Validation of the Decision model of the Burden of Hearing loss Across the Lifespan (DeciBHAL) in Chile, India, and Nigeria

*Ethan D. Borre,[a,b] Austin Ayer,[c] Carolina Der,[d] Titus Ibekwe,[e] Susan D. Emmett,[f,g] Siddharth Dixit,[g,h] Minahil Shahid,[g,h] Bolajoko Olusanya,[i] Suneela Garg,[j] Mohini Johri,[b] James E. Saunders,[k] Debara L. Tucci,[l] Blake S. Wilson,[f,g,m,n] Osondu Ogbuoji,[a,b,g,h] and Gillian D. Sanders Schmidler[a,b,o]**

[a]Department of Population Health Sciences, Duke University School of Medicine, Durham, NC, USA
[b]Duke-Margolis Center for Health Policy, Duke University, Durham NC, USA
[c]Duke University School of Medicine, Durham, NC, USA
[d]Facultad de Medicina Universidad del Desarrollo, Clínica Alemana de Santiago, Santiago, Chile
[e]Department of Ear, Nose and Throat, Head & Neck, University of Abuja Teaching Hospital, Gwagwalada Abuja, Nigeria
[f]Department of Head and Neck Surgery and Communication Sciences, Duke University School of Medicine, Durham, NC, USA
[g]Duke Global Health Institute, Duke University, Durham, NC, USA
[h]Center for Policy Impact in Global Health, Duke Global Health Institute, Durham NC, USA
[i]Centre for Healthy Start Initiative, Lagos, Nigeria
[j]Maulana Azad Medical College and Associated Hospitals, New Delhi, India
[k]Department of Surgery, Geisel School of Medicine, Dartmouth University, Lebanon, NH, USA
[l]National Institute on Deafness and Other Communication Disorders, National Institutes of Health, Bethesda, MD, USA
[m]Department of Biomedical Engineering, Pratt School of Engineering, Duke University, Durham, NC, USA
[n]Department of Electrical & Computer Engineering, Pratt School of Engineering, Duke University, Durham, NC, USA
[o]Duke Clinical Research Institute, Duke University School of Medicine, Durham NC, USA

Summary

Background There is no published decision model for informing hearing health care resource allocation across the lifespan in low- and middle-income countries. We sought to validate the Decision model of the Burden of Hearing loss Across the Lifespan International (DeciBHAL-I) in Chile, India, and Nigeria.

Methods DeciBHAL-I simulates bilateral sensorineural hearing loss (SNHL) and conductive hearing loss (CHL) acquisition, SNHL progression, and hearing loss treatment. To inform model inputs, we identified setting-specific estimates including SNHL prevalence from the Global Burden of Disease (GBD) studies, acute otitis media (AOM) incidence and prevalence of otitis-media related CHL from a systematic review, and setting-specific pediatric and adult hearing aid use prevalence. We considered a coefficient of variance root mean square error (CV-RMSE) of ≤15% to indicate good model fit.

Findings The model-estimated prevalence of bilateral SNHL closely matched GBD estimates, (CV-RMSEs: 3.2-7.4%). Age-specific AOM incidences from DeciBHAL-I also achieved good fit (CV-RMSEs=5.0-7.5%). Model-projected chronic suppurative otitis media prevalence (1.5% in Chile, 4.9% in India, and 3.4% in Nigeria) was consistent with setting-specific estimates, and the incidence of otitis media-related CHL was calibrated to attain adequate model fit. DeciBHAL-projected adult hearing aid use in Chile (3.2-19.7% ages 65-85 years) was within the 95% confidence intervals of published estimates. Adult hearing aid prevalence from the model in India was 1.4-2.3%, and 1.1-1.3% in Nigeria, consistent with literature-based and expert estimates.

Interpretation DeciBHAL-I reasonably simulates hearing loss natural history, detection, and treatment in Chile, India, and Nigeria. Future cost-effectiveness analyses might use DeciBHAL-I to inform global hearing health policy.

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Keywords: Hearing loss; Decision modeling; Global health policy

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*Corresponding author at: 100 Fuqua Drive, Box 90120, Durham, NC 27708, USA.
E-mail address: gillian.sanders@duke.edu (G.D. Sanders Schmidler).

Research in context

Evidence before this study

In a previously published systematic review, we searched MEDLINE on 14 June 2020 using the search string: {"Hearing Loss"[Mesh]OR "hearing"[tiab]} AND {"Costs and Cost Analysis"[-Mesh] OR "Cost-Benefit Analysis"[Mesh] OR "cost-bene-fit"[tiab] OR "cost-effectiveness"[tiab] OR "costutility"[tiab] OR"economic evaluation"[tiab] OR "eco-nomic 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])}. We extended the search to EMBASE, Cochrane Library, and Global Index Medicus. This review identified few published decision models that addressed in low- and middle-income settings, and none that considered multiple interventions across the lifespan.

Added value of this study

This study sought to extend Decision model of the Burden of Hearing loss Across the Lifespan (DeciBHAL), previously validated in the United States, to three international settings: Chile, India, and Nigeria. DeciBHAL is a Markov microsimulation model of the prevention, natural history, diagnosis, and treatment of hearing loss. This study provides the first validated decision modeling framework of hearing loss across the lifespan in these settings.

Implications of all the available evidence

Our modeling framework, input with setting-specific cost and utility data, may be used to inform decisions around scarce resource allocation to hearing healthcare. DeciBHAL allows for comparison of hearing healthcare interventions at multiple points in the lifespan, and across different points in the care cascade, from prevention of hearing loss to diagnosis to retention on effective therapy. In conjunction with the Lancet Commission on Hearing Loss, planned cost-effectiveness analyses may guide policy conversations in global hearing health.

Introduction

Eighty percent of the global burden of hearing loss lies in low- and middle-income countries (LMIC), and the vast majority of hearing loss in these settings remains untreated.[1] Untreated disabling hearing loss affects all aspects of daily life, can limit human potential, and may carry an economic burden of nearly $1 trillion USD per year.[2,3] While effective prevention, diagnosis, and treatment strategies exist, the optimal allocation of scarce resources to hearing healthcare interventions in LMIC is unknown. A recent systematic review found that only 1 in 5 model-based cost-effectiveness analyses were set in LMIC, and no model considered multiple interventions across the lifespan to allow for comparison of several hearing healthcare interventions simultaneously.[4]

The Decision model of the Burden of Hearing loss Across the Lifespan (DeciBHAL) is a decision modeling framework of hearing loss throughout the lifespan that was previously validated in the United States setting.[5] Decision models support decision making in the public health policy sector by providing an analytic framework to compare alternative healthcare interventions. Decision modeling frameworks may be used to predict health and economic outcomes under different decisions and are the main analytic tool underlying model-based cost-effectiveness analyses. As an example, decision analyses demonstrating the cost-effectiveness of newborn hearing screening programs were likely influential in the expansion of universal newborn hearing screening in the United States.[6,7] This model is novel since it simulates persons with and without hearing loss, as well as the hearing loss cascade including prevention, diagnosis, and treatment uptake and discontinuation. Working with participants in the Lancet Commission on Hearing Loss,[8] our objective was to extend a previously validated decision model of hearing loss natural history, diagnosis, and treatment (DeciBHAL) to three settings: Chile, India, and Nigeria. The aim and scope of this model will be to contribute to the Commission's goal of identifying cost-effective strategies to scale up hearing healthcare worldwide.

Methods

Analytic overview

Our objective was to validate DeciBHAL-I, a decision model of hearing loss across the lifespan in Chile, India, and Nigeria. To develop the DeciBHAL International (DeciBHAL-I) model versions, we consulted with hearing loss clinical experts in Chile, India, and Nigeria, and with experts in the Lancet Commission on Hearing Loss. In choosing DeciBHAL-I settings, all countries with stakeholder representation on the Lancet Commission were considered. The final settings were chosen based on data availability and to ensure differences in geography, income level, and hearing loss epidemiology to better inform global hearing health policy in future analyses. We first discussed key model structure and input data within DeciBHAL that would need adjusting to better simulate hearing loss prevention, natural history, detection, diagnosis and treatment in Chile, India, and Nigeria. Our discussions consisted of teleconferences and email correspondence with hearing healthcare experts in our target settings (including co-authors CD, TI, BO, and SG). We followed the Assessment of the Validation Status of Health-Economic decision models (AdViSHE) framework, and following this model our discussions with collaborators consisted of questions

regarding the face validity of the model structure, identification of input data, and validity of model-projected results.[9] We then used a previously published method for validating DeciBHAL in the US to validate our model-projected outputs to external estimates across the natural histories of sensorineural hearing loss (SNHL) and conductive hearing loss (CHL), and the hearing loss cascade of care.[5] Throughout the subsequent narrative model description, we delineate key modeling assumptions.

Model overview and hearing loss health states

DeciBHAL-I is a microsimulation model, parameterized with input data from the published literature, and implemented in TreeAge software (Williamstown, MA).[5] Briefly, health states within the model are determined by: 1) the presence of hearing loss, 2) hearing loss type (SNHL, CHL, chronic suppurative otitis media (CSOM)-associated CHL), and 3) treatment modality if applicable. The full model structure is graphically represented in Appendix 1. Consistent with the Global Burden of Disease (GBD) studies and World Health Organization (WHO), DeciBHAL-I hearing loss severity is categorized based on the pure tone average (PTA) of auditory thresholds at 500, 1,000, 2,000, and 4,000 hertz in the better-hearing ear: 20-34 decibels (dB) is mild, 35-49 dB is moderate, 50-64 dB is moderately severe, 65-79 is severe, 80-94 is profound, and 95+ is complete hearing loss.[2,10] In the model, simulated persons are assigned demographic characteristics and each year undergo setting-specific probabilities of acquiring hearing loss, progression of existing hearing loss, and treatment uptake or discontinuation. We incorporated age- and sex-specific mortality rates from the WHO and United Nations Population Division.[11,12] The presence and severity of SNHL and CHL are tracked for each simulated person independently in PTA thresholds and health state utility is dependent on the more severe of the two.

Incidence of SNHL

We used GBD 2019 estimates[13] of age- and sex-specific prevalence of hearing loss in Chile, India, and Nigeria, combined with life-table data, to derive input incidences of hearing loss (Table 1).[10] For SNHL, we used the GBD categorization of age-related and other hearing loss. DeciBHAL-I simulates only bilateral SNHL to remain consistent with the input data. Model-projected SNHL prevalence was then compared to GBD estimates in an internal validation exercise.

Cause-specific SNHL

We assumed SNHL was due to one of three etiologies: 1) meningitis, 2) ototoxicity, or 3) age-related and additional causes other than meningitis or ototoxicity (referred to as "age-related and other causes" throughout this report; CHL is discussed distinctly below). While age-related and other SNHL accounts for substantially more hearing loss prevalence than the other two etiologies, we included meningitis-related and ototoxic SNHL in the model structure due to the potential for prevention of these types of hearing loss through vaccination programs or reduction in ototoxic medication use. We ensured use of epidemiologic estimates that accounted for the differential contributions of these etiologies to total hearing loss prevalence. We estimated the age-specific proportion of SNHL due to meningitis by adjusting data on setting- and age-specific meningitis incidences, case-fatality rates, and probabilities of hearing loss after meningitis (Table 1).[14-18] For ototoxicity, we newly developed model structure to consider aminoglycoside treatment for multi-drug resistant tuberculosis (MDR-TB) and platinum-based chemotherapeutics (cisplatin and carboplatin) as contributors to hearing loss (Appendix 1). However, we did not utilize this model structure in the current validation exercises due to current data limitations. This exclusion did not affect any validations presented herein and ongoing efforts may provide the necessary data to inform this DeciBHAL-I sub-module. Previously published estimates of the yearly number of new hearing loss cases due to MDR-TB treatment may be incorporated as a proportion of hearing loss at each age.[19] All other sensorineural hearing loss was assumed to be age-related, and we assumed that simulated persons can only experience one cause of SNHL throughout their lifetime.

SNHL progression

After acquiring SNHL of any cause, simulated persons are assigned an etiology-specific SNHL PTA severity (in dB) based on the average hearing loss PTA for each etiology (Table 1).[18,20,21] We assigned a PTA severity of 25 dB HL for all persons upon acquiring age-related and other SNHL. We used US-based estimates of the yearly age-specific decline in hearing for persons age 35+, defined as a mean 1.05dB/year (SD=0.4) PTA increase in dB HL.[22,23] We included a model input to allow for calibration of SNHL progression to better match external data sources such as the GBD.[22]

Natural history of otitis media-related and other CHL

As described previously, DeciBHAL simulates acute otitis media (AOM), otitis media with effusion (OME), and chronic suppurative otitis media (CSOM) as distinct CHL etiologies, and simulates all other causes of CHL in aggregate.[5] Yearly AOM incidence for each setting was derived from a systematic review, and 17% of AOM cases persisted for greater than 1 year.[24,25] OME was simulated as a sequela of AOM after resolution, or spontaneously. Yearly rates of spontaneous (non-AOM-

Variable	Chile		India		Nigeria		Reference
Bilateral SNHL probability, yearly, %							
	Males	Females	Males	Females	Males	Females	
Age 0y	0.12	0.08	0.16	0.14	0.46	0.48	
Ages 1-3y	0.15	0.11	0.31	0.28	0.53	0.66	
Ages 4-7y	0.13	0.11	0.30	0.26	0.56	0.57	
Ages 8-12y	0.07	0.06	0.18	0.16	0.19	0.16	
Ages 13-17y	0.13	0.12	0.23	0.22	0.11	0.13	
Ages 18-27y	0.35	0.24	0.65	0.57	0.52	0.46	[10]
Ages 28-37y	0.44	0.29	0.76	0.66	0.73	0.55	
Ages 38-47y	0.79	0.45	1.86	1.75	1.02	0.85	
Ages 48-57y	2.47	1.46	3.23	2.99	2.15	1.89	
Ages 58-67y	4.16	3.17	3.31	3.17	2.65	2.03	
Ages 68-77y	5.61	4.76	4.46	4.17	2.50	2.30	
Ages 78+y	7.00	6.22	5.50	4.91	1.30	1.19	
SNHL Severity, PTA, by etiology							
Meningitis (dB)			68				[18]
Ototoxicity (dB)			39				[20]
SNHL Progression, PTA decline in dB, mean (SD)							
All ages			1.05 (0.4)				[22]
AOM Probability, yearly*							
Age 0.5y	7.75		15.80		30.43		
Age 2y	8.72		21.31		42.33		
Age 7y	3.75		8.53		17.76		
Age 12y	1.54		7.92		19.86		
Age 17y	1.63		4.24		9.39		[24]
Age 22y	1.6		3.79		8.12		
Age 30y	0.89		1.92		4.05		
Age 40y	0.89		1.93		4.10		
Age 50y	1.05		2.32		4.98		
Age 60y	1.14		2.52		5.37		
Age 70y	1.27		2.8		5.97		
Age 80y	1.44		3.18		6.83		
Age 90y	1.39		3.06		6.82		
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							
Year 1			70.5				
Year 2			25.0				[55]
Year 3			25.0				
Hearing loss, PTA, during CSOM, dB, mean			34.2				[29]
Hearing loss, PTA, after CSOM, dB, mean (SD)			17.0 (18.6)				[30]

Table 1 *(Continued)*

Variable	Chile		India		Nigeria		Reference
Yearly probability of HA uptake, %*	PTA < 40dB	PTA ≥ 40 dB	PTA < 40dB	PTA ≥ 40 dB	PTA < 40dB	PTA ≥ 40 dB	
Age 0y	58.1	58.1	1.5	1.5	2.5	2.5	33,41,42
Ages 1-5y	1.6	1.6	1.25	1.25	1.75	1.75	
Ages 19-55y	0.1	0.8	0.4	1.5	0.03	0.1	
Age 65y†	0.1	0.8	0.04	0.2	0.03	0.1	10,33-35,37-40
Age 75y†	0.2	1.9	0.06	0.2	0.04	0.1	
Age 85y†	0.4	5.3	0.06	0.2	0.04	0.1	
Yearly probability of HA d/c, %, ages 1-18 years	3.0						44
Yearly probability of HA d/c, ages 18+, range 1-10+ years after use	3.5-12.9%						39,40
Yearly probability of CI implantation, %							
Adults with severe+ HL with hearing aid, %	0.5		0.1		0.01		47,48
Children with severe+ HL with hearing aid, %	18.6		0.1		0.01		

***Table 1*: Selected model input data.**
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.
* Linear interpolation was used between ages not displayed.
† In Chile, the yearly probability of hearing aid uptake changed at ages 60, 70, and 80 years to better match input data.

related) OME were derived using data from the Netherlands given lack of setting-specific data for the target countries.[26,27]

Simulated persons who experience recurrent AOM, or OME persisting ≥1 year, enter a distinct health state (recurrent AOM/persistent OME) during the subsequent model cycle. In this health state (average duration 2 years), patients are subject to annual age- and setting-specific probabilities of developing CSOM.[24] We calibrated the average duration of CSOM to setting-specific estimates of the prevalence of CSOM (1.2% in Chile, 7.8% in India, and 3.6% in Nigeria).[28] During active disease, CSOM causes CHL with an assumed PTA of 34 dB HL. Following CSOM resolution, a proportion of simulated persons experience residual CHL (Mean=17 dB air conduction threshold, SD=18.6 dB).[29,30] The probability of residual CHL after CSOM was calibrated to literature-derived estimates.[24] Given data limitations, we used US data to derive the yearly probability of permanent CHL not due to CSOM, with average PTA assumed to be 40 dB HL.[31]

Mixed hearing loss

In DeciBHAL, simulated persons may acquire both SNHL and CHL according to age- and sex-specific incidences. Given data limitations, we assumed independence between SNHL and CHL despite emerging evidence associating SNHL and CHL.[30,32] The model tracks the severity of hearing loss due to SNHL and CHL independently, and severity-dependent parameters are dependent on the more severe PTA.

Hearing loss cascade of care

We derived probabilities of hearing aid uptake in Chile, India, and Nigeria from the published literature where available. In Chile, we used data on the number of hearing aids distributed by the national health program to adults age >65 years in 2016, and the number of persons with untreated hearing loss, to derive a yearly probability of hearing aid provision.[10,33] We used Chilean estimates of the prevalence of hearing aid use by age and severity to derive age- and severity-specific yearly uptake probabilities.[34] Lastly, we incorporated a delay-to-diagnosis factor into our uptake rates to better match estimates of HA uptake in Chile.[34] A National Disability in India household survey reported that 19.1% of adults with a hearing disability used a hearing aid.[35] Because this data was self-reported and underestimated the prevalence of hearing loss by a factor of 10 compared to a high-quality audiometric study in India,[36] we applied a multiplier of 0.10, representing the probability of hearing loss diagnosis. This yielded a hearing aid prevalence

calibration target of 1.91%. A sensitivity analysis was performed varying this multiplier from 0.1-1.0 (Appendix 2). Assuming this calibration target represented persons with 40 dB HL or greater hearing loss at a mean age of 75 years, and incorporating age- and severity-specific risk ratios of hearing aid ownership from China, we derived yearly probabilities of hearing aid uptake in India.[37] We were unable to identify nationally representative data on adult hearing aid use in Nigeria. One study estimated that of 498 patients evaluated for hearing loss at an ear nose and throat clinic, 3 adults (1.4%) eventually procured hearing aids.[38] Given evidence of low uptake, even among those with diagnosed hearing loss, we relied on expert opinion to assume that 0.5-1% of Nigerian adults with hearing loss used hearing aids at ages 65-85 years. Given a lack of setting-specific estimates of hearing aid discontinuation, we assumed the yearly probability of hearing aid discontinuation to be equivalent to that observed in the United States (4-13%/year).[39,40]

For pediatric hearing aid use in Chile, we derived the yearly probability of uptake using the number of hearing aids provided by the Chilean government to infants and children as well as the number of persons with hearing loss in those age groups (hearing aid uptake probability: 58%/year infants, 1.6%/year children age 1-4 years, 1.0%/year children age 5-18).[10] For the Indian setting, we used a published estimate of 6% hearing aid use among children with hearing loss at age 12 to derive a hearing aid uptake probability of 1.0-1.5%/year.[41] Lastly, for the Nigerian setting we used a published estimate of 5% hearing aid use at age 7 to derive a hearing aid uptake probability of 1.0-2.5%/year.[42] We assumed a pediatric hearing aid discontinuation rate of 3%/year in all settings, and projected the yearly proportion of children ages 0-18 with aidable hearing loss (defined as PTA≥20 dB HL in the better ear) using hearing aids.[43-45]

To derive the yearly probability of cochlear implantation, we used DeciBHAL to estimate the number of children and adults with severe and profound hearing loss using hearing aids in each setting. We then scaled these estimates to the populations using age-specific population data.[46] Incorporating the estimated number of yearly cochlear implants by setting (n=209 in Chile,[33] n=2,000 in India,[47] and n=5 in Nigeria[48]), we estimated the yearly probability of cochlear implant provision, given severe or greater hearing loss and hearing aid use, in each setting. We assumed a 1% annual probability of cochlear implant discontinuation in adults, and 1.3% per year in children.[49,50]

Statistical analysis (validation)

Our model inputs and outputs were reviewed by experts in the Lancet Commission on Hearing Loss, including experts in the Commission from Chile, India, and Nigeria. We validated across setting-specific epidemiologic and treatment estimates and describe the simulations for each validation run in the Results. Internal validation exercises were used to ensure that model-projected outputs sufficiently matched the published estimates used to derive model inputs. In addition to ensuring clinical and policy expert face validity of our modeling assumptions and results, we validated our model-projected outcomes to expected results quantitatively. 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.[51,52] Additional detail on internal model validation exercises, including model code review, and examination of simulated patient trace files, can be found in the original DeciBHAL publication.[5] Please see Appendix 3 for a table indicating the model input components and potential policy or program development implications associated with each outcome used in validation analysis.

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Results

Prevalence of sensorineural hearing loss by age and sex

Figure 1 presents the DeciBHAL-I-projected and GBD-estimated prevalence of SNHL across the lifespan, simulating persons from birth to death. The DeciBHAL-I projected age- and sex-specific prevalence of SNHL in Chile increased with age from 0.2% at age 1 year to 88.3% at age 87 years. The prevalence of SNHL likewise varied with age from 0.4% to 87.9% in India, and from 1.0% to 68.8% in Nigeria. A comparison of model-estimated and literature-based SNHL prevalence is presented in Figure 1. The CV-RMSE comparing GBD estimates to model-estimated SNHL prevalence were 6.0% (males) and 7.4% (females) in Chile, 5.6% and 5.4% in India, and 4.0% and 3.2% in Nigeria.

Progression of sensorineural hearing loss

When we incorporated an estimated 1.05 dB HL/year decline derived from longitudinal audiometric data for

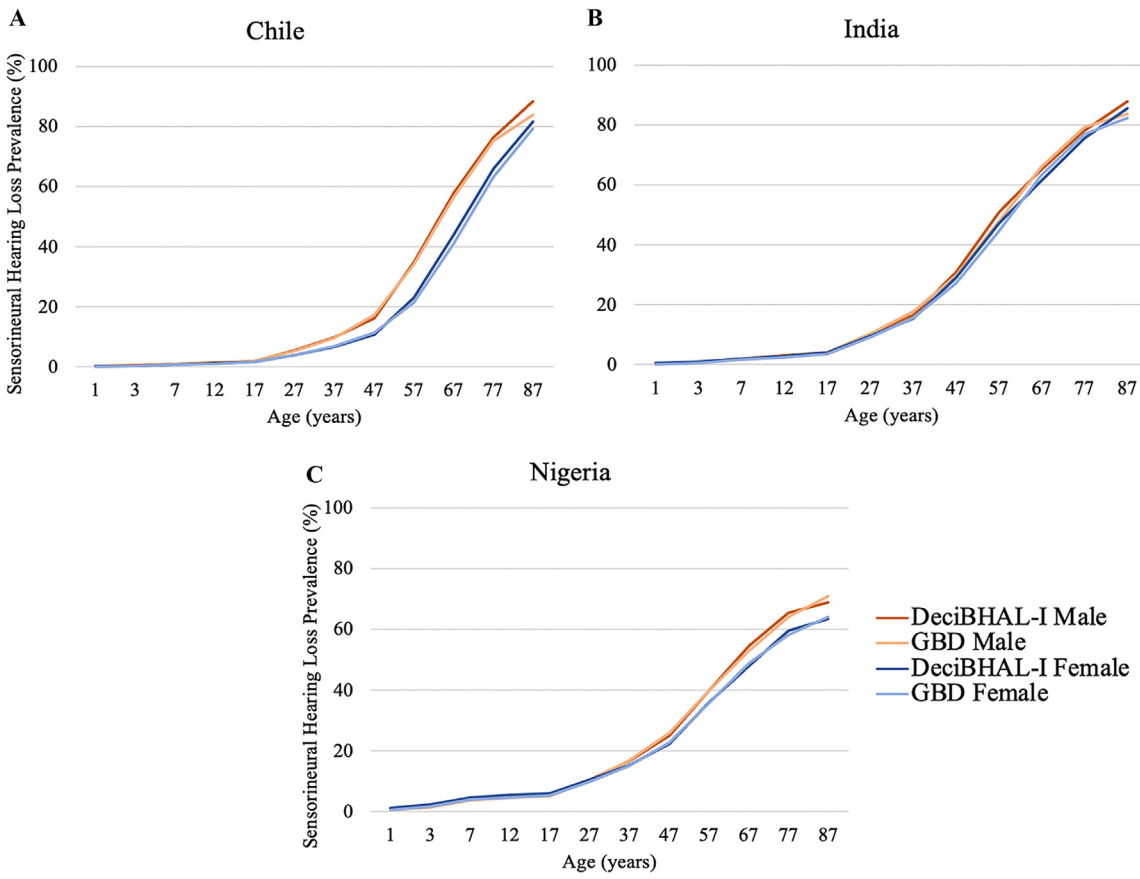

Figure 1. DeciBHAL-projected prevalence compared to Global Burden of Disease prevalence of bilateral sensorineural hearing loss by age.

Compares the model-projected prevalence of sensorineural hearing loss (lighter colors) to that estimated by the Global Burden of Disease (darker colors) for males (orange) and females (blue) across the three settings: A) Chile, B) India, and C) Nigeria. Model-projected SNHL prevalence matched published estimates well across all ages. Abbreviations: DeciBHAL: Decision model of the Burden of Hearing loss Across the Lifespan; GBD: Global Burden of Disease.

the United States, we projected significantly more severe, profound, and complete hearing loss as a percent of all hearing loss compared to the GBD (Appendix 4). For the basecase analysis, we chose to incorporate the 1.05dB/year increase in dB HL due to several published longitudinal studies in high income settings finding similar results.[22,53,54]

Acute otitis media and chronic suppurative otitis media

Comparing the model-projected incidence of AOM at ages 0-90 years with published estimates, we achieved adequate fit across the three settings, with CV-RMSE ranging between 5.0-7.5%.[24] The derived CSOM incidence rates produced an average yearly CSOM prevalence across all ages of 1.5% in Chile, 4.9% in India, and 3.4% in Nigeria, consistent with setting-specific estimates of CSOM prevalence.[28]

Prevalence of otitis media-related conductive hearing loss

The model-projected otitis media-related CHL, in cases/10,000 persons, ranged from 28.9-258.7 in India, 1.0-11.6 in Chile, and 11.3-111.1 in Nigeria (Table 2). The prevalence values were compared to those from a systematic review of global otitis media-associated CHL, with resulting CV-RMSE values all below 25%.[24]

Age-specific hearing aid use

For pediatric hearing aid use in all three settings, we simulated persons from birth through age 18 and recorded the hearing aid use prevalence among those with permanent hearing loss (SNHL or CHL without an acute infectious process) at each age. Hearing aid use prevalence at age 1 year was 50.0%, 1.3%, and 2.7% in Chile, India, and Nigeria respectively, and at age 18 was 8.9%, 6.4%, and 4.5%, respectively (Appendix 5).

Age	Chile, prevalence per 10,000		India, prevalence per 10,000		Nigeria, prevalence per 10,000	
	Model-predicted estimate	Literature estimate	Model-predicted estimate	Literature estimate	Model-predicted estimate	Literature estimate
5 - 9	1.0	3.0	28.9	69.8	11.3	26.0
10 - 14	1.0	3.3	66.3	73.2	23.0	27.7
15 - 19	2.0	3.5	76.9	77.1	28.2	29.3
20 - 24	2.0	4.0	85.6	87.2	31.4	33.2
25 - 34	4.1	4.5	104.4	97.2	33.0	37.8
35 - 44	6.2	5.6	120.7	116.6	39.8	46.3
45 - 54	6.3	6.3	130.8	130.7	42.2	52.1
55 - 64	6.5	7.6	143.2	157.8	49.6	61.5
65 - 74	7.1	9.6	154.7	195.9	79.3	78.0
75 - 84	9.2	11.6	210.5	231.8	97.7	96.8
85 +	11.6	13.1	258.7	255.9	111.1	125.0
CV-RMSE	23.8%		14.3%		14.8%	

***Table 2*: Model-projected bilateral conductive hearing loss due to otitis media by age.**
Abbreviations: CV-RMSE – coefficient of variance of the root mean square error.

Age	Hearing Aid Use Prevalence					
	Chile, % of persons with hearing loss		India, % of persons with hearing loss >40 dB		Nigeria, % of persons with hearing loss	
	Model Outcome	Published Estimate (95% CI)	Model Outcome	Adjusted Published Estimate	Model Outcome	Estimate
65	3.2	3.0 (1.3-4.8)	1.4	-	1.1	0.5-1.0†
75	7.9	6.9 (4.4-9.5)	2.2	1.9*	0.9	0.5-1.0†
85	19.7	18.9 (13.9-24.0)	2.3	-	1.3	0.5-1.0†

***Table 3*: Hearing loss cascade of care validation.**
Abbreviations: CI: confidence interval, dB: Decibel.
* Age of reference population not stated, assumed to be 75 years. Published estimate adjusted by factor of 0.1 to reflect underestimation of hearing loss prevalence.
† Estimate range assumed based on expert opinion.

We similarly validated age-specific hearing aid uptake probabilities for adults (Table 3). In Chile, we simulated persons aged 35 years until death, collecting the proportion of persons using hearing aids among those with hearing loss at age 65, 75, and 85 years. Including a delay-to-diagnosis factor, the model-projected outcomes were 3.2%, 7.9%, and 19.7%, respectively, and the CV-RMSE was 7.4%. None of the model-projected hearing aid use prevalence values in Chile were outside adjusted 95% confidence intervals from a Chilean national survey.[34] For the Indian setting, the model-projected prevalence of hearing aid use among persons age 75 years with hearing loss >40 dB HL was 2.2%, comparable to an adjusted calibration target of 1.9% derived from the Indian National Disability Survey. In Nigeria, we assumed a low rate of hearing aid uptake throughout adulthood such that 1.1%, 0.9%, and 1.3% of simulated persons with hearing loss were using hearing aids at ages 65, 75, and 85 years, respectively.

Discussion

The efforts and results presented in this report extend DeciBHAL's natural history framework of hearing loss prevention, natural history, diagnosis, and treatment to three international settings: Chile, India, and Nigeria. Model-projected results achieved reasonable fit to published estimates in validation exercises. We incorporated data from the GBD and high-quality systematic reviews or observational studies to inform hearing loss natural history inputs across both SNHL and CHL. Hearing aid and cochlear implantation were simulated as treatments for all causes of hearing loss, and we calibrated DeciBHAL treatment rates to current best estimates of coverage in the three settings.

DeciBHAL-I is the first validated decision model of hearing loss natural history and treatment throughout the lifespan in these settings. Because DeciBHAL simulates the current standards of care in Chile, India, and Nigeria, it provides a framework to be populated with

cost and utility data to estimate the economic efficiency of alternative hearing health scale-up strategies. Such estimates may be useful to finance ministers and health policy makers tasked with allocating limited resources to achieve maximum health utility benefit. Previously published decision models of hearing loss and its treatment in LMIC are limited in that those models consider single interventions only and do not allow for direct comparison of, for example, hearing screening at different ages.[4] DeciBHAL simulates males and females across all ages and incorporates incident SNHL and CHL to allow for such direct comparisons and better inform hearing health policy. While input data, such as bilateral SNHL incidence, is occasionally collapsed across age groups, DeciBHAL is able to simulate outcomes for any user-determined age group (e.g., the under 5-year pediatric population).

Among the most significant differences between DeciBHAL across the settings is the epidemiology and etiology of hearing loss. In higher income settings, such as the United States and Chile, the majority of hearing loss is experienced later in life and is SNHL, whereas hearing loss in Nigeria and India occurs earlier in life and a higher proportion of hearing loss is otitis-media related CHL. At ages 55-64 years, there are a projected 7.6/10,000 cases of bilateral permanent hearing loss due to otitis-media in Chile, compared to 157.8/10,000 in India and 61.5/10,000 in Nigeria.[24] These significant differences in hearing loss epidemiology suggest that the optimal allocation of treatment dollars to different hearing loss prevention and treatment programs are likely to differ among the settings. The ability of DeciBHAL to simulate CHL and its treatment is an advance over other simulation models and may inform optimal allocation through planned cost-effectiveness analyses.

Given the lack of longitudinal audiometric studies in Chile, India, and Nigeria, we incorporated data from high-income settings on the progression of SNHL. Across several studies and settings, SNHL progression converged around a 1dB/year increase in PTA dB HL.[22,53,54] When incorporated into DeciBHAL-I, the projected proportions of persons with moderate, severe, and profound hearing loss were higher than GBD estimates.[10] While DeciBHAL has a calibration factor to allow for slowing the rate of SNHL decline, in our base-case analysis we did not adjust to GBD data. This decision was based on: 1) agreement among our clinical collaborators that the rate of hearing loss progression would not be slower in Chile, India, and Nigeria compared to the US and Australia, and 2) emerging data suggesting that hearing loss may be more severe in low- and middle-income settings than previously thought. Future analyses might calibrate hearing loss severity to better match GBD data in sensitivity analyses, or to setting-specific longitudinal studies as they become available.

We incorporated setting-specific estimates of hearing aid and cochlear implant uptake to simulate the hearing cascade of care in Chile, India, and Nigeria. In Chile, we were able to incorporate data from the Ministry of Health reporting the number of pediatric and adult hearing aids provided each year and validate to a nationally representative survey of hearing aid use. In India, we did not have estimates of adult hearing aid uptake and thus calibrated the yearly probability of hearing aid uptake to results from a National Disability survey in that country. We were unable to identify any nationally representative estimates of adult hearing aid use in Nigeria, so we relied on expert opinion to adjust published rates of hearing aid uptake among persons who acquired hospital-based otolaryngologic care. As the true rates of current hearing aid uptake is uncertain, especially in India and even more so in Nigeria, this parameter should be explored in sensitivity analyses.

DeciBHAL is purposefully setting-specific to allow for high-quality estimations of hearing healthcare policy effects in Chile, India, and Nigeria. These locations were chosen due to data availability but also differences in region, income-level, and hearing loss epidemiology and treatment. Results of future and planned cost-effectiveness analyses set in Chile, India, and Nigeria may be generalizable to other settings with similar epidemiologic and demographic characteristics. However, the results will likely not be generalizable to many settings and other methods will be required to apply DeciBHAL results outside of its validated settings. As most published model-based analyses are in high-income settings, there is a great need for modeling frameworks in low- and middle-income settings. One option would be to create an openly available web-based model version that would allow entries of country- or region-specific input values to tailor results. While a fully validated model in another setting would require identification and derivation of all setting-specific inputs listed in Table 1, future research might clarify a subset of these inputs that are most influential and could be tailorable in a web-based version of DeciBHAL.

The extended model DeciBHAL-I has several limitations, primarily related to assumptions made in the absence of high quality, setting-specific data. We worked with clinical and policy stakeholders to simplify the complex natural history and treatment of hearing loss across the lifespan to allow for feasible creation of a policy decision model. DeciBHAL is populated with high quality setting-specific estimates of hearing loss acquisition, progression, and treatment; however, there were data limitations, especially pertaining to treatment uptake in India and Nigeria, that required model calibration based on expert opinion. In some cases, we incorporated data from high-income settings such as the United States when we were unable to find similar setting-specific estimates. We were also unable in the current model version to include distributions around all input parameters (as would be necessary to compute 95% confidence intervals around model-projected

outcomes) due to data limitations. In all cases, the impact of these uncertain estimates should be explored in sensitivity analyses in studies using DeciBHAL. Additionally, there is a lack of robust epidemiologic data on cause-specific contributors to SNHL. DeciBHAL includes meningitis and ototoxicity as explicit causes of SNHL. However, the epidemiologic data to inform estimates of the proportion of SNHL due to ototoxicity are currently under investigation and future model versions should incorporate this factor. We were unable to attain the target CV-RMSE value of ≤15% for the calibration of the prevalence of otitis media-related CHL in Chile. Our model-projected prevalence estimates were all within 2-3/10,000 of the target, but given the low absolute number of people with otitis media-related CHL in Chile, we were unable to attain a CV-RMSE≤15%. Lastly, persons in DeciBHAL-I are assigned an SNHL PTA severity of 25 dB HL upon acquiring age-related and other hearing loss. This is different than the minimum PTA threshold suggested by the WHO of 20 dB HL and the effects of assigning persons a threshold of 20 dB HL at SNHL onset should be explored in future sensitivity analysis.

We find that DeciBHAL-I reasonably simulates hearing loss prevention, natural history, diagnosis, and treatment in Chile, India, and Nigeria. As policymakers worldwide prioritize scarce resource allocation across hearing and other health policies, DeciBHAL may provide setting-specific estimates to guide optimal allocation.

Contributors

Conceptualization: EDB, AA, CD, OO, GDS
Methodology: EDB, OO, GDS
Software: EDB, AA, SD, MS, OO, GDS
Validation: All authors
Formal analysis: EDB, AA, SD, MS, OO, GDS
Investigation: EDB, AA, SD, MS, OO, GDS
Resources: OO, GDS
Data curation: EDB, AA, SD, MS, OO, GDS
Writing - original draft: EDB, AA, GDS
Writing - review & editing: All authors
Visualization: EDB, AA, SD, MS, OO, GDS
Supervision: OO, GDS
Funding Acquisition: EDB, OO, GDS

Data sharing statement

Model code and input data may be requested from the corresponding author.

Declaration of interests

The authors have no conflicts of interest to declare.

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