The prevalence of bilateral hearing loss in the United States in 2019: a small area estimation modelling approach for obtaining national, state, and county level estimates by demographic subgroup

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Summary

Background The goal of this study was to re-estimate rates of bilateral hearing loss Nationally, and create new estimates of hearing loss prevalence at the U.S. State and County levels.

Methods We developed small area estimation models of mild, and moderate or worse bilateral hearing loss in the U.S. using data from the National Health and Nutrition Examination Survey (2001–2012, 2015–2018), the American Community Survey (2019), Census County Business Patterns (2019); Social Security Administration Data (2019); Medicare Fee-for-Service and Advantage claims data (2019); the Area Health Resources File (2019), and other sources. We defined hearing loss as mild (>25 dB through 40 dB), moderate or worse (>40 dB), or any (>25 dB) in the better hearing ear based on a 4-frequency pure-tone-average threshold, and created estimates by age group (0–4, 5–17, 18–34, 35–64, 65–74, 75+), gender, race and ethnicity, state, and county.

Findings We estimated that 37.9 million (95% Uncertainty Interval [U.I.] 36.6–39.1) Americans experienced any bilateral hearing loss; 24.9 million (95% U.I. 23.6–26.0) with mild and 13.0 million (95% U.I. 12.1–13.9) with moderate or worse. The prevalence rate of any hearing loss was 11.6% (95% U.I. 11.2%–12.0%). Hearing loss increased with age. Men were more likely to have hearing loss than women after age 35, and non-Hispanic Whites had higher rates of hearing loss than other races and ethnicities. Higher hearing loss prevalence was associated with smaller population size. West Virginia, Alaska, Wyoming, Oklahoma, and Arkansas had the highest standardised rate of bilateral hearing loss, and Washington D.C., New Jersey, New York, Maryland, and Connecticut had the lowest.

Interpretation Bilateral Hearing loss varies by State and County, with variation associated with population age, race and ethnicity, and population size. Geographic estimates can be used to raise local awareness of hearing loss as a problem, to prioritize areas for hearing loss prevention, identification, and treatment, and to guide future research on the hearing loss risk factors that contribute to these differences.

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Introduction

Once considered a relatively benign aspect of aging, hearing loss (HL) has emerged as a serious public health concern. HL is a highly prevalent condition in the U.S. affecting as many as 23% of Americans ages 12 years and older in at least one ear.[1] Research suggests HL,

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Research in context

Evidence before this study

Using the search terms ("hearing loss" [MeSH Terms] OR ("hearing" [All Fields] AND "loss" [All Fields]) OR "hearing loss" [All Fields]) AND ("epidemiology" [MeSH Subheading] OR "epidemiology" [All Fields] OR "prevalence" [All Fields] OR "prevalence" [MeSH Terms] OR "prevalance" [All Fields] OR "prevalences" [All Fields] OR "prevalence s" [All Fields] OR "prevalent" [All Fields] OR "prevalently" [All Fields] OR "prevalents" [All Fields]) AND ("united states" [MeSH Terms] OR ("united" [All Fields] AND "states" [All Fields]) OR "united states" [All Fields]) in PubMed results in 2709 articles, with 10 including all terms in the title. Of these, the most relevant study used 2001 to 2010 National Health and Nutrition Examination Survey (NHANES) data to estimate the United States prevalence of bilateral hearing loss, defined as an inability to hear a 4-frequency pure-tone average at less than 25 decibels in the better hearing ear.[1] This study estimated a national prevalence of bilateral hearing loss of 38.3 million or 1 in 7 people ages 12 and older.[1] Additional research found variations in rates of hearing loss by demographic factors and industry of employment.[2,3] Other research has found that rates of self-reported disability measured by the American Community Survey are both clustered at the county level and vary spatially,[4] No studies provided estimates of hearing loss prevalence at the U.S. State or County level or below.

Added value of this study

In this study we combined the NHANES national estimates with other data sources using small area estimation (SAE) models which resulted in four concrete benefits; 1) we updated the source data included in national hearing loss prevalence estimates, 2) we expanded previously available hearing loss estimates to include children younger than age 12; 3) we reduced the uncertainty of estimates of hearing loss for people ages 12 and older; and 4) we created estimates of bilateral hearing loss by age group, gender, and race and ethnicity at the U.S. State and County levels. At the national level, our results are similar to, but slightly lower than previous estimates. However, the primary contribution of our work is the addition of geographic information which can be used to focus public health efforts to mitigate the impacts of hearing loss.

Implications of all the available evidence

Like previous research, we found that bilateral hearing loss in the United States is a highly prevalent problem, especially among adults ages 35 and older. We newly estimated rates of hearing loss prevalence at the state and county level, stratified by age, gender, and race and ethnicity, and found that rural areas are experiencing the highest rates of hearing loss in the United States. Geographically specific estimates can help public health practitioners target resources for hearing loss prevention, identification, and treatment. Research extensions of this study may involve collecting evaluated hearing loss measures across urban and rural areas to refine this study's modelled estimates, and exploring the causative factors of higher rates of hearing loss in rural areas.

particularly when unaddressed, is associated with multiple negative health and quality of life outcomes.[1–3] HL is under-treated due to the high cost of hearing aids and other treatments, sparse accommodations provided by society, poor access to HL care and lack of awareness and recognition of HL by those who experience it.[2] To date, there is a lack of detailed geographic prevalence estimates of hearing loss for the U.S.

Hearing loss is associated with negative health and social consequences across the lifespan. In children, HL impacts speech and language development, educational achievement, and elevates family stress.[3] Among adults, hearing difficulty and tinnitus are associated with lower quality of life and increased suicidal behaviour.[4] Among older adults, HL is associated with an increased risk of depression, falls, cognitive decline, and dementia.[2,5,6] Research on HL and dementia has culminated in the Lancet Commission on Dementia Prevention indicating HL as the largest attributable risk factor for global cases of dementia.[7] HL is also linked to a higher risk of all-cause mortality in older adults.[8]

Importantly, for many individuals, HL is amenable to treatment and intervention. Prevention, treatment, and rehabilitation services can address HL at any stage and age-group, improving health-related quality of life.[9] However, many people with HL report barriers to accessing treatment services including shortages of health professionals and the costs of medical services.[10] Federal and state government-led public health interventions for addressing the low uptake in hearing care, including the recent availability of over-the-counter hearing aids for adults with mild and moderate hearing loss, are underway.

Geography may play an important role in the risk for hearing loss, as well as access to hearing care services. Age, race, and sex, which vary geographically across the US, are significant population-level risk factors for HL.[11] Moreover, research suggests the prevalence of HL is higher among persons with low incomes and lower levels of educational attainment and is greater among those living in rural and small cities than those in metropolitan areas.[12] Noise exposure, a strong risk factor for hearing loss, may play a role in these associations as studies suggest working-class individuals, including factory and farm workers, may experience a higher risk of HL due to prolonged occupational exposure to loud noises.[13] Concurrently, low-income and rural areas of the U.S. are less likely to have access to hearing care services.[14]

Existing estimates of HL prevalence based on NHANES are accurate at the national level,[1] but have high uncertainty especially at younger ages, do not provide detailed State- or County-level information, and omit children ages 0 to 5 for whom data were not collected. In this study we use small area estimation (SAE) models to improve national estimates of bilateral mild and moderate and worse HL, and to estimate HL prevalence for States and Counties by age group, gender, and race and ethnicity.

Methods

Strategy

We developed two SAE models, the first for national estimates of mild, and moderate or severe HL by age group, gender, and race and ethnicity, using National Health and Nutrition Examination Survey (NHANES) data measured by trained technicians. The second model estimated county level prevalence of self-reported HL by age-group from American Community Survey (ACS) data. We used raking, a calibration method, to transform county-level estimates of self-reported HL into the currency of the national estimates and to adjust for differences by gender and race and ethnicity. We employed a Hierarchical Bayes implementation of the models and used Markov Chain Monte Carlo to approximate the posterior distribution of the parameters of interest, and to compute predictions and uncertainty measures for the prevalence for each domain, including the calibrated hearing loss measures.

Data

For national estimates, we used pooled data from the NHANES collected from 2001 to 2012, and 2015–2018 (NHANES 2013–2014 did not include the audiometry exam or questionnaire) and Medicare payment claim diagnosis information from 2019. The NHANES collects air-conduction pure-tone audiometry thresholds (e.g., lowest level an individual can respond to presented tones) by trained technicians using best-practice threshold-seeking methods in a sound-attenuated booth with a calibrated audiometer in mobile examination centres. During the assessment, a repeat threshold 1000 Hz is obtained to ensure consistent responses by the participant.[15] We removed participants with repeat 1000 Hz thresholds that were inconsistent (>10 dB HL difference) and may suggest an inability to complete the task or equipment concerns. Consistent with previous epidemiologic hearing studies, we derived a 4-frequency pure-tone average at the frequencies important for comprehending speech information (500, 1000, 2000, and 4000 Hz). We categorised hearing loss based on the participants' better-hearing ear (e.g., lower 4-frequency pure-tone average) using the American Speech-Language-Hearing Association (ASHA) cut-points of normal/slight HL (herein referred to as normal) as <25 dB HL [decibels hearing level], mild HL as 25–40 dB HL (for mild), and moderate, moderately severe, severe, and profound prevalence consistent with the former (prior to 2022) World Health Organization hearing loss cut points for normal, mild, and moderate or greater hearing loss used in most epidemiologic research.[11,16–18]

We calculated survey weights for NHANES using the 2-year audiometry weight for years 2001–2004 and the 2-year Mobile Examination Center (MEC) weights for years 2005–2012 and 2015–2018, and adjusted the weights based on how many survey cycles were combined for each age category. We used the data to estimate the prevalence of normal, mild, and moderate or worse categories of HL stratified by age group (ages 5–17, 18–34, 35–64, 65–74, and 75+), gender, and race and ethnicity (Hispanic, non-Hispanic Black, non-Hispanic Other, non-Hispanic White). NHANES, does not collect data for children ages 0–5. For interpretability and consistency with the American Community Survey (ACS) public estimates, we created age groups of 0–4 and 5–17. This results in a small amount of error in the 5–17 estimate in that the NHANES direct estimate used in the model to estimate ages 5–17 contained only children ages 6 to 17. However, given the extremely low rates of hearing loss in the group and the high uncertainty of the estimates, this error is negligible. For Medicare data, we estimated the diagnosed prevalence of all HL among people ages 65 and older using an ICD-10 diagnosis code indicating HL in both ears, separate claims indicating HL in the left and the right ear, or a claim indicating HL in the left or right ear and a second claim indicating HL in an unspecified ear (Appendix A).

For county-level estimates we used a special tabulation by the U.S. Census Bureau of 2015–19 American Community Survey (ACS) five-year estimates of endorsements of the question "Is this person deaf or does he/she have serious difficulty hearing?" stratified by the age groups above plus an additional age group for children ages 0–4. We additionally used county-level variables from the 2019 Census County Business Patterns to measure the percent of workers employed in each of 20 categories of industries; 2019 Census Population Estimates; Social Security Administration Data (2019) measuring disabled workers per capita; 2019 Area Health Resource File measuring median home value, and active doctors per capita; 2019 CMS Medicare data, and other sources for variables that were not selected for the final model (Appendix B).

Race and ethnicity were obtained using self-reported values. Until 2011, the NHANES categorised race or ethnicity as Mexican American, Other Hispanic, Non-Hispanic White, Non-Hispanic Black, and other race (including Asian individuals of any origin, American

Indian individuals, Alaskan Native individuals, Pacific Islander individuals, multiracial individuals, and other groups not otherwise classified). For consistency across years, we retained this classification for all years of data, although beginning in 2011, NHANES supports estimation for Asian people separately. Medicare uses self-reported values and algorithmic adjustments for missing responses. ACS also uses self-reported data. We based race and ethnicity stratification on NHANES categories after collapsing Mexican American and other Hispanic into a single category.

Estimation

In our first model, we produced NHANES estimates of normal, mild, and moderate or worse HL for the age groups above and for age group 0 to 4 (for which no NHANES data were collected), by gender and race and ethnicity resulting in 48 estimates and uncertainty intervals (U.I.) for each level of HL. Estimates for the 0–4 age group were obtained from the model based on the covariates used (Appendix C). We used a continuation-ratio multinomial logit normal model with random effects to estimate the probability of normal, mild, or moderate or worse HL in each subgroup strata.[19] The model parametrized the probability of having any bilateral hearing loss, and the probability of moderate/severe hearing loss given any hearing loss as a function of covariates and random effects. Covariates for the probability of any HL were the logit transformed proportion of Medicare diagnosed hearing loss (any bilateral HL Diagnosis) ages 65 and up; an indicator for the age group being 65 and up; the median age within an age group category, and race fixed effects (for Hispanic, Non-Hispanic Black, and ``other"). Covariates for the probability of having moderate or severe HL were a gender fixed effect (Female), median age within a stratum, and race and ethnicity fixed effects. We selected this model specification out of 8 candidates using a version of leave-one-out (loo) cross-validation. The candidate models were selected among many others using Pareto Smoothed Importance Sampling loo cross-validation (PSIS-loo, Appendix D).

We specified a second model to estimate county-level variation in HL prevalence by age group based on the observed prevalence of self-reported HL measured in the ACS using a binomial logit normal model.[20–22] We stratified HL by age-group only due to insufficient county-level sample size to further cross-stratify. We selected variables for inclusion using an iterative k-fold (k = 10) cross-validation process which compared three candidate models (two selected using stepwise selection based on Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC) respectively, and one developed based on hypotheses about predictors of hearing loss). The model that performed best based on cross-validation was refined by adding age-group interaction terms and evaluating inclusion exclusion of variables from the two other models based on BIC statistics. The resulting final model was then re-validated using the same k-fold validation samples and criteria. Covariates in the final model included state and age-group fixed effects, standardized number of disabled workers per capita, logit-transformed percent of U.S. population in each strata, logit transformed proportions of workers who worked in each of 5 industry categories (Mining, Quarrying, and Oil and Gas Extraction; Wholesale Trade; Retail Trade; Arts, Entertainment, and Recreation; and Accommodation and Food Services), Medicare proportions of individuals 65 and older with HL; standardised county median home values; and standardised number of active physicians per capita. In addition, the model included interactions between age group and both the standardised number of disabled workers per capita and the logit-transformed percent of U.S. population in each strata.

Modelling resulted in 1) national estimates by HL level, age-group, gender, and race and ethnicity in the NHANES currency which can be thought of as our best estimate of the total national rate of HL by level and demographic strata, and 2) county-level estimates of total HL by age-group in the ACS currency which can be thought of as our best measure of county variation in rates of all levels of HL. We used calibration to reconcile and combine these estimates to create county-level estimates by HL level and by age-group, gender, and race and ethnicity in the NHANES currency using inputs from both models and ACS population data. To do so, we first multiplied prevalence proportion estimates from the NHANES and ACS models by their respective ACS population totals to create prevalence counts. We next post-stratified ACS estimates to the NHANES model's normal, mild, and moderate and severe hearing loss totals, forcing agreement with the respective NHANES estimates. Finally, we used raking to adjust individual county by strata estimates under the constraints that the prevalence proportions for all hearing loss categories within a strata must equal 1 and the sum of the county-level prevalence counts by strata must equal the sum of the corresponding strata from the NHANES model.

We fit models using a Bayesian approach with the posterior means and uncertainty intervals computed using Markov Chain Monte Carlo (MCMC) sampling. To account for the uncertainty from the NHANES and ACS models, as well as that of the ACS population counts, we used 1000 replications of MCMC draws from each model, including a model of the ACS population counts assuming a lognormal distribution. We performed calibration and raking for each set of replications and estimated the posterior means, variances, and U.I.s from the resulting approximate posterior distributions. We estimated the models using the JAGS, R, and Stan software packages.

Validation

For the NHANES and ACS models, we checked that the model estimates were similar to their corresponding direct survey estimates for large sample sizes, since the direct survey estimates are very accurate in such cases. For the ACS model, we also checked that summing model estimates to high levels of aggregation would give similar results to the corresponding direct ACS estimates, since at high levels of aggregation these have low/approximately negligible sampling variances. For the NHANES model, we checked that aggregated model estimates fell within the confidence intervals of the NHANES direct estimates. For both the NHANES and the ACS model, we performed cross-validation analysis.

We examined whether the model predictions had posterior variances that are lower than the variances of the direct estimators in large sample instances. We checked that the expected monotonicity of hearing loss across ages generally held within counties, gender, and race and ethnicity groups.

Role of the funding source

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Results

Mild hearing loss

We estimated a total of 24.9 million people with mild HL (95% U.I. 23.6–26.0) in 2019, and a prevalence rate of 7.6% (95% U.I. 7.2%–7.9%) (Table 1). Rates of mild HL were greater for men (8.5%, 95% U.I. 7.9%–9.0%) than for women (6.8%, 95% U.I. 6.3%–7.2%). Estimated rates of mild HL increased monotonically by age group, with much higher rates observed above age 35 than below. Rates of mild HL were higher among non-Hispanic White Americans (9.4%, 95% U.I. 8.8%–9.9%) as compared to non-Hispanic Blacks, Hispanics, and those of other race and ethnicities in over 95% of replications. U.I.s for other differences among race and ethnicity contained zero, suggesting the model was unable to detect differences.

Moderate or worse hearing loss

We estimated a total of 13.0 (95% U.I. 12.2–13.9) million people with moderate or worse HL, a prevalence rate of 4.0% (95% U.I. 3.7%–4.2%). Rates of moderate or worse HL were greater for men (4.6%, 95% U.I. 4.3%–5.0%) than for women (3.3%, 95% U.I. 3.0%–4.2%). Rates of moderate or worse HL increased monotonically by age group, with higher rates observed at ages 35 and older than at younger ages. Rates of moderate or worse HL were higher among non-Hispanic Whites (5.2%, 95% U.I. 4.8%–5.6%) as compared to non-Hispanic Blacks, Hispanics, and those of other race and ethnicities. As with mild HL, the model was not able to detect differences in moderate or worse HL among non-Hispanic Blacks, Hispanics, and those of other race and ethnicities.

Any hearing loss

We estimated a total of 37.9 million (95% U.I. 36.6–39.2) million Americans with any bilateral HL, or 11.6% (95% U.I. 11.2%–11.95%) of Americans. The prevalence rate among people ages 0 to 34 was 0.5% (95% U.I. 0.3%–0.6%) as compared to the prevalence rate for people ages 35 and older of 13.8% (95% U.I. 13.1%–14.5%). Rates for any hearing loss were higher for men than for women, increased monotonically by age, and were higher for Whites than for other race and ethnicity groups.

State and county variation

Prevalence rates corresponded approximately with state rurality, the percentage of population that was non-Hispanic White, and median state age. West Virginia, Maine, Montana, Wyoming, Vermont, and New Mexico each had a prevalence rate of any HL of 15.0% or higher (Fig. 1, Appendix E). California, New York, Georgia, New Jersey, Utah, Maryland, and Washington D.C. had prevalence rates of any HL that were 10.0% or lower. After standardising each state's populations by age group, gender, and race and ethnicity to match the U.S. population, we observed the highest rates of any HL in West Virginia, Alaska, Wyoming, Oklahoma, and Arkansas, and the lowest rates in Washington D.C., New Jersey, New York, Maryland, and Connecticut (Appendix F). The trend of prevalence counts of all levels of HL corresponded approximately with state population size.

Rates of any HL varied widely by county (Fig. 2). When stratifying counties by 9-level rural/urban continuum codes, counties with higher levels of rurality experienced higher rates of any HL (Fig. 3). The exception to this was the category for Urban population of 20,000 or more, not adjacent to a metro area, which includes micropolitan areas such as Juneau, Alaska, Eagle, Colorado, and Des Moines, Iowa. East coast counties and California had relatively low rates of HL compared to other areas. Concentrated groups of counties with high rates of any HL were observed in Florida, Central Appalachia, the Ozarks, and Southeastern Oklahoma, and the underpopulated Mountain West, but hot spots of high HL prevalence were observed nationwide.

Validation

We calculated instances in which our model estimated a lower prevalence of HL in an older age group than for the previous younger age groups overall and for each

	Prevalence count	2.5th percentile	97.5th percentile	Prevalence rate	2.5th percentile	97.5th percentile
Mild[a]						
Total	24,894,276	23,624,225	26,019,499	7.59%	7.20%	7.94%
Female	11,260,337	10,458,329	12,043,736	6.76%	6.28%	7.23%
Male	13,633,940	12,732,822	14,534,255	8.45%	7.89%	9.00%
0–4 years	18,353	7622	35,846	0.09%	0.04%	0.18%
5–17 years	102,485	58,346	160,800	0.19%	0.11%	0.30%
18–34 years	467,652	330,941	615,442	0.61%	0.43%	0.81%
35–64 years	9,045,363	8,164,261	9,922,030	7.18%	6.48%	7.87%
65–74 years	7,341,236	6,676,021	7,957,312	24.57%	22.34%	26.63%
75+ years	7,919,177	7,420,148	8,454,503	36.81%	34.49%	39.30%
Non-Hispanic Black	1,745,705	1,556,345	1,964,979	4.37%	3.90%	4.92%
Hispanic	2,972,611	2,656,633	3,301,814	4.82%	4.30%	5.35%
Non-Hispanic Other	1,658,358	1,432,497	1,898,352	5.70%	4.92%	6.52%
Non-Hispanic White	18,517,606	17,408,145	19,581,264	9.39%	8.83%	9.93%
Moderate or worse[b]						
Total	13,006,560	12,187,678	13,870,352	3.97%	3.72%	4.23%
Female	5,513,890	4,947,514	6,103,386	3.31%	2.97%	3.67%
Male	7,492,670	6,863,602	8,137,918	4.64%	4.25%	5.04%
0–4 years	4345	447	16,868	0.02%	0.00%	0.08%
5–17 years	42,339	18,975	76,116	0.08%	0.04%	0.14%
18–34 years	78,305	34,420	146,556	0.10%	0.05%	0.19%
35–64 years	2,159,259	1,722,767	2,629,672	1.71%	1.37%	2.09%
65–74 years	2,998,698	2,577,583	3,472,618	10.03%	8.63%	11.62%
75+ years	7,723,613	7,228,648	8,241,711	35.90%	33.60%	38.31%
Non-Hispanic Black	723,325	585,385	864,432	1.81%	1.47%	2.16%
Hispanic	1,316,664	1,126,662	1,529,346	2.13%	1.83%	2.48%
Non-Hispanic Other	786,713	616,087	960,841	2.70%	2.12%	3.30%
Non-Hispanic White	10,179,862	9,410,484	11,000,457	5.16%	4.77%	5.58%
Any hearing loss[c]						
Total	37,900,836	36,613,204	39,180,270	11.56%	11.17%	11.95%
Female	16,774,227	15,898,329	17,639,868	10.08%	9.55%	10.60%
Male	21,126,611	20,191,067	22,133,594	13.09%	12.51%	13.71%
0–4 years	22,698	8512	50,484	0.11%	0.04%	0.25%
5–17 years	144,824	89,167	221,814	0.27%	0.16%	0.41%
18–34 years	545,957	390,091	721,817	0.71%	0.51%	0.94%
35–64 years	11,204,621	10,258,244	12,160,961	8.89%	8.14%	9.65%
65–74 years	10,339,934	9,613,337	11,028,771	34.60%	32.17%	36.91%
75+ years	15,642,790	15,167,163	16,150,353	72.71%	70.49%	75.06%
Non-Hispanic Black	2,469,030	2,260,799	2,731,955	6.18%	5.66%	6.84%
Hispanic	4,289,275	3,939,998	4,623,767	6.95%	6.38%	7.49%
Non-Hispanic Other	2,445,071	2,206,101	2,709,664	8.40%	7.58%	9.31%
Non-Hispanic White	28,697,468	27,485,055	29,927,508	14.56%	13.94%	15.18%

[a]Able to hear sounds between 25 and ≤40 dB in the better hearing ear, but not sounds below 25 dB. [b]Unable to hear sounds below 40 dB in the better hearing ear. [c]Unable to hear sounds below 25 dB in the better hearing ear, i.e. all people with mild, moderate, or worse HL.

Table 1: **Estimated prevalence count of people living with mild, moderate or worse, and any hearing loss overall and by gender, age group, and race and ethnicity, and corresponding prevalence rates.**

HL-level in each county by gender and by race and ethnicity group. For overall HL, this condition was violated in 6.4% of cases, almost exclusively when comparing ages 0 to 4 to 5–17 and ages 5–17 to ages 18–34 where HL rates are extremely low. In comparisons where any HL was higher for ages 0–4 than ages 5–17, the mean difference was $4e^{-7}$ indicating that the model estimated equivalent values for these two groups. Similarly, in comparisons where any HL for ages 5–17 was higher than for ages 18–34, the mean difference was 0.003. Comparisons at older ages violated this condition in only 0.01% of comparisons.

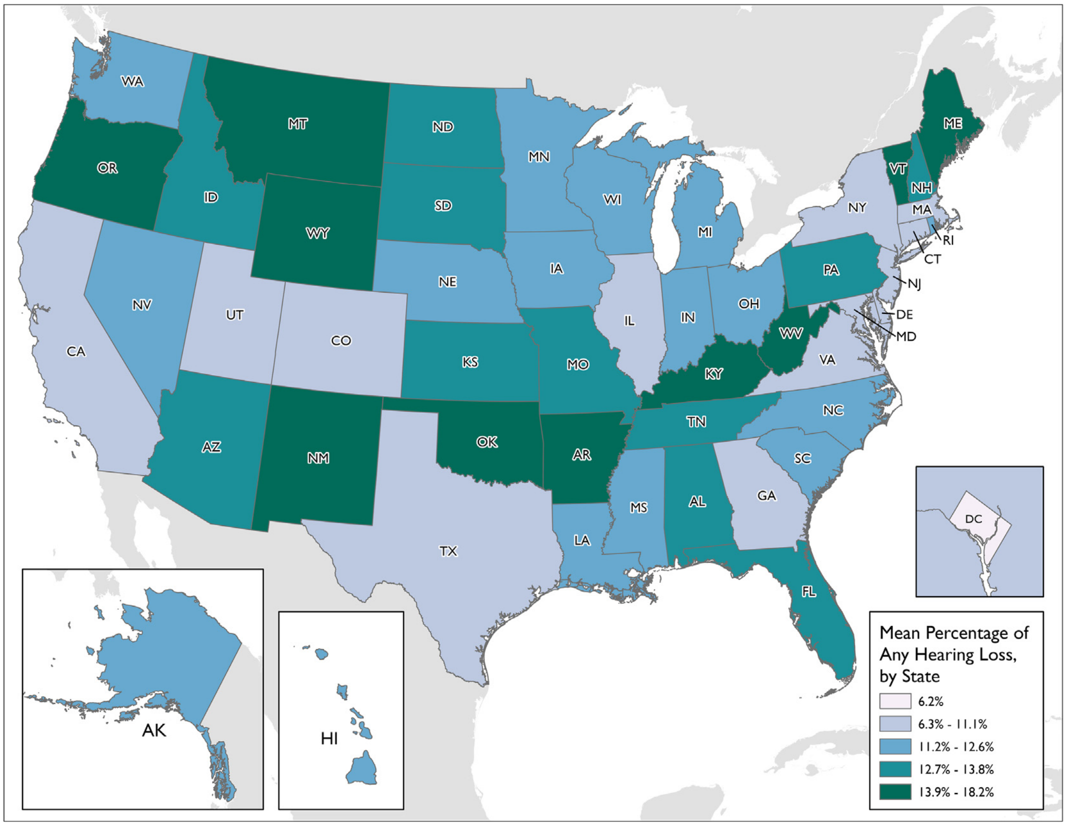

Fig. 1: **Raw prevalence of any hearing loss by U.S. State.**

The violation occurred in 4.8% of comparisons for mild HL, almost always when comparing mild HL for age group 0–4 to age group 5–17 when rates of HL are low or when comparing ages 65–74 to ages 75+ because the model estimated higher rates of moderate or worse HL for ages 75+. For moderate or worse HL, the condition was violated in 13.4% of comparisons, virtually always when comparing groups 0 to 4 to 5–17 or ages 5–17 to ages 18–34. Appendix D contains additional detailed validation results, including cross-validation and other checks, performed in both the ACS and NHANEs model.

Discussion

Approximately 25 million Americans had mild bilateral HL in 2019, a level of impairment that requires adaptive listening strategies, and, as HL is often progressive and cumulative, puts individuals at risk for more severe HL in the future. Another 13 million had moderate or greater HL, a level of hearing loss that impedes speech recognition.[23] Consistent with previous analyses of NHANES data,[1] we estimated a high degree of HL in the U.S., particularly among older adults. In 2019, Approximately 1 in 8 Americans of all ages had some degree of HL, a rate that increased to just under 1 in 7 for people ages 35 and older, and 1 out of every 1.4 people ages 75 and older.

Our National estimates are consistent with those from Goman and Lin (2016) who also used NHANES data and the same definition of any bilateral HL.[1] They found that 1 in 7 people ages 12 and older had bilateral hearing loss, as compared to our study which found that 1 in 8 people had bilateral HL, but our estimate includes children younger than 12 who have very low rates. Similarly, Goman and Lin (2016) estimated an overall rate of HL of 81.5% (95% Confidence Interval [C.I.], 78.1%–84.8%) for persons 80 and older as compared to our study's estimate of 72.7% (95% U.I. 70.5%–75.1%) for persons ages 75 and older. Gorman and Lin's (2016) estimate for persons ages 70 to 79 was 54.6% (95% C.I. 49.3%–60.0%).

The key contribution of our research is our ability to estimate HL at the U.S. State and County level, information that can be used to target hearing loss prevention, identification, and management strategies. After controlling for differences in county age distribution, County HL prevalence was positively associated with the number of disabled workers per capita, and the percent of all workers employed in the industry categories, Mining, Quarrying, and Oil and Gas Extraction; Retail

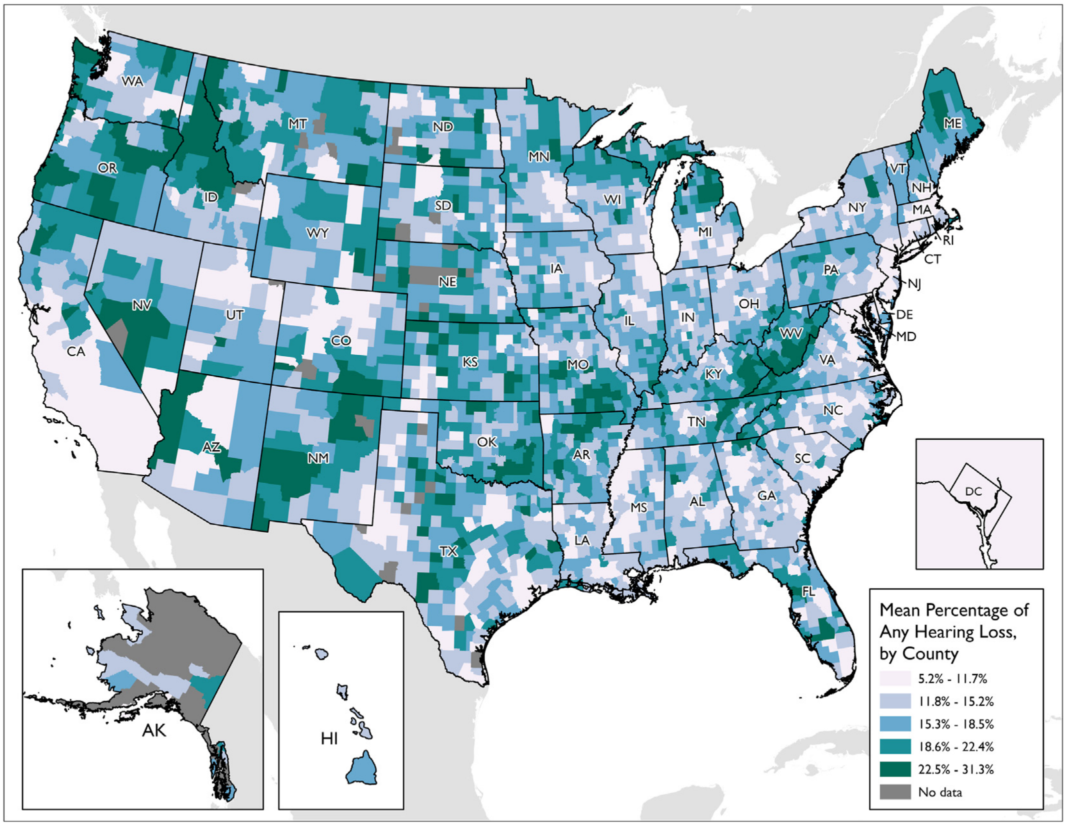

Fig. 2: **Raw prevalence of any hearing loss by U.S. County.**

Trade; and Accommodation and Food Services. County HL prevalence was negatively associated with larger population size, median home value, number of active physicians per capita, and the percent of workers employed in the industries of Wholesale Trade and Arts, Entertainment, and Recreation. CDC and others have found that occupational noise exposure is associated with higher levels of hearing loss, especially in the mining and construction sectors.[24] Our model results suggest that those living in rural areas experience higher rates of HL, perhaps due to potential noise exposure from outdoor work and recreation such as forestry, all-terrain vehicles, and recreational firearms.[25] However, it is important for readers to be aware that our models were developed to achieve accurate predictions rather than interpretation of parameters, and additional research is needed to evaluate the causes of differential rates of HL at the county level.

Our study has limitations. First, we used the full series of auditory measurements taken from 2001 to 2012 and 2015–2018 to increase sample size to support subgroup estimates. One study which evaluated HL among adults ages 20 to 69 detected a decline in mild or worse HL prevalence between the 1999 and 2004 and the 2011–2012 cycles of NHANES.[26] Analyses of NHANES at younger ages identified no secular trends in the data.[27] Future applications of SAE should attempt to estimate temporal differences in HL, and estimate prevalence among additional demographic subgroups. Second, we used the ACS measure of self-reported HL to measure geographic variation in HL stratified by age group. This assumes that subjective HL measured by ACS is associated with evaluated HL in a consistent manner across counties. County-specific differences in the propensity to report HL are not captured by our model. Third, the relationship between subjective measures of HL, such as that in the ACS HL question, and objectively measured HL, such the NHANES measure, differs by age, gender, and race and ethnicity.[28] We addressed this problem by using raking to force agreement between the ACS model estimates at the county level and the NHANES model estimates at the National level by demographic group to account for systematic under- or over-reporting by gender, race and ethnicity, and age. This approach propagates differences by gender and race and ethnicity seen in the NHANES data to the counties by inflating and deflating self-reported measures by subgroup across counties until they match the prevalence county of HL obtained using evaluated measures.

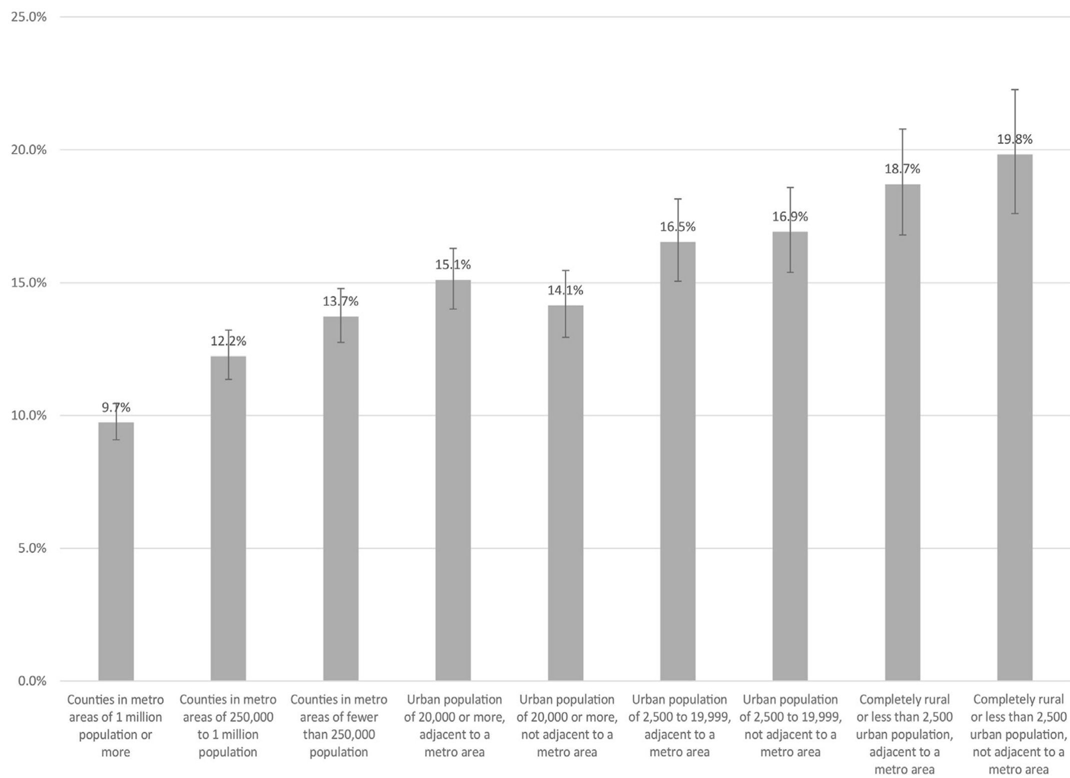

Fig. 3: **Rates of any hearing loss by rural/urban continuum code with 95% uncertainty intervals**.

Fourth, our model specifications are limited by available data sources and information suitable for use in the model. We identified 42 potential candidate variables for inclusion and used a combination of cross-validation and fit statistics to select the variables included in final estimation models. We were not able to include data with a large degree of missing information or data that was not aggregated at the county level. Although, we performed cross-validation to select the best fitting models from our available covariates, it is possible that the model is mis-specified by lack of inclusion of other variables and data that we are not aware of and did not obtain. There is also the possibility of other model assumptions being violated since some of the these are difficult to verify. However, our model validation and diagnostic results suggest that our models were effective at predicting hearing loss at the local level. The primary contribution of this modelling approach is its predictions at a granular level, and additional research on the causes of hearing loss, and how these may be affected by location, demography, and risk factors is needed.

The current estimates reveal previously unmeasured differences in prevalence estimates of hearing loss across geographic locations that are important to guide resource allocation, prevention efforts, and improve access to hearing services. Moreover, the current estimates could serve as the baseline for future evaluations of the recently enacted Food and Drug Administration regulatory category of over-the-counter hearing aids, which may reduce the price of hearing aids and increase device access.[29] However, the over-the-counter hearing aids do not necessarily address hearing care support services. Additional efforts to increase access to hearing specialists, subsidize the price of these devices, and reduce stigma and misperceptions of hearing aid use are warranted.[10,30] Lastly, given the strong association between age and hearing loss, the number of people with hearing loss in the U.S. can be expected to increase as the baby boomer generation ages.

Conclusion

Approximately 37.9 million Americans had bilateral HL in 2019. Higher rates of HL were most strongly associated with increased age, male gender, and non-Hispanic White Race and ethnicity. Estimates of geographic variation showed concentrations of HL in rural areas. This study's results can be used to increase awareness of HL as a problem, and to target education and assistance efforts at the state and county level.

Contributors

Rein was the Principal Investigator on the project. He was responsible for conceptualizing the idea to develop small area estimates of hearing loss at the county level, acquiring funding, and supervision. Rein wrote the first draft of the manuscript, tables, and completed revisions and edits in response to other authors comments, and wrote the first draft of Appendixes A, B, E, & F. He reviewed and suggested edits on Appendixes C and D. He worked closely with Franco in making methodological choices, reviewing model results, and developing validation tests of the estimated results.

Franco was the lead statistician on the project. She developed and coded the small area estimation models, produced project results, and wrote the first draft, and made subsequent revisions to Appendixes C and D. She reviewed and provided substantive comments on the manuscript and Appendixes A, B, E, & F.

Reed was a subject matter expert on the project. He provided guidance on hearing loss case definitions, supplied code used to analyse the NHANES data, reviewed and made substantive editorial suggestions to improve the manuscript.

Herring-Nathan provided data curation support to handing missing data issues in the Medicare and American Community Survey data.

Lamuda provided data curation support on the Area Health Resources File, and other data sources that were used in the model but were not selected as covariates. She reviewed and provided substantive comments on the manuscript. Lamuda also supported the acquisition of funding and served as the project manager handling administrative tasks essential to the project.

Alfaro Hudak analysed the primary NHANES data to create estimates that were used in subsequent small area estimation models. She reviewed and provided substantive comments on the manuscript.

Hu and Hartzman extracted and curated Medicare diagnostic data that was used in small area estimation models.

White reviewed and made substantive editorial suggestions to improve the manuscript.

Wittenborn performed data curation of data sources used in the modelling and coordinated organization of model estimates for presentation on the project website. Wittenborn also collaborated with Rein to conceptualize the project, supported funding acquisition, and reviewed and made substantive editorial suggestions to improve the manuscript.

Franco and Rein had direct access to and verified the underlying data reported in the manuscript. Wittenborn provided an additional level of project data curation and verification after results were generated for dissemination.

Data sharing statement

This study used publicly available data for most data inputs which can be accessed freely online at each survey's website. Detailed study results can be accessed at the project website www.Soundcheckmap.org. Medicare data used in the model is restricted access.

Editor note

The Lancet Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

Declaration of interests

This study was supported by CDC's National Center for Chronic Disease Prevention and Health Promotion, Division of Population Health via grant no. NU58DP007059, "Expanding the National Approach to Hearing Loss Education and Awareness." Franco has served in a leadership role for the following organizations: Chair, American Statistical Society's Committee on international Relations in Statistics, Member of Editorial Board of the Journal of the Royal Statistical Society (i.e. Associate Editor), Nominating Committee, International Association of Survey Statisticians, Nominating Committee, Morris Hansen Lecture, Washington Statistical Society, International Advisory Committee, 2023 Small Area Estimation Meeting in Lima, Peru, Program Committee, 2022 Small Area Estimation Meeting in College Park, MD, Guest Editor, Calcutta Statistical Association Bulletin (for a special issue on SAE). Reed reports grants from the National Institute on Aging, a speaking fee from the John A. Hartford Foundation, and participation on the Advisory Board, Neosensory. White reports a Cooperative Agreement from the Maternal and Child Health Bureau of the Health Resources and Services Administration. No other authors declared interests.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lana.2023.100670.

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