 million (95% UI 2·20–2·93) cases of meningitis and an all-age incidence rate of 31·5 (27·2–36·4) per 100 000 (table 2; appendix 2 figure S1). The percentage decline in the incidence rate was 57·5% (54·5–60·5) from 1990 to 2023 and 18·5% (17·1–20·0) from 2015 to 2023 (table 2). The largest burden of cases globally was in children younger than 5 years (953 000 [780 000–1 140 000]), and the largest

	1990		2015		2023		Percentage change in incidence rates between 1990 and 2023	Percentage change in incidence rates between 2015 and 2023
	Cases	Incidence rate per 100 000	Cases	Incidence rate per 100 000	Cases	Incidence rate per 100 000		
All ages	3 960 000 (3 290 000 to 4 710 000)	74·2 (61·7 to 88·3)	2 860 000 (2 470 000 to 3 340 000)	38·6 (33·3 to 45·0)	2 540 000 (2 200 000 to 2 930 000)	31·5 (27·2 to 36·4)	–57·5 (–60·5 to –54·5)	–18·5 (–20·0 to –17·1)
<5 years	2 230 000 (1 740 000 to 2 780 000)	363·2 (283·6 to 453·0)	1 170 000 (941 000 to 1 420 000)	172·1 (138·5 to 208·5)	953 000 (780 000 to 1 140 000)	148·1 (121·3 to 177·4)	–59·1 (–62·1 to –56·0)	–13·9 (–16·1 to –11·7)
5–14 years	659 000 (416 000 to 952 000)	58·9 (37·1 to 85·0)	504 000 (337 000 to 714 000)	39·4 (26·3 to 55·8)	447 000 (304 000 to 633 000)	32·3 (22·0 to 45·8)	–44·7 (–49·3 to –38·8)	–17·8 (–20·4 to –15·2)
15–49 years	662 000 (490 000 to 893 000)	24·4 (18·0 to 32·9)	713 000 (553 000 to 923 000)	18·7 (14·6 to 24·3)	684 000 (537 000 to 882 000)	17·1 (13·4 to 22·0)	–29·6 (–36·1 to –23·7)	–8·8 (–10·8 to –6·6)
50–69 years	244 000 (181 000 to 329 000)	35·8 (26·5 to 48·2)	253 000 (199 000 to 334 000)	20·4 (16·0 to 26·8)	241 000 (192 000 to 315 000)	16·1 (12·8 to 21·0)	–54·7 (–58·0 to –51·0)	–20·8 (–22·7 to –19·1)
≥70 years	164 000 (117 000 to 223 000)	80·5 (57·8 to 109·5)	222 000 (176 000 to 282 000)	54·0 (42·7 to 68·5)	212 000 (171 000 to 265 000)	39·4 (31·7 to 49·2)	–50·7 (–56·1 to –45·1)	–26·9 (–29·4 to –25·1)

Estimates are presented as rounded values and therefore might not sum to estimated aggregates. Data in parentheses are 95% uncertainty intervals.

Table 2: **Non-fatal estimates of meningitis globally by age in 1990, 2015, and 2023**

incidence rate was also seen in children younger than 5 years (148·1 [121·3–177·4] per 100 000; appendix 2 figure S1). For all ages, about the same number of cases of meningitis occurred in males (1·28 million [1·11–1·48]) and females (1·26 million [1·09–1·46]; appendix 2 table S8), and both males (31·6 [27·3–36·5] per 100 000) and females (31·4 [27·2–36·3] per 100 000) had a similar incidence rate of meningitis (appendix 2 table S8). More detailed meningitis burden results by age and sex across locations and years are available in the GBD Results Tool.

For the **GBD Results Tool** see https://vizhub.healthdata.org/gbd-results/

Aetiology results

Globally, the aetiology responsible for the most all-age deaths in 2023 was *S pneumoniae* (41 400 [95% UI 32 200–53 600]) followed by *N meningitidis* (34 400 [26 600–44 500]), NPEVs (18 200 [13 700–23 900]), and other viral aetiologies (18 000 [14 000–23 100]; appendix 2 figure S2, table S3). Across all bacterial aetiologies considered by WHO to be largely preventable—that is, *S pneumoniae, N meningitidis, H influenzae,* and Group B streptococcus—we estimated a total of 98 700 (77 000–127 000) deaths in 2023, a 27·4% (9·6–43·4) decline since 2015, when there were 126 000 (99 200–163 000) deaths (appendix 2 table S4). Likewise, for this same pathogen group, we estimated 594 000 (514 000–686 000) cases in 2023, a 16·3% (14·8–18·2) decrease from 653 000 (560 000–762 000) cases in 2015 (appendix 2 table S4). In 1990, the leading pathogen

Figure 2: **Meningitis mortality rates (A) and incidence rates (B) by aetiology and age group in 2023**
For aetiology results in 1990, please see appendix 2 figure S4.

causing meningitis-related deaths was *N meningitidis* (79 900 [62 100–99 100]), followed by *S pneumoniae* (60 600 [47 000–75 900]), NPEVs (43 100 [33 200–54 100]), and *H influenzae* (40 300 [29 500–51 900]; appendix 2 figure S3). The pathogen responsible for the most cases of meningitis in 2023 was NPEVs (870 000 [735 000–1 030 000]), followed by *N meningitidis* (232 000 [197 000–274 000]; appendix 2 figure S2, table S5). In 1990, the largest number of cases also came from NPEVs (1·70 million [1·38–2·06]), followed by *N meningitidis* (373 000 [302 000–456 000]; appendix 2 figure S3).

In children younger than 5 years, the pathogen responsible for the most deaths in 2023 was *S pneumoniae* (14 000 [95% UI 8630–23 800]), with a mortality rate of 2·2 (1·3–3·7) per 100 000 (figure 2; appendix 2 figure S2). *N meningitidis* had the second largest number of deaths in children younger than 5 years (11 400 [7050–19 600]), with a mortality rate of 1·8 (1·1–3·1) per 100 000 in this age group (figure 2; appendix 2 figure S2). Group B streptococcus was responsible for the third largest number of deaths in children younger than 5 years (8540 [5420–14 500]), with a mortality rate of 1·3 (0·8–2·3) per 100 000 in this age group (figure 2; appendix 2 figure S2). Among age groups within the under-5 population, the Group B streptococcus meningitis mortality rate was highest in the early neonatal age group (ie, age <7 days; 93·1 [56·6–148·1] deaths per 100 000), followed by the late neonatal age group (ie, age 7–27 days; 22·1 [13·5–36·9] deaths per 100 000; appendix 2 table S9). In 2023, the pathogen responsible for the most meningitis cases in children younger than 5 years was NPEVs (327 000 [264 000–402 000], with an incidence rate of 50·9 [41·1–62·6] per 100 000), followed by *N meningitidis* (88 200 [72 000–107 000], with an incidence rate of 13·7 [11·2–16·7] per 100 000), and other viral aetiologies of meningitis (74 100 [60 400–90 400], with an incidence rate of 11·5 [9·4–14·1] per 100 000; figure 2; appendix 2 figure S2).

Of the newly modelled fungal aetiologies of meningitis from GBD 2023, *Candida* spp was responsible for 92 200 (95% UI 77 200–108 000) cases and 13 700 (10 600–17 700) deaths, and other fungi were responsible for 110 000 (90 700–141 000) cases and 13 300 (9730–19 200) deaths in 2023 (appendix 2 table S3, figure S2).

Risk factors of meningitis

Globally, in 2023, the greatest risk factor contributing to meningitis deaths was low birthweight, responsible for 7660 (95% UI 4940–12 300) deaths, followed by short gestation (3540 [2280–5720]), household air pollution (2690 [1700–4350]), and ambient particulate matter pollution (554 [348–917]; table 3). Between males and females, the ranking of these risk factors in 2023 did not vary from the ranking for both sexes combined (table 3). The meningitis mortality rate attributable to low birthweight decreased substantially between 1990 and 2023, by 73·8% (49·7–85·2) in both sexes combined (table 3). The mortality rates attributed to short gestation, household air pollution, and ambient particulate matter pollution all declined rapidly from 1990 in both sexes combined: mortality from short gestation decreased by 72·1% (45·8–83·9), mortality from household air pollution decreased by 70·5% (42·2–83·7), and mortality from ambient particulate matter pollution decreased by 77·4% (57·7–87·8; table 3; appendix 2 table S10).

The meningitis belt

Across the countries of the meningitis belt in 2023, the country with the largest meningitis all-age mortality rate was Nigeria (30·2 [95% UI 21·5–41·1] per 100 000), followed by Niger (30·0 [18·4–44·9] per 100 000) and Chad (28·8 [18·4–44·6] per 100 000; figure 3; appendix 2

	Both sexes combined			Male			Female		
	Deaths	Mortality rate per 100 000	Percentage change in mortality rate between 1990 and 2023	Deaths	Mortality rate per 100 000	Percentage change in mortality rate between 1990 and 2023	Deaths	Mortality rate per 100 000	Percentage change in mortality rate between 1990 and 2023
Ambient particulate matter pollution	554 (348 to 917)	0·0 (0·0 to 0·0)	–77·4 (–87·8 to –57·7)	319 (168 to 599)	0·0 (0·0 to 0·0)	–78·0 (–88·8 to –48·0)	235 (127 to 388)	0·0 (0·0 to 0·0)	–76·5 (–90·0 to –46·9)
Household air pollution from solid fuels	2690 (1700 to 4350)	0·0 (0·0 to 0·1)	–70·5 (–83·7 to –42·2)	1530 (785 to 2810)	0·0 (0·0 to 0·1)	–70·9 (–84·6 to 27·0)	1160 (624 to 1880)	0·0 (0·0 to 0·0)	–70·0 (–87·0 to –30·3)
Low birthweight	7660 (4940 to 12 300)	0·1 (0·1 to 0·2)	–73·8 (–85·2 to –49·7)	4390 (2280 to 8140)	0·1 (0·1 to 0·2)	–74·8 (–86·6 to –39·4)	3270 (1830 to 5470)	0·1 (0·0 to 0·1)	–72·2 (–87·3 to –37·1)
Short gestation	3540 (2280 to 5720)	0·0 (0·0 to 0·1)	–72·1 (–83·9 to –45·8)	2010 (1060 to 3770)	0·0 (0·0 to 0·1)	–74·4 (–86·0 to –36·8)	1540 (828 to 2620)	0·0 (0·0 to 0·1)	–68·4 (–85·6 to –31·6)

Estimates are presented as rounded values and therefore might not sum to estimated aggregates. The both sexes combined category is calculated as males plus females. Data in parentheses are 95% uncertainty intervals. Ambient particulate matter pollution is defined as the population-weighted annual average mass concentration of particles with an aerodynamic diameter less than 2·5 μm (PM2·5) in a cubic metre of air. Household air pollution from solid fuels is estimated from both the proportion of individuals using solid cooking fuels and the level of exposure to particulate matter less than 2·5 μm in aerodynamic diameter (PM2·5). Low birthweight refers to any birthweight less than the birthweight theoretical minimum risk exposure level (TMREL). Short gestation is used to refer to all gestational ages below the gestational age TMREL. For risk factor results in 1990, please see appendix 2 table S11.

Table 3: **Risk factors of fatal meningitis globally by sex in 2023**

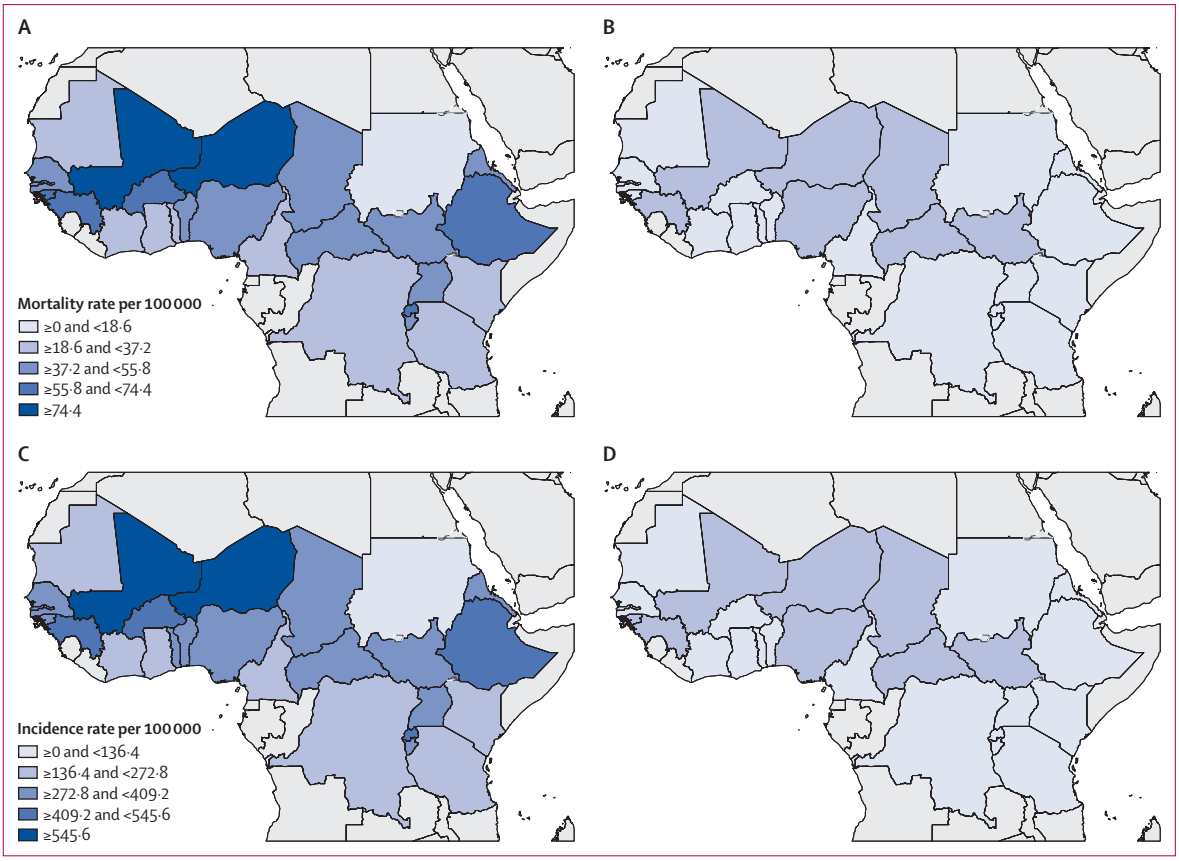

Figure 3: **Meningitis mortality rates in the meningitis belt in 1990 (A) and 2023 (B), and incidence rates in the meningitis belt in 1990 (C) and 2023 (D)**

table S6); these countries also had the highest mortality rates globally. In Nigeria, the pathogen responsible for the most deaths in 2023 was *S pneumoniae* (11 800 [8320–16 000]; appendix 2 table S3).

The country with the largest all-age incidence rate in 2023 was Nigeria (239·3 [95% UI 203·7–280·7] per 100 000), followed by Chad (230·6 [198·6–265·3] per 100 000) and Niger (222·9 [182·8–259·3] per 100 000; appendix 2 table S6); these three countries also had the highest incidence rates globally. In Nigeria, most cases of meningitis in 2023 were attributable to NPEVs (226 000 [187 000–267 000]; appendix 2 table S5).

In the meningitis belt, both mortality and incidence rates declined substantially for most countries between 1990 and 2023 (figure 3). The percentage decrease in the mortality rate was greater than 80% in Sudan, Rwanda, and Ethiopia and the percentage decrease in the incidence rate was greater than 80% in Sudan and Rwanda (appendix 2 table S6).

Discussion

This study presents estimates of the meningitis burden attributable to a comprehensive set of 17 pathogen categories by age group and sex, across countries, regions, and globally, from 1990 to 2023. Of these pathogen categories, seven are newly modelled in GBD 2023.

Although mortality and incidence have declined substantially since 1990, progress since 2015 has slowed and remains insufficient to meet the WHO 2030 targets for vaccine-preventable meningitis. We estimated 259 000 (95% UI 202 000–335 000) deaths attributable to meningitis worldwide in 2023, including 86 600 (53 300–149 000) deaths in children younger than 5 years. The burden of disease remained disproportionately high in low-income countries, particularly in the African meningitis belt, where Nigeria, Chad, and Niger recorded the highest mortality and incidence rates.

Across all studied pathogens, S *pneumoniae* and *N meningitidis* remained the leading causes of meningitis mortality in 2023. These vaccine-preventable bacterial species present with high fatality and complication rates. The WHO 2023 global roadmap targets a reduction in vaccine-preventable bacterial meningitis incidence by 50% and deaths by 70% compared with 2015, requiring annualised decreases of approximately 8·0% for deaths and 4·6% for incidence. These vaccine-preventable aetiologies, as defined in the roadmap—*S pneumoniae*, *N meningitidis*, *H influenzae*, and Group B streptococcus—were collectively responsible for an estimated 98 700

(95% UI 77 000–127 000) deaths and 594 000 (514 000–686 000) cases in 2023. Despite substantial progress in vaccination and health-systems strengthening over past decades, the annualised rate of decline across the four aetiologies combined was 4·1% for deaths and 2·2% for incidence between 2015 and 2023, underscoring the need for accelerated efforts to further reduce the global burden of vaccine-preventable bacterial meningitis and achieve the ambitious benchmarks set by WHO.[29] Progress in the 2000s and 2010s has largely been driven by highly successful vaccination campaigns, including the MenAfriVac campaign, which nearly eliminated *N meningitidis* serogroup A in the meningitis belt, as well as the global introduction of pneumococcal and Hib vaccinations into routine childhood immunisation schedules.[8,30]

However, due to serogroup and serotype replacement, non-vaccine serotype meningitis incidence has, in relative terms, risen, inhibiting progress towards the benchmarks set by WHO.[31–33] Non-typeable *H influenzae*, traditionally regarded as non-invasive, has been increasingly detected as a cause of meningitis in the post-vaccine era,[34,35] although its incidence remains much lower than that of Hib before the rollout of its immunisation.[36] In the WHO Global Invasive Bacterial Vaccine-Preventable Disease Surveillance Network, more than half (52·9%) of pneumococcal meningitis cases identified since rollout of the post-pneumococcal conjugate vaccine (PCV) in 2014–19 were non-PCV13 strains, and nearly half (49·4%) of global meningococcal cases were serogroup B, although Y and W were most commonly detected in the African region.[33] These findings further reinforce the importance of accurate diagnostics, not only for accurate patient treatment but also for robust pathogen surveillance that can drive future vaccine development and vaccination policy.

For the first time, we estimated the global incidence of and mortality due to meningitis caused by NPEVs. NPEVs were responsible for most meningitis cases worldwide in 2023 and were also the third-leading pathogen cause of meningitis mortality. NPEVs are a diverse group of pathogens responsible for a wide range of clinical syndromes, from asymptomatic infections to serious conditions, including meningitis.[37] Although the current study does not estimate viral serotype distribution, a 2019 systematic review estimated that echovirus 30 was the commonest global serotype.[38] Echovirus 30 outbreaks typically occur over large geographical areas and are common in Europe, the USA, Asia, and South America.[39] This finding highlights a pressing need for surveillance frameworks and diagnostic readiness in low-income and middle-income countries, where enterovirus outbreaks often go undetected. Although there is no known global surveillance network for NPEVs,[40] regional networks such as the European Non-Polio Enterovirus Network (ENPEN) and the Asia-Pacific Network for Enterovirus Surveillance (APNES) are examples of systems for early detection of enterovirus outbreaks.[41,42]

Antimicrobial resistance poses a major barrier to achieving WHO goals for meningitis control. *N meningitidis* isolates resistant to penicillin and fluoroquinolones have become widespread over the past decade.[43,44] A global systematic review noted the highest fluoroquinolone (ciprofloxacin) *N meningitidis* resistance in Africa (30·3% [95% CI 14·1–53·5]) followed by Asia (6·3% [0·2–73·3]), although most studies from these continents used the disk diffusion method, which could substantially overestimate the resistance rate.[44] Resistance to cephalosporins remains rare[43,44] but highly concerning as these antimicrobials are the first-line therapy for meningitis in adults and children worldwide. *S pneumoniae* resistance displays a similar pattern, with frequent resistance to penicillin, and a rare but worrisome resistance to cephalosporins. The Antimicrobial Testing Leadership and Surveillance (ATLAS) study estimated global resistance rates of *S pneumoniae* to penicillin, ceftriaxone, and ceftaroline at 36·6%, 6·0%, and 0·4%, respectively.[45] Substantial geographical variability was observed, with ceftriaxone resistance rates of up to 34% in China and South Korea, while North America and Europe maintain resistance rates lower than 5%.[45] Despite this rising proportion of resistant isolates, a study by the GBD 2021 Antimicrobial Resistance Collaborators[26] estimated that the total number of deaths attributable to antimicrobial resistance in *S pneumoniae* across all sites of infection has fallen, from an estimated 258 000 (95% UI 179 000–336 000) in 1990 to 155 000 (122 000–188 000) in 2021, most likely due to a decline in overall *S pneumoniae* infections following the rollout of global vaccination. Among non-vaccine preventable, often health-care-associated pathogens, including *K pneumoniae* and *S aureus*, antimicrobial resistance poses an even greater threat. Carbapenem-resistant Enterobacterales, including *K pneumoniae*, are classified by WHO as critical priority pathogens representing one of the greatest threats to public health.[46] Ultimately, antimicrobial resistance jeopardises common treatments and increases the risk of fatality associated with meningitis. Strategies to address this threat include a global focus on drug development, ensuring the quality and availability of full antibiotic courses, and robust antibiotic stewardship alongside bolstering existing vaccine frameworks and novel vaccine development.

Although no licensed vaccines against Group B streptococcus are commercially available, it is still considered a preventable infection, as the incidence of invasive Group B streptococcus in neonates is substantially reduced in settings that administer intrapartum antibiotics for women who screen Group B streptococcus-positive during pregnancy.[47,48] A recent global systematic review has shown that policies targeting all women who screen positive for Group B streptococcus,

rather than risk-based approaches, are associated with the largest reduction in neonatal early-onset Group B streptococcus infection without an appreciable risk in first-line antibiotic resistance.[48] However, implementing screening at 36–37 weeks, as is done in the USA, might be impractical in low-resource settings, as regular access to antenatal care and accurate pregnancy dating are not always available.[49] A potential solution is screening during labour, although this risks the infant being born before antibiotics can be administered.[50] A maternal Group B streptococcus vaccine serves as a potential solution to these challenges, and several promising vaccines are in development.[51,52] After vaccine approval, challenges in rollout, equity, and vaccine acceptance, such as those that have been seen with the recent approval of the maternal respiratory syncytial virus vaccine, could be the next frontier for Group B streptococcus prevention.[53,54]

To the best of our knowledge, this is the first study to systematically estimate the global incidence and mortality attributable to meningitis from the following pathogens: *Candida* spp, coagulase-negative staphylococci, NPEVs, other fungi, and other *Streptococcus* species. Although no comprehensive review exists on the leading meningitis-causing *Candida* species, case series suggest that *Candida albicans* is the most common cause in both neonatal and post-surgical patient populations.[55,56] This species was named by WHO in 2022 as one of four critical fungal priority pathogens because of its global ubiquity and high CFR for an invasive disease (an estimated 20–50% despite appropriate antifungal treatment).[57] Across all invasive *Candida* infections, the incidence of previously rare *Candida* spp, including the drug-resistant *Candida auris*, is on the rise.[58] Candidal meningitis is particularly difficult to treat, as several antifungal agents cannot penetrate the blood–brain barrier, requiring regimens with the powerful antifungal amphotericin B. Concerningly, amphotericin B-resistant isolates of *C auris* have been detected in invasive infections,[59] underscoring the importance of continued development of novel antifungal and antimicrobial agents, as well as infection prevention across hospital systems. In high-risk patients who have recently undergone neurosurgery, a common demographic for *Candida* spp as well as coagulase-negative *Staphylococcus* infection, meningitis risk may be reduced by reducing the duration of drain placement and avoiding unnecessary drain manipulation.[60] In infants, preventing risk factors for invasive infection, such as preterm birth and very low birthweight, can help reduce the incidence of invasive meningitis.[55]

This study has several limitations. First, meningitis data are scarce, with gaps that are particularly pronounced in low-resource settings, where meningitis cases and deaths often go undocumented. This contributes to wide uncertainty intervals for estimates that reflect the burden concentrated in low-income locations. With more robust data, uncertainty intervals would narrow substantially, leading to more stable estimates. Second, meningitis is difficult to diagnose, particularly in neonates and infants. Its symptoms often overlap with those of other conditions, including encephalitis and neonatal sepsis.[61] This overlap could affect the accuracy of the meningitis burden estimates, especially in locations where data are sparse or where sensitive, accurate diagnostic methods are unavailable. Third, viral pathogens are not often included in surveillance networks, are more difficult to detect using conventional culture methods, and tend to cause milder disease that might be less likely to come to medical attention. This could contribute to an underestimation of viral meningitis. We worked to address this limitation by supplementing surveillance data with data from different settings, including hospital data and insurance claims. Fourth, we directly applied meningitis aetiology proportions from our pathogen distribution models to our overall estimates of meningitis-related deaths, even though the two methods have slightly different definitions of meningitis. More specifically, the GBD definition of meningitis-related deaths includes only instances in which meningitis was the underlying cause of death, whereas the pathogen distribution model definition includes any instance where meningitis was present in the causal chain, irrespective of the underlying cause of death. This one-cause-per-death approach additionally poses its own limitations, as most deaths, including those in children, often have multiple addressable conditions in the causal chain; a recent study based on CHAMPS data resulted in a 16-fold increase in estimated infant meningitis-related deaths when including all causes along the chain. This has implications for resource allocation, as deaths for which meningitis is in the causal chain, even if it is not the underlying cause of death, could be preventable with proper meningitis treatment. Fifth, estimates for newly modelled pathogens, including *Candida* spp and NPEVs, are model-dependent and should be compared with outputs from further research for validation. Sixth, the current study does not incorporate serotype data for any pathogens, thus limiting its utility to track specific meningitis-causing strains. Seventh, these annual estimates do not account for seasonal and regional outbreak patterns, which, especially in areas such as the African meningitis belt, can hide true peaks and limit the ability to assess the efficacy of control measures. Eighth, a key limitation of DALY methodology is that prevalence-based calculations of years lived with disability capture disability at a single timepoint, rather than over survivors' lifetimes. Because people who recover from meningitis often live many years with disability, these point-in-time estimates might underestimate the true population impact.

In summary, although global vaccination campaigns have driven substantial declines in meningitis cases and deaths caused by vaccine preventable bacterial pathogens,

progress remains insufficient to meet the ambitious WHO roadmap targets for 2030. Accelerated efforts—including expanding immunisation, improving access to care, and strengthening diagnostics and surveillance—are essential to achieve these targets. Additionally, we have shown that meningitis, including viral meningitis, still poses a substantial global burden. NPEVs, which cause less severe meningitis and a lower likelihood of mortality than bacterial pathogens, were the most common pathogen causing meningitis incident cases, both in 1990 and in 2023. Furthermore, we have characterised the burden attributable to the rare but highly hazardous *Candida* meningitis, emphasising the growing threat of antimicrobial resistance, particularly in health-care-associated infections or in immunocompromised patients. Targeted investment in WHO pillars, including expanded vaccination coverage, new vaccine development, antibiotic stewardship, region-specific outbreak preparedness, and advances in treatment access and equity, could help to prevent disability and mortality caused by meningitis.

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See Online for appendix 3
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To download the data used in these analyses, please visit the Global Health Data Exchange website at: https://ghdx.healthdata.org/gbd-2023.

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