Development and validation of DeciBHAL-US: A novel microsimulation model of hearing loss across the lifespan in the United States

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Summary

Background Hearing loss affects over 50% of people in the US across their lifespan and there is a lack of decision modeling frameworks to inform optimal hearing healthcare delivery. Our objective was to develop and validate a microsimulation model of hearing loss across the lifespan in the US.

Methods We collaborated with the Lancet Commission on Hearing Loss to outline model structure, identify input data sources, and calibrate/validate DeciBHAL-US (Decision model of the Burden of Hearing loss Across the Lifespan). We populated the model with literature-based estimates and validated the conceptual model with key informants. We validated key model endpoints to the published literature, including: 1) natural history of sensorineural hearing loss (SNHL), 2) natural history of conductive hearing loss (CHL), and 3) the hearing loss cascade of care. We reported the coefficient of variance root mean square error (CV-RMSE), considering values ≤15% to indicate adequate fit.

Findings For SNHL prevalence, the CV-RMSE for model projected male and female age-specific prevalence compared to sex-adjusted National Health and Nutrition Examination Survey (NHANES) data was 4.9 and 5.7%, respectively. Incorporating literature-based age-related decline in SNHL, we validated mean four-frequency average hearing loss in the better ear (dB) among all persons to longitudinal data (CV-RMSE=11.3%). We validated the age-stratified prevalence of CHL to adjusted NHANES data (CV-RMSE=10.9%). We incorporated age- and severity-stratified time to first hearing aid (HA) use data and HA discontinuation data (adjusted for time-period of use) and validated to NHANES estimates on the prevalence of adult HA use (CV-RMSE=10.3%).

Interpretation Our results indicate adequate model fit to internal and external validation data. Future incorporation of cost and severity-stratified utility data will allow for cost-effectiveness analysis of US hearing healthcare interventions across the lifespan. Further research might expand the modeling framework to international settings.

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Research in context

Evidence before this study

A recent systematic review identified few existing decision models that simulate hearing loss natural history, prevention, and treatment across the lifespan. The search was performed on 14 June 2020 in MEDLINE, EMBASE, Cochrane Library, and Global Index Medicus. Search terms on MEDLINE were {"Hearing Loss"[Mesh] OR "hearing"[*tiab*]} AND {"Costs and Cost Analysis"[Mesh] OR "Cost-Benefit Analysis"[Mesh] OR "cost-benefit"[tiab] OR "cost-effectiveness"[tiab] OR "cost utility"[tiab] OR "economic evaluation"[tiab] OR "economic evaluations"[tiab] OR "economic model"[tiab] OR "economic models"[*tiab*]} AND English[lang] AND {NOT (Editorial[ptyp] OR Letter[ptyp] OR Case Reports[ptyp] OR Comment[*ptyp*]) NOT (animals[mh] NOT humans [*mh*])}. Similar search strategies were used across the other databases.

Added value of this study

Our objective was to develop and validate Decision model of the Burden of Hearing loss Across the Lifespan (DeciBHAL-US), a novel microsimulation model of hearing loss. We collaborated with stakeholders on the Lancet Commission on Hearing Loss to outline model structure and we parameterized the model with inputs from the published literature. We then compared model-projected results to published estimates and found our modeling framework to provide a reasonable simulation of hearing loss natural history, diagnosis, and treatment across the lifespan.

Implications of all the available evidence

Our decision modeling framework may be populated with health utility and cost data to perform cost-effectiveness analyses and inform US hearing health policy. Expansion of the modeling framework to low- and middle-income countries might help guide policy in those settings.

Introduction

One in three US adults over the age of 60 have hearing loss, and the prevalence of hearing loss climbs to over 90% by age 80.[1] Hearing loss has a significant impact on quality of life, learning and early development, and emerging evidence suggests hearing loss may negatively impact general and cognitive health.[2-5] Furthermore, persons with hearing loss have higher medical costs compared to those without hearing loss and the annual direct medical costs of hearing loss in the US range from $3.3–12.8B, varying with age and method of estimation.[6-8] Lost economic productivity due to hearing loss may cost up to $194B per annum.[8] Effective treatments for hearing loss exist, yet recent estimates suggest many are severely underutilized.[9] As innovations in hearing healthcare service delivery and technology are developed, frameworks to understand their potential clinical and economic impacts are increasingly important.

Cost-effectiveness analysis in hearing healthcare can guide policymakers towards optimal resource allocation and diverse stakeholders have called for research into the cost-effective provision of hearing healthcare in the US and abroad.[10-12] Decision modeling is a quantitative method that underlies many cost-effectiveness analyses and allows for evidence synthesis to simulate alternative policy or treatment interventions over a long time horizon.[13] However, almost all currently available decision models do not consider prevention, diagnosis, and treatment of hearing loss across the lifespan, which limits the generalizability and applicability of their results to policymakers and hearing healthcare providers.[14] A decision model that allows for consideration of numerous different interventions across ages and etiologies of hearing loss would provide better information on optimal implementation of hearing healthcare interventions.

Our objective was to develop and validate a decision analytic model of hearing loss natural history, prevention, diagnosis, and treatment in the US across the lifespan to inform policymakers and providers on the expected clinical and economic outcomes of alternative hearing healthcare strategies. This work was conducted as a part of an ongoing Lancet Commission on Hearing Loss, and contributes a US-specific component to the broader Commission goal of generating a decision model of hearing loss across the lifespan that can be populated with setting-specific data and applied in various international settings.[15]

Methods

Analytic overview

This study was motivated by stakeholder engagement through the Lancet Commission on Hearing Loss and a recent systematic review, both revealing a gap in the current hearing healthcare decision modeling literature.[14] To address this gap, we set out to develop and validate DeciBHAL-US (Decision model of the Burden of Hearing loss Across the Lifespan) as a policy simulation

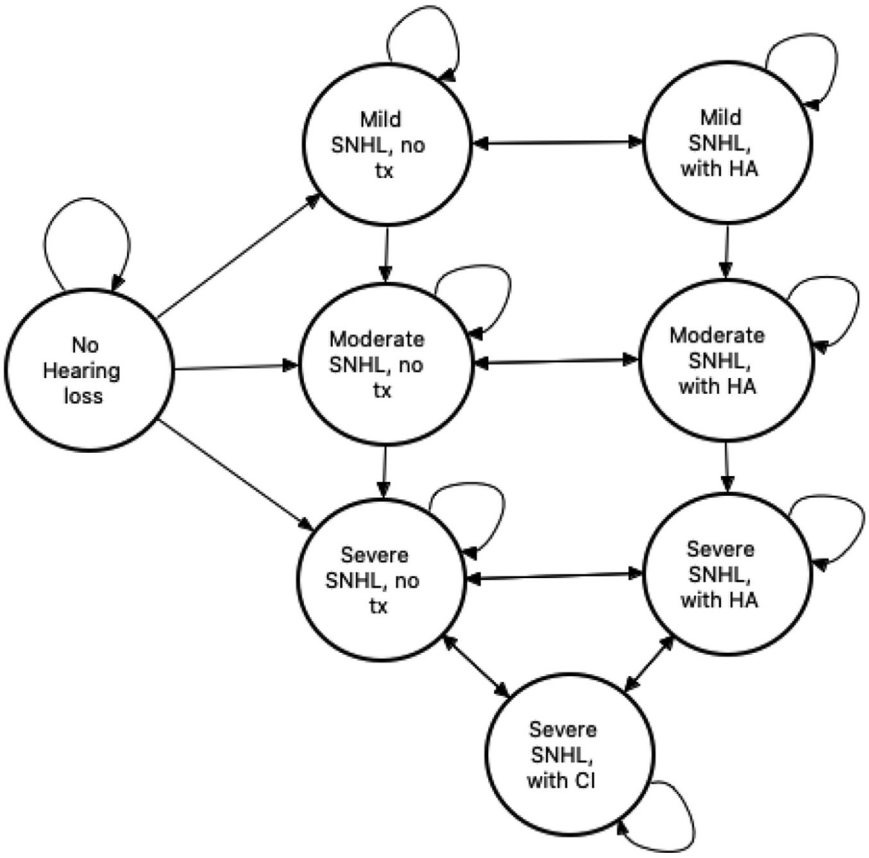

Figure 1. Sensorineural hearing loss health state diagram.

This figure shows a schematic of the microsimulation model, where each circle represents a distinct health state. The arrows between health states, or returning to the health state, represent transition probabilities informed by the literature as described in the Methods. This Figure only shows the health states for untreated and treated sensorineural hearing loss, stratified by severity. Simulated persons experience yearly probabilities of acquiring sensorineural hearing loss, worsening of existing hearing loss, and uptake or discontinuation of hearing loss treatment. An absorbing health state, death, is not shown.

CI: cochlear implant, HA: hearing aid, SNHL: sensorineural hearing loss, tx: treatment.

model. We first consulted with hearing loss clinicians, public health, and policy experts to define the health states of the model. We then populated the model with literature-based estimates of the incidence and prevalence of sensorineural hearing loss (SNHL) and conductive hearing loss (CHL), natural histories of SNHL and CHL, and treatment probabilities. We then performed validation exercises, specifically in three key areas: 1) natural history of SNHL, 2) natural history of CHL, and 3) the hearing loss cascade of care. Wherever possible, we followed the Assessment of the Validation Status of Health-Economic decision models (AdViSHE) framework to guide our validation efforts.[16]

Model overview and hearing loss health states

DeciBHAL-US is an individual-level microsimulation model implemented in TreeAge software (Williamstown, MA). Model health states are based on: 1) presence of hearing loss, 2) hearing loss type (SNHL, CHL, chronic suppurative otitis media (CSOM)-associated CHL), and 3) treatment modality if applicable. Figure 1 shows a schematic for the SNHL health states for post-lingual hearing loss (e.g., hearing loss after the time of language acquisition). Hearing loss severity is categorized based on better ear pure tone average (PTA) thresholds at 500, 1000, 2000, and 4000 hertz: 26–40 decibel (dB) is mild, 41–60 dB is moderate, 61–80 dB is severe, and 81+ dB is profound hearing loss.[1] Simulated persons are assigned set characteristics and experience yearly probabilities of acquiring hearing loss, progression or cure of their hearing loss, and receiving or leaving treatment. Traditionally, hearing loss is classified as 1) SNHL, due to damage or degeneration of the inner ear or neural structures proximal to the inner ear, 2) conductive hearing loss (CHL), due to pathology

Variable	Value		Reference
Bilateral SNHL probability, yearly,%	Males	Females	1,18-20
Age 0y	0.100	0.100	
Ages 1−15y	0.004	0.004	
Ages 16−25y	0.024	0.023	
Ages 26−35y	0.220	0.216	
Ages 36−45y	0.762	0.057	
Ages 46−55y	1.216	0.360	
Ages 56−65y	2.334	1.251	
Ages 66−75y	5.385	3.827	
Ages 76+*y*	10.422	9.168	
SNHL severity, PTA, by etiology			
Meningitis (dB)	68		21
Ototoxicity (dB)	39		22
SNHL progression, PTA decline in dB, mean (SD)			23
Ages 35−65y	1.05 (0.4)		
Ages 65+, PTA <40 db HL	1.37 (0.4)		
AOM probability, yearly*			24
Age 0.5y	6.97		
Age 2y	8.68		
Age 7y	3.52		
Age 12y	2.39		
Age 17y	1.65		
Age 22y	1.53		
Age 30y	0.81		
Age 40y	0.82		
Age 50y	0.98		
Age 60y	1.06		
Age 70y	1.18		
Age 80y	1.34		
Age 90y	1.30		
Probability of recurrent AOM after AOM,%	17.0		25
Probability of OME ≥3 months after AOM,%	26.0		25
Probability of OME resolution after OME≥3 month onset,% yearly,			28
Year 1	70.5		
Year 2	50.0		
Year 3	50.0		
Probability of spontaneous OME≥3 months, yearly,%*			24,25,30
Age 0y	3.09		
Age 1y	4.67		
Age 2y	4.52		
Age 3y	2.72		
Age 4y	3.04		
Age 5y	3.49		
Age 6y	1.61		
Age 7y	0.01		
Ages 8 + *y*	0.10		
Hearing loss, PTA, during CSOM, dB, mean	34.2		35
Hearing loss, PTA, after CSOM, dB, mean (SD)	17.0 (18.6)		36
Probability of non-CSOM-associated CHL, yearly,%*			1,18,19,24
Age 0y	0.004		
Age 15y	0.004		
Age 25y	0.003		
Age 35y	0.003		
Age 45y	0.023		

Table 1 *(Continued)*

Variable	Value		Reference
Age 55y	0.054		
Age 65y	0.005		
Ages 75+y	0.005		
Yearly probability of HA uptake,%*	PTA < 40dB	PTA ≥ 40 dB	
Age 0y	75.95	75.95	47
Ages 1−5y	18.94	18.94	46
Ages 19−55y	0.54	2.35	39,40
Age 65y	0.51	4.60	
Age 75y	0.60	8.14	
Age 85y	0.71	7.20	
Yearly probability of HA d/c,%, ages 1−18 years	3.00		49
Yearly probability of HA d/c, ages 18+,%			41,42
1 year after use	12.90		
2 years after use	9.47		
3 years after use	6.04		
4 years after use	5.68		
5 years after use	5.31		
6 years after use	4.95		
7 years after use	4.59		
8 years after use	4.23		
9 years after use	3.86		
10+ years after use	3.50		
Yearly probability of CI implantation,%			
Adults with severe+ HL with hearing aid,%	1.3		43
Children with severe+ HL with hearing aid,%	10.0		

***Table 1*: Selected model inputs.**

* Linear interpolation was used between ages not displayed.**Abbreviations:** AOM: acute otitis media; CHL: conductive hearing loss; CI: cochlear implant; CSOM: chronic suppurative otitis media; dB: decibel; d/c: discontinuation; HA: hearing aid; HL: hearing loss; OME: otitis media with effusion; PTA: pure tone average; SD: standard deviation; SNHL: sensorineural hearing loss; y: year.

involving the outer or middle ear, and 3) mixed SNHL and CHL. DeciBHAL assumes independence between SNHL and CHL and simulated persons may acquire SNHL, CHL, or both at each yearly time step. To clearly delineate the etiologies that contribute to SNHL and CHL across the lifespan, we collaborated with hearing health experts to create an etiology framework of hearing loss (Appendix 1). Age- and sex-specific mortality rates from 2017 US lifetables were incorporated into the model.[17] SNHL and CHL are tracked for each simulated person in PTA thresholds and utility is dependent on the more severe of the two. Each year of the model, a cohort of newly born persons can enter the simulation. The model runs for 100 cycles (years) or until all simulated persons are in the death state.

Natural history of SNHL

We derived age- and sex-specific incidences of bilateral SNHL from recent prevalence estimates from the National Health and Nutrition Examination Survey (NHANES) and US lifetables, assuming a lifetime duration after acquisition of SNHL (Appendix 2).[1,17-20] We only simulate bilateral SNHL to remain consistent with input data definitions of hearing loss based on better-ear PTA and other economic analyses of hearing healthcare. Upon acquiring SNHL, the age-specific etiology is divided proportionally between ototoxic (e.g., after cisplatin or aminoglycoside use), meningitis, and age-related and other causes. We assumed simulated persons can only experience one cause of SNHL in their lifetime. After acquiring SNHL of any cause, simulated persons receive a SNHL PTA severity in dB; assumed to be >=25 dB hearing loss (HL) for age-related hearing loss and, for the other etiologies, based on the average hearing loss PTA for each etiology (Table 1).[21,22] Age-specific decline in hearing loss is incorporated as a yearly PTA increase in dB (mean=1.05 dB/year; SD=0.4) for persons ages 35+ years and is based on longitudinal studies.[23] This PTA determines hearing loss severity, which subsequently affects other model parameters as described, such as hearing aid (HA) uptake and health state utilities.

Natural history of otitis media-related and other CHL

DeciBHAL incorporates acute otitis media (AOM), persistent otitis media with effusion (OME), and chronic

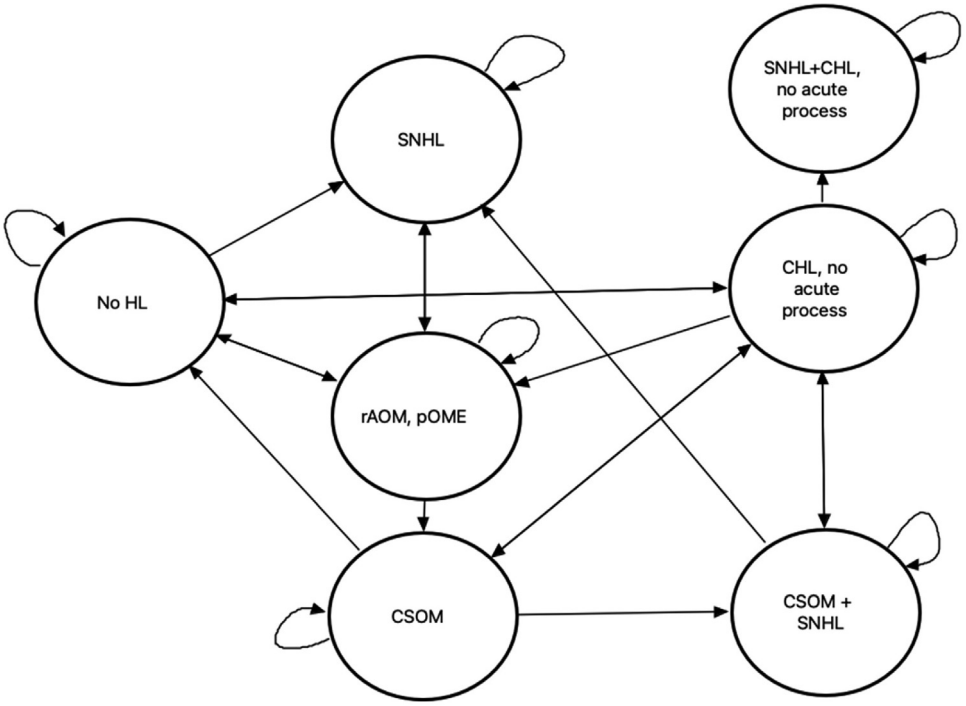

Figure 2. Conductive hearing loss health state diagram.

This health state transition diagram shows a schematic of the microsimulation model, where each circle represents a distinct health state and arrows represent transition probabilities. This figure illustrates the health states related to otitis media and conductive hearing loss in the simulation model. Simulated persons experience yearly probabilities of at least one episode of acute otitis media (AOM) and otitis media with effusion (OME) ≥3 months in the *No HL* state. A proportion of these patients might transition to the recurrent acute otitis media and persistent otitis media with effusion health state (*rAOM, pOME*). Patients with recurrent acute otitis media or persistent otitis media with effusion have a yearly probability of acquiring chronic suppurative otitis media (*CSOM*). After CSOM resolution (average of 3 years), simulated persons may resolve with no permanent conductive hearing loss, or transition to permanent conductive hearing loss. Non-otitis-media-related causes of conductive hearing loss are modeled in aggregate. All patients with conductive hearing loss have the potential to acquire sensorineural hearing loss each year. We assume that, once acquired, conductive and sensorineural hearing loss persist for the remaining lifetime. For simplicity, treated states and an absorbing health state, death, are not shown.

AOM: acute otitis media, CHL: conductive hearing loss, CSOM: chronic suppurative otitis media, pOME: persistent otitis media with effusion, HL: hearing loss, rAOM: recurrent acute otitis media, SNHL: sensorineural hearing loss.

suppurative otitis media (CSOM) as explicit etiologic contributors to CHL, and simulates all other causes of CHL in aggregate (Figure 2). All persons in the model, except those with active CSOM, experience age- and region-specific yearly probabilities of at least 1 episode of AOM.[24] We assumed simulated persons that have at least 1 episode of AOM during ages 0–12 years experience an average of 2.8 episodes per year, and those older than age 12 experience 1 episode per year.[25] The model stratifies two risk groups of persons based on AOM history during the first 2 years of life: persons experiencing 2 or more episodes of AOM receive double the risk of subsequent AOM and OME throughout their lifetime.[26,27] In the absence of adult-specific data, we assume that 17% of all simulated patients who have at least 1 episode of AOM in a year develop recurrent AOM (defined as ≥3 episodes in 1 year) and transition to the recurrent AOM/persistent OME health state the subsequent year (described below).[25]

In the model, persistent OME may occur after an episode of AOM or spontaneously. Based on a meta-analysis of placebo controlled AOM trials, 26% of simulated patients experience OME of ≥3 months after an episode of AOM.[25] Of OME episodes that persist for ≥3 months, 71% of episodes resolve before 1 year.[28] OME episodes that persist for at least one year are assumed to have a mean duration of 21 months, with 75% of patients experiencing spontaneous resolution after 2 years, and 25% after 3 years.[29] Spontaneous rates of OME were calibrated to attain estimates of persistent OME prevalence. In the absence of US-specific data on OME prevalence lasting ≥3 months, by age group, we calibrated to Dutch data and assumed similar demographic characteristics to the US.[30,31] As outlined by US

treatment guidelines, OME persisting for ≥3 months of known duration is considered for surgical management.[28] We assumed 26% of patients with OME ≥3 months receive treatment with tympanostomy tubes within 1 year, and treatment reduces the proportion with effusion at 1 year by 53%.[32,33] The remainder have persistence of their OME for ≥1 year despite treatment, or spontaneous resolution or persistence without treatment (See Appendix 3 for the decision nodes of OME, including surgical treatment).[29]

Simulated patients with recurrent AOM (defined as ≥3 episodes in the previous 12 months) or OME that persists ≥1 year enter a distinct health state (*recurrent AOM and persistent OME*). We simulated these conditions as a single health state due to clinical expert opinion positing the state as a continuum rather than two distinct entities. Patients in this state experience yearly probabilities of acquiring CSOM, based on CSOM incidence data from the US and Canada.[24] The average duration of CSOM (including the US mix of treated and untreated CSOM), 3 years, was calibrated to attain estimates of the US CSOM prevalence (<1%).[34] Probabilities for surgical intervention (including tympanoplasty and mastoidectomy) for CSOM are not explicitly incorporated, rather are included in the average duration of CSOM, and costs for baseline rates of surgical intervention will be estimated as the average yearly costs of patients with CSOM. CSOM results in a PTA of 34 dB hearing level CHL during active disease, and after resolution a proportion has a residual CHL (Mean=17 dB air conduction threshold, SD=18.6 dB).[35,36] The probability of residual CHL after CSOM was calibrated to attain literature-based estimates.[24] Permanent CHL not due to CSOM is simulated in aggregate and incidences are derived to attain adjusted NHANES estimates of US CHL-prevalence, with average PTA assumed to be 40 dB hearing level (Table 1).[37]

Mixed hearing loss

We recognize that some etiologies that cause CHL can also subsequently cause SNHL, however due to an absence of data on the temporal relationship and quantified audiometric effects of this relationship, we assumed independence between etiologic contributors to SNHL and CHL. As such, all patients in the model may acquire both SNHL and CHL through similar age- and sex-specific incidences. DeciBHAL tracks SNHL in dB hearing level and CHL in dB hearing level independently, and severity-dependent parameters are based off the more severe PTA.

Pre-lingual hearing loss

For persons with pre-lingual hearing loss, intervention before the time of language acquisition has different downstream outcomes than interventions for persons losing their hearing after language acquisition. In the model, simulated children with bilateral, profound hearing loss with an onset before age 2 years who do not receive a cochlear implant, enter a separate health state with a pathway of sign language education, and remain for their lifetime (not shown). In the context of pre-lingual severe and profound hearing loss, DeciBHAL primarily addresses the impact of early diagnosis and intervention on efforts to improve access to spoken language and the acquisition of verbal communication. The costs and utilities in these health states will be informed by the published literature detailing the benefit of early intervention for severe and profound hearing loss.[3,38]

Hearing loss cascade of care

In conjunction with expert stakeholders on the Lancet Commission on Hearing Loss, we mapped a conceptual framework for the hearing loss cascade of care (Appendix 4). Simulated persons with hearing loss experience yearly probabilities of going on or off treatment derived from the literature. While there are multiple complex factors influencing treatment access and uptake, transition probabilities in DeciBHAL are based on the final step − treatment uptake or not. Specific intermediary points in the treatment uptake cascade might be incorporated within the treatment uptake probability as needed in future analyses. We considered hearing aids, and re/habilitation (for example, including early speech and language development for children, aural rehabilitation), as treatment for all causes of hearing loss. We included cochlear implantation (i.e., the device and the surgery) for patients with severe and profound SNHL. For patients with CHL, we included non-implantable and implantable bone conduction devices as a proportion of the amplification therapy. The age- and hearing loss severity-specific yearly probabilities of all adult hearing aid acquisition were based on estimates of the average time to uptake of hearing aids after hearing loss onset (mean=8.9 years).[39,40] Hearing aid discontinuation rates were derived from a National Institute on Deafness and Other Communication Disorders/Veteran's Affairs longitudinal study and adjusted to account for a high rate of hearing aid discontinuation in the first year after acquisition, and declining rates thereafter (13 −4%/year).[41,42] We incorporated a delay to diagnosis factor, calibrated to achieve NHANES prevalence estimates of adult hearing aid use. We calibrated the yearly probability of cochlear implantation for persons with severe to profound hearing loss to achieve yearly estimates of cochlear implantation in US children and adults (n = 18,000).[43] We incorporated a 1% annual probability of cochlear implant discontinuation in adults, and 0.2−1.8% per year in children depending on age at implantation.[44,45]

For pediatric hearing aid use, we incorporated time to uptake data to inform yearly probabilities of acquiring

hearing aids (age 1 year: mean=15.8 months, SD=16.8 months; ages 2–5 years: 31.68 months, SD=18.32 months).[46,47] We assumed a linear decline in hearing aid acquisition from age 5 years to adulthood. Combined with a discontinuation rate of 3%/year, we projected the yearly proportion of children with aidable hearing loss (defined as PTA≥25 dB in the better ear) using hearing aids.[48-50] The yearly probability of pediatric cochlear implantation was calibrated to achieve 50% of eligible patients provided with a cochlear implant by age 18 years.[43,51]

Internal validation

We performed internal validation exercises as recommended by AdViSHE. Co-authors who are experts in decision modeling independently reviewed the model code and programming for accuracy. We undertook extreme value testing and report our results in Appendix 5. We examined over 20 patient trace files to ensure the logic of the model and present two annotated patient trace files in Appendix 6.

External validation

All model outcomes were reviewed by hearing health expert co-authors and collaborators on the Lancet Commission on Hearing Loss for face validity. Expert reviewers analyzed DeciBHAL output data in virtual meetings and the model logic and input data were refined based on their feedback. We then focused our external validation efforts on validation to published data as described above. Cohort characteristics for external validation simulations were adjusted for each validation scenario and are described in the Results. We used coefficient of variance root mean square error (CV-RMSE) to compare model projected outcomes with the published literature, and considered CV-RMSE≤15% to indicate adequate model fit.[52,53] We also compared model-projected results with published 95% confidence intervals whenever possible. For select model outcomes, we present low and high ranges based on input value computed 95% confidence intervals in Appendix 7.

Ethics approval and patient consent

All data included in this study was identified from the published literature. No primary patient data was collected for this study.

Role of the funding source

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Results

Prevalence of sensorineural hearing loss by age and sex

We validated our age- and sex-stratified incidences of bilateral SNHL at each decile to published NHANES estimates adjusted to remove CHL stratified by sex as an internal validation exercise (Table 2). We simulated males and females separately from birth to death and collected the prevalence of bilateral SNHL at each decile. The CV-RMSE for model-projected male and female age-specific prevalence compared to adjusted NHANES data was 4.9% and 5.7%. No estimates were outside of the adjusted NHANES 95% confidence intervals.

Progression of sensorineural hearing loss

DeciBHAL incorporates age-related decline in SNHL from published longitudinal data. We simulated 35-year-old males and females without any hearing loss throughout their lifetime, applying SNHL incidences and age-specific progression of SNHL to the PTA in dB hearing level. We assumed that persons without hearing loss had a linear decline in their dB hearing level from 0 to 20 dB hearing level between ages 35–85 years. The model projected population average hearing loss, measured as the PTA in dB hearing level, at each decile was compared to published data from the Baltimore Longitudinal Study on Aging (Figure 3).[54] The CV-RMSE of model data compared to published data was 11.3%.

Acute otitis media, persistent otitis media with effusion, and chronic suppurative otitis media

The model-projected incidence of at least 1 episode of AOM at each decile was consistent with the input data (CV-RMSE=6.5%).[24] We validated model-projected yearly prevalence of OME≥3months during ages 0–9 years to adjusted estimates from the Netherlands (CV-RMSE=12.2%; Appendix 8). The derived CSOM incidence rates produced an average yearly CSOM prevalence between ages 2–80 years of 0.4%, consistent with US estimates of CSOM prevalence.[34]

Prevalence of conductive hearing loss by age

As described above, simulated persons can acquire CHL during and after CSOM, or from other etiologies modeled in aggregate. Simulating persons from birth to death, we validated model-projected age-stratified prevalence of CHL to adjusted NHANES data (CV-RMSE=10.9%).

Age	Bilateral SNHL Prevalence, Males		Bilateral SNHL Prevalence, Females		CHL Prevalence, Males and Females		Hearing Aid Use Prevalence,% of persons with hearing loss	
	Model Outcome,%	NHANES,% (95% CI*)	Model Outcome,%	NHANES,% (95% CI*)	Model Outcome,%	NHANES,%	Model Outcome,%	NHANES,% (95% CI)
15	0.13	0.16 (0.07–0.28)	0.08	0.16 (0.07–0.28)	0.46	0.37	–	–
25	0.38	0.39 (0.0–0.97)	0.31	0.39 (0.0–0.97)	0.59	0.59	–	–
35	2.4	2.5 (0.2–3.1)	2.4	2.5 (0.2–3.1)	0.41	0.41	–	–
45	9.9	9.7 (6.4–13.6)	3.0	3.0 (2.0–4.2)	0.56	0.62	–	–
55	20.0	20.3 (15.1–25.9)	6.6	6.3 (4.7–8.1)	1.03	1.14	3.8	4.3 (0–8.8)
65	36.7	37.2 (31.2–43.9)	17.5	16.9 (14.2–20.0)	1.31	1.45	7.8	7.3 (3.6–10.9)
75	64.4	66.5 (60.5–73.7)	45.6	43.7 (39.8–48.5)	1.26	1.43	14.7	17.0 (12.4–21.6)
85	89.7	86.4 (83.7–90.9)	79.4	77.0 (74.6–81.0)	1.30	1.39	21.0	22.1 (18.5–25.8)

***Table 2*: Model validation results.**
Abbreviations: B/l: bilateral, CHL: conductive hearing loss, CI: confidence interval, NHANES: National Health and Nutrition Examination Survey, SNHL: sensorineural hearing loss.
* 95% confidence intervals from published NHANES estimates are adjusted to derive male- and female-specific values, and to remove conductive hearing loss (see Methods). Therefore, the confidence intervals presented in this table are likely too narrow to reflect the underlying uncertainty. We presented the narrower confidence intervals here to remain conservative in assessing model fit, however any future analyses using DeciBHAL-US should use wider confidence intervals in sensitivity analysis to better reflect this uncertainty.

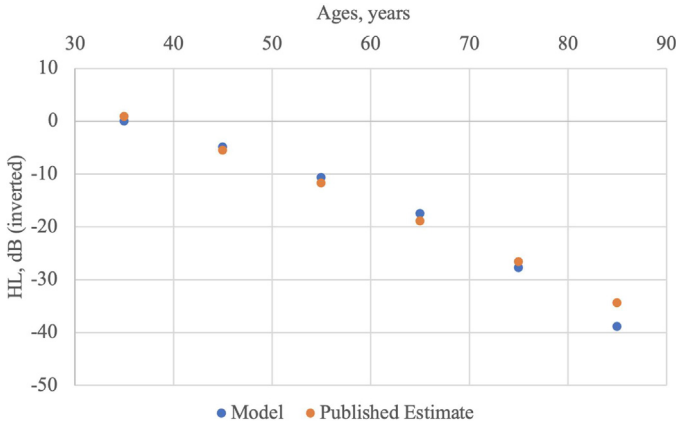

Figure 3. Model projected bilateral sensorineural hearing loss severity compared to the Baltimore Longitudinal Study on Aging.
This figure shows model projected mean hearing loss (PTA in dB HL) across all simulated persons (with and without hearing loss) compared to those reported by the Baltimore Longitudinal Study on Aging. Age progresses on the x-axis from ages 30–90 years, with results shown at each decile. The blue points are model-represented means and the orange points are the published estimates from the Baltimore Longitudinal Study on Aging.
dB HL: decibel hearing level, PTA: pure tone average.

Age-specific hearing aid use

For children, we simulated persons without hearing loss from time of birth to age 18, collecting the proportion of patients with bilateral, permanent hearing loss using a hearing aid yearly (see Appendix 9). Identified estimates ranged between 54 and 79% in this age group, which is consistent with identified estimates from the US and other high-income settings.[48-50] For adults, we simulated persons aged 35 years without hearing loss throughout the rest of their lifetime, collecting the proportion of people with acquired hearing loss using hearing aids at ages 55, 65, 75, and 85 (Table 2). We achieved adequate model fit compared to published NHANES data (CV-RMSE=10.3%).

Cochlear implantation

We adjusted the yearly probability of adults with severe-profound hearing loss receiving a cochlear implant to match yearly implantation estimates from 2019 (model=13,000, estimate=13,000).

Discussion

We developed and validated DeciBHAL-US, among the first microsimulation models of hearing loss prevention, natural history, diagnosis, and treatment across the lifespan in the US. Our decision modeling framework was validated by hearing healthcare clinical and public health experts. We populated the framework

with published estimates of hearing loss epidemiology and current US-based estimates on treatment uptake and discontinuation, and validated model-projected outcomes to published estimates. We demonstrated adequate fit of DeciBHAL-US projections to literature-based estimates across several validation targets, including NHANES epidemiologic estimates of the natural history of SNHL and CHL, and the hearing healthcare cascade of care.

DeciBHAL-US has several novel contributions to the hearing loss decision modeling literature. First, it simulates males and females without and with hearing loss, incorporating published NHANES epidemiologic data, across the lifespan. Most existing decision models evaluating hearing healthcare interventions begin with a cohort of persons with hearing loss and do not incorporate age-related incident hearing loss.[14] The use of robust epidemiologic data on incident hearing loss across the entire lifespan gives DeciBHAL-US the potential to identify optimal points of intervention for hearing healthcare, and potential effects of hearing loss prevention interventions. The population of DeciBHAL-US with US-specific health state utility values and costs will enable projection of long-term clinical and economic effects of alternative hearing healthcare interventions and treatment scale-up. Comparing multiple hearing healthcare interventions in the same modeling structure will produce directly comparable cost-effectiveness estimates to inform policy and decision makers. DeciBHAL-US further includes both SNHL and CHL, which provides a framework to better simulate interventions targeting hearing loss prevention interventions, as well as more accurate costing analysis.

DeciBHAL-US additionally simulates the current cascade of hearing healthcare in the US, incorporating current rates of screening, diagnosis, linkage, and severity-dependent treatment uptake/discontinuation to project the number of people diagnosed and in care throughout the life course. This allows for simulation of scale-up interventions (hearing aid, CI, and other) at any point in the hearing healthcare cascade. The novel inclusion of treatment uptake and discontinuation rates allows DeciBHAL-US to simulate treatment and screening interventions over a long time-horizon, a key limitation in the current hearing loss decision modeling literature. Given the uncertainty in several important parameters informing the hearing healthcare cascade of care, for example the introduction of over-the-counter hearing aids in the US, future analyses might assign appropriate distributions to uncertain parameters to allow for value of information analysis. Value of information analysis is a quantitative methodology that estimates the monetary value of reducing decision uncertainties, and may provide research funders an estimate of the maximum return on investment expected for their research dollars.[55]

DeciBHAL-US currently does not include health state utility values and medical and societal costs of hearing loss. There is large variability and uncertainty in the economic modeling literature around health state utility values and indirect economic costs for hearing loss, with many modeling analyses assigning Global Burden of Disease calculated disability-adjusted life-years (DALYs) for severity-specific hearing loss health states and assuming a 1-severity lower DALY for treated hearing loss.[9] While robustly measured, these DALY values might not be appropriate in all settings and treatment states. Indeed, two ongoing systematic reviews as part of the Lancet Commission on Hearing Loss are currently underway to inform untreated and treated DeciBHAL-US health state utility values, as well as the costs of lost productivity attributed to hearing loss.[56,57]

The natural history framework in DeciBHAL-US necessarily simplified across important hearing loss etiologies. We worked with key stakeholders to create a framework of etiologic contributors to hearing loss across the lifespan. We then built off this framework to identify published estimates and simulate hearing loss natural history in DeciBHAL. We used NHANES data as the most representative estimates of hearing loss stratified across age and severity. We made simplifying assumptions to divide the NHANES data into SNHL and CHL, given the different natural histories and treatment, and costs of these conditions. While policymakers will not likely target treatment of persons with SNHL or CHL, rather persons with hearing loss of any etiology, the model necessarily simulates hearing loss natural history and progression. Additionally, separating by etiology provides a framework for simulating alternative hearing loss prevention interventions in future analyses. However, dividing NHANES projections into SNHL and CHL does not account for the relationship between SNHL and CHL, with some data showing that CHL predisposes persons to have SNHL earlier and at higher severities.[58] Additionally, we did not incorporate surgical interventions for CHL, such as stapedectomy for otosclerosis, and future model versions evaluating these interventions might incorporate a sub-module to account for hearing and cost outcomes related to otosclerosis and its treatment.

As currently structured, DeciBHAL does not explicitly consider the contributions of hearing loss to the increased risk of other physical health outcomes and dementia. Hearing loss is a modifiable risk factor with potential to affect dementia risk reduction worldwide and, therefore, prevention or treatment of hearing loss, and the associated sensory deprivation and social isolation, may reduce the incidence of dementia.[2,59,60] Future versions of DeciBHAL might project the potential clinical and economic benefits of those possibly averted cases of dementia and other health conditions, without necessarily simulating the natural history of these disorders.

DeciBHAL incorporates current published estimates on the prevalence of hearing aid and cochlear implant

use to simulate the cascade of hearing healthcare. The rates of hearing aid uptake were based on estimates of time to first hearing aid after hearing loss onset in an older population, and included a calibration factor to better match NHANES estimates.[40] We acknowledge that hearing aid discontinuation rates could also be adjusted (increased) instead of uptake to better match NHANES estimates, and the different clinical and economic outcomes from these alternative calibration factors should be explored in any future DeciBHAL analyses. Data informing the pediatric hearing aid use prevalence were sparse, and our estimates may overestimate the true number of children with an aidable hearing loss using a hearing aid. Equally important to simulating the hearing healthcare cascade, the role of stigma in adult patient decisions to acknowledge their hearing loss and seek help for their hearing difficulties might be incorporated indirectly in DeciBHAL as an effect on age-specific hearing aid uptake rates.[61]

Additionally, while we based model transition probabilities on acquisition of a hearing aid or cochlear implant, hearing healthcare often involves a multidisciplinary healthcare team and longitudinal approach to achieve optimal treatment outcomes, most evident in the care pathway for children with congenital hearing loss. DeciBHAL does not explicitly simulate re/habilitation that should be provided to hearing aid and cochlear implant users, but rather models all persons with either treatment in aggregate.[62] DeciBHAL's health states are inherently based on health outcomes and do not represent educational and cultural outcomes. Future model input values, such as health state utility values and costs, might incorporate the proportion of treated patients receiving appropriate re/habilitative care, and the effects of appropriate care on patient outcomes, including improved communication and quality of life, and healthcare costs. There is also the future potential to use DeciBHAL to examine the benefits of early intervention for non-auditory interventions, which may be more feasible in some contexts.

Our analysis and DeciBHAL-US have several limiting assumptions. First, as with all modeling studies we made simplifying assumptions in both the model structure and input data. We were transparent about these assumptions in this validation analysis, and any future studies using DeciBHAL-US should robustly test the effect of these assumptions on projected outcomes. One such assumption is excluding age-period-cohort effects, using cross-sectional data to project future outcomes, despite the presence of cohort effects in exposures that DeciBHAL-US does not capture. Data on cohort effects in hearing loss and methods for their application in long-term simulation modeling might be incorporated in future analyses using DeciBHAL-US. Another simplification was the exclusion of an explicit health state for impacted cerumen, a common and costly condition in the US that is associated with mild levels of hearing loss.[63] We chose to focus the model structure on permanent hearing loss given the yearly time step, however future analyses might include impacted cerumen across all health states — carrying associated quality of life effects and costs — to better represent the costs of hearing care in the US. Second, we chose what we believed to be the highest-quality and most generalizable estimates to validate model-projected outcomes. These estimates were selected among other possibilities through discussions with clinical and policy experts in the Lancet Commission on Hearing Loss. Third, some model inputs did not have US-specific data and required either derivation from other known inputs, or imputation from population-based estimates from other high-income settings. In particular, US-specific estimates for pediatric hearing loss natural history and treatment were sparse and we incorporated estimates from other high-income settings (predominately Europe and Australia) to inform our model inputs.[64] All uncertain inputs, and especially those adjusted from a non-US setting, should be robustly tested in sensitivity analysis in future model applications.

Fourth, we defined hearing loss as bilateral, based on PTA, and did not include unilateral hearing loss, which can also have significant effects on quality of life and healthcare costs. We made this assumption to remain consistent with input data sources and other economic analyses of hearing loss, and to remain conservative in our calculation of the burden of hearing loss. PTA is a commonly accepted metric for defining hearing loss, and most often found in our input data sources, however it does not directly assess functional hearing abilities and may under- or overestimate actual hearing loss burden. Additionally, for validation purposes, we defined severities in line with NHANES, which is different than updated severity definitions from the Global Burden of Disease and the 2021 WHO World Report on Hearing.[1,9] Sensitivity analysis loosening these assumptions will be important in analyses utilizing DeciBHAL-US. Fifth, given the complexity of the model we were unable to assign distributions to every parameter and compute uncertainty intervals. Instead, we present several deterministic sensitivity analyses in the Appendix. Lastly, there are large, documented disparities in the provision of and access to hearing healthcare within the US, and DeciBHAL currently does not account for differential outcomes based on patient race, ethnicity, or socioeconomic status.[47,65,66] Future model versions should incorporate the impacts of racism, classism, and other structural inequities on hearing health outcomes.[67]

The vast majority of hearing loss burden lies in low- and middle-income countries, and the opportunities for hearing healthcare scale-up are equally large in these settings.[12] Future collaboration with clinicians and researchers from low- and middle-income countries, and select populations in high-income settings like the

rural US, might allow for population of DeciBHAL with setting-specific epidemiologic and treatment parameters and expansion to other settings.[68] Ongoing efforts are identifying the other data inputs necessary to build a hearing loss modeling framework in international settings, and similar validation efforts will be required for those frameworks.

In conclusion, DeciBHAL-US provides a reasonable simulation of hearing loss natural history, diagnosis, and treatment when validated to published estimates. Use of DeciBHAL-US for economic analysis might provide a major advance in hearing healthcare decision modeling literature by projecting comparable cost-effectiveness ratios for multiple interventions for men and women across the lifespan. The availability of comparable and transparent cost-effectiveness estimates from DeciBHAL could help guide policy makers in the optimal allocation of resources to alleviate the substantial burden of hearing loss and limited treatment uptake in the US and ultimately in other countries and world regions.

Declaration of interests

JRD reports grants from the National Institutes of Health, participation on the National Institute on Deafness and Other Communication Disorders Data Safety Monitoring Board (DSMB) and the National Institute on Aging ACHIEVE (Aging and Cognitive Health Evaluation in Elders) DSMB, and participation on the Board of Directors of the Hearing Health Foundation and on the Executive Council of the Acoustical Society of America. All other authors declare no competing interests.

Data sharing statement

Model code and input data may be requested from the corresponding author. Please see Appendix 10 for a complete schematic of the model structure.

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Software: EDB, ERM, MMD, DY, OO, GDSS
Supervision: OO, GDSS
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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.eclinm.2021.101268.

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