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Hearing loss configurations in low- and middle-income countries

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ABSTRACT

Objective: The majority of individuals with hearing loss worldwide reside in low- and middle-income countries (LMICs), but there is limited information regarding the characteristics of hearing loss in these regions. This descriptive study aims to address this knowledge gap by analysing audiogram patterns in LMIC populations. Greater knowledge about the properties of hearing loss in LMICs allows for improved planning of interventions.

Study sample: Retrospective data from 23 collaborating centres across 16 LMICs were collected. All participants were adults seeking help for hearing problems. A machine learning approach was utilised to classify the hearing threshold data and identify representative profiles. The study comprised 5773 participants.

Results: The results revealed mildly sloping audiometric patterns with varying severity. The patterns differed from previous studies conducted in high-income regions which included more steeply sloping losses. The findings also indicated a higher proportion of more severe levels of hearing loss.

Conclusions: These variations could be attributed to population-level differences in the causative mechanisms of hearing loss in LMICs, such as a higher prevalence of infectious disease-related hearing loss. The results may also reflect differences in health seeking behaviours. This study highlights the need for tailored, scalable, hearing interventions for LMICs.

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Introduction

The majority of persons with hearing loss globally reside in low- and middle-income countries (LMICs); however, only a small proportion of the world's rehabilitative resources are allocated to these regions, resulting in a vast unmet need (Orji et al. 2020). In Africa for example, less than 3% of persons who need hearing aids are able to access these devices (Bisgaard et al. 2022). Untreated hearing loss has a significant impact on an individual's quality of life, impairing social interactions, educational and

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vocational outcomes, and has been linked to poorer cognitive outcomes in older adults (World Health Organization 2021). Furthermore, untreated hearing loss incurs a substantial economic cost, with considerable potential cost savings if societies can prevent, detect early, and rehabilitate the impairment (World Health Organization 2021).

Although large-scale epidemiological studies have investigated the prevalence and characteristics of hearing loss in high-income countries (Agrawal, Platz, and Niparko 2008; Cruickshanks et al. 1998; Davis 1989; Gopinath et al. 2009; Humes 2023), such data is sorely lacking in LMICs (see Stevens et al. (2013) for a review). Public health officials, policy makers, researchers, and clinicians use such epidemiological data to make evidence-based decisions about health priorities, and spending. The limited data that is available detailing the characteristics in LMICs suggests that age adjusted prevalence rates are higher than in high income regions (Stevens et al. 2013). Additionally, there are indications that the severity and configurations of hearing loss differ in LMICs due to unique environmental risk factors and other contributors to hearing loss, with a greater proportion of individuals experiencing more significant impairments (Newall et al. 2020; Wang et al. 2010).

The absence of reliable data hinders the efforts of those attempting to develop hearing technology and service delivery models tailored to local requirements (Clinton Health Access Initiative 2019). Specifically, understanding the common audiometric patterns in LMIC populations would enable the development or selection of appropriate hearing aids for these populations. Technologies such as pre-programmed and over-the-counter hearing aids offer potentially scalable interventions, but are designed without explicit thought to the needs of users in LMICs. Past studies have employed various machine learning (ML) approaches to analyse large audiometric datasets, enabling the extraction of key audiometric patterns (Bisgaard, Vlaming, and Dahlquist 2010; Charih et al. 2020; Elkhouly et al. 2023; Ellis and Souza 2021; Lee et al. 2010; Wasmann et al. 2022). ML approaches, a branch of artificial intelligence, use unsupervised adaptive algorithms and statistical methods to model data and draw inferences. However, studies utilising these methods typically focus on high-income populations, potentially limiting the generalisability of their conclusions.

In this study, we aimed to use an ML approach, vector quantisation, to classify audiometric data from various LMICs. This approach is a clustering algorithm which aims to divide a large number of inputs into a smaller number of representative groups. This and similar approaches have been used previously to categorise audiological data successfully (Bisgaard, Vlaming, and Dahlquist 2010). This allowed us to compare the identified patterns to those observed in high-income regions and assess the implications for developing hearing intervention programs in these areas.

Materials and methods

Study setting

We collected retrospective data on ear and hearing assessments from a group of 23 collaborating centres across 16 countries known collectively as the Global Hearing Co-operative. All centres were in LMICs including centres in; East Asia and Pacific (Cambodia, China, Indonesia, Malaysia, The Philippines, Samoa, and Thailand), Europe and Central Asia (Russia and Turkey), Latin America and the Caribbean (The Dominican Republic), The Middle East and North Africa (Egypt and Jordan), South Asia (India and Nepal), and Sub-Saharan Africa (Malawi and South Africa). Primary Institutional Review Board approval for the study was granted by Macquarie University Human Ethics Committee and site-specific approvals were confirmed from all partner organisations.

Eligibility criteria

The aim of this study was to collect a clinical sample, rather than a population-based sample, consisting of individuals with hearing loss actively seeking help for their hearing problems. A minimum of 200 consecutive cases were obtained from each clinic involved in the study. Data collected prior to the COVID-19 pandemic (before November 1st, 2019) was utilised to circumvent any potential influence of the pandemic on clinical load and case presentations. Inclusion criteria for participants were as follows: (i) $\geq$18 years of age, (ii) primary complaint of hearing difficulties, (iii) worse ear four-frequency pure-tone average (0.5, 1, 2 and 4 kHz) greater than 20 dB HL, (iv) case did not present as part of a screening program. Potential surgically remediable cases (e.g. due to conductive hearing loss) were included if they met all inclusion criteria.

Data extracted

The following data was extracted from clinical records by a member of the clinical team at each site: (1) Demographic data including age, gender, occupation (where possible), rural/urban, referral source, history of noise exposure, hearing device status (not previously aided/aided unilaterally/aided bilaterally/bone anchored device/cochlear implant), whether a hearing aid was recommended (at this visit), whether the case was referred for ENT or surgical remediation. (2) Audiometric data: pure-tone audiogram thresholds (including bone conduction thresholds where available), otoscopic findings (where available), tympanometric findings (where available, either Jerger type or raw data), speech recognition scores (where available).

Statistical analysis

A machine learning approach – vector quantisation (VQ) – was used to derive audiological profiles for each dataset. VQ is a data-driven method used to learn a set of representative vectors from a dataset.

The algorithm works as follows:

1. For each clinical/demographic scenario the number (N) of required audiometric profiles is selected.
2. The base audiometric profiles are assigned uniformly distributed random values in the range 0–40 dB (one value per frequency) to initialise the algorithm.
3. The algorithm selects a data sample/patient audiometric profile and compares it to each of the base profiles by using a mean squared error (MSE) calculation. The minimum MSE corresponds to the closest match.
4. The base profile to which the data sample most closely matches (minimum MSE) is updated by calculating the mean of the initial base profile values and all current and previous matching data samples.
5. Step 3 and 4 are repeated for all data samples in the database for a given clinical/demographic scenario.

Table 1. General demographic information ($N = 5773$).

		Percent (*n*)
Gender	Female	50.3 (2904)
	Male	49.7 (2869)
Rural	Rural	29.8 (1721)
	Urban	56.7 (3276)
	Unknown	13.4 (776)
World Bank Country Income Group	Low income	3.5 (200)
	Lower middle income	35.8 (2064)
	Upper middle income	60.8 (3509)
Age Grading	18–40	22.3 (1286)
	41–60	27.9 (1618)
	61–80	41.7 (2398)
	>80	8.1 (471)
History of noise exposure	No	60.8 (3508)
	Yes	13.2 (762)
	Unknown	26.0 (1503)
Type of hearing loss[a]	SNHL	73.8 (8521)
	Mixed or CHL	26.2 (3025)

[a]Calculated as number of ears rather than number of persons

Table 2. Sample size by World Bank Region.

Region	Number of participants
Sub-Saharan Africa	403
East Asia and the Pacific	1743
Europe and Central Asia	1694
Latin America and the Caribbean	328
The Middle East and North Africa	446
South Asia	1159

This algorithm produces the most representative *N* audiological profiles for a given dataset, which can be used as template audiometric profiles for a population group that fits a given clinical/demographic scenario. Whilst in theory, any number of profiles can be generated, very large numbers fail to provide a helpful summary of common profiles in a population and small numbers miss potentially important variation in the population. In this case 4 and 7 profiles were selected, this was done with implementation in mind. This number represents a reasonable number of potential profiles that could be included in pre-configured/pre-programmable hearing aids.

Linear regression was utilised to investigate the relationship between the GNI per capita of regions involved in the study and the four-frequency average better ear hearing threshold obtained from those regions, controlling for age and gender.

Results

Participants

Participants included 5773 individuals (50.3% Female) with an average age of 57 (range 18–111). Demographic details of the sample are shown in Table 1, further details of the sample can be found in the Scalable hearing rehabilitation for low- and middle-income countries (SHRLMIC) Final report (Global Hearing Co-operative 2021). After removing any audiograms with questionable or missing data at each of the frequencies 250, 500, 1000, 2000, 4000 and 8000 Hz, a total of 11,545 individual ears with complete audiometric information were included in the full analysis. Comparison of sample sizes across regions (see Table 2) reveals that some regions were oversampled (Europe and Central Asia) and some under sampled (Sub-Saharan Africa and Latin America and Latin America and the Caribbean) when compared to the region's true population size as a proportion of the global population.

The full sample comprised individuals with sensorineural, conductive, mixed, and unknown types of hearing loss. Figure 1 top panel shows the full sample with four and seven different audiometric patterns classified, respectively. Identified in the sample is one normal audiometric configuration (red), representing the normal hearing ears of those with unilateral hearing loss. The rest of the configurations are mildly sloping in the mild (yellow and bright green), mild to moderate (aqua green), moderate to moderately severe (blue), moderately severe to profound (purple) and profound (pink) regions.

Although for most cases bone conduction was available, in approximately 30% no or incomplete bone conduction data was available and the type of loss was therefore unknown. A separate analysis was completed for the 8263 ears/cases where bone conduction was available, and sensorineural hearing loss was confirmed (see Figure 1 bottom panel for classifications of audiometric patterns in groups of four and seven). The main distinction between the whole sample and the sensorineural hearing only sample is that the profiles of the latter have slightly better thresholds.

The sample was also split into approximately 20-year age groups; 18–40, 41–60, 61–80, and >80 years of age, for analysis. The results of this analysis are shown in Figure 2 for the classification of 7 audiometric patterns and shows remarkable similarities across groups.

Figure 3 displays the proportion of the sample falling into each WHO hearing loss category (better ear classification) in each of the data collection regions, organised by GNI per capital (PPP, 2018 Atlas method). This figure shows a general increase in the proportions of more significant levels of hearing loss as GNI decreases. Figure 4 presents the better ear four-frequency average hearing loss plotted against the GNI per capita (PPP, 2018 Atlas method) for each study region. Regression analysis of GNI per capita and the four-frequency average better ear hearing threshold, accounting for age and gender, revealed that each $1000 increase in GNI was associated with a 0.55 dB improvement in hearing threshold. This translates to approximately a 15 dB difference in hearing threshold between the lowest and highest GNI groups in the sample, $F(3,5767) = 147.37$, $p < 0.005$, $R^2 = 0.071$.

Discussion

In this paper, we identify a variety of audiometric patterns representative of clinical populations in LMICs. These patterns provide a concise way to understand the shape and levels of hearing loss commonly found in these populations. The results reveal a relatively consistent mildly sloping pattern with varying levels of severity. The entire sample and sensorineural patterns exhibit similar shapes/slopes but with slightly varied severity. When separated by age group, the patterns remain remarkably similar, with the only apparent deviation seen in the 40–60 and 60–80 year groups, which display a single pattern with a more steeply sloping configuration (Figure 2, Blue line). Further analysis by region did not appear to show consistent differences.

This study is unique in that it derives from a large sample of LMICs rather than from single high-income regions, as is the case in most prior research in this area (Bisgaard, Vlaming, and Dahlquist 2010; Chang et al. 2019; Charih et al. 2020; Lee et al. 2010; Margolis and Saly 2007; Parthasarathy et al. 2020; Pittman and Stelmachowicz 2003). There are some similarities to the previous research, but overall, this study suggests that audiometric patterns in LMICs vary from those in high-income countries.

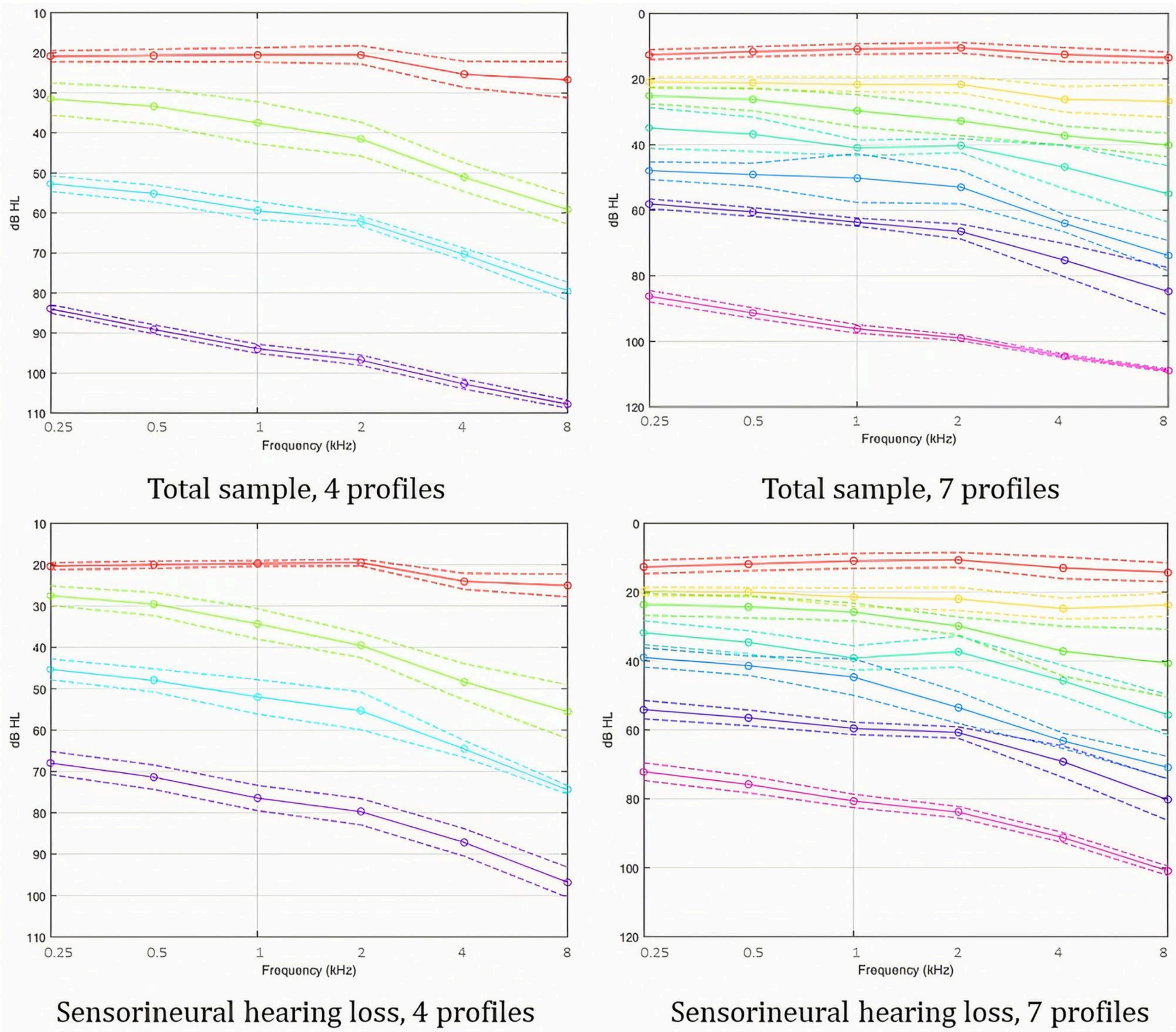

Figure 1. Audiometric patterns for both 4 and 7 hearing profiles for the total sample (top) and for those with sensorineural hearing loss only (bottom). Colours represent each of the different profiles.

The most evident and consistent difference between the current results and previous studies is that flatter audiometric profiles predominate in this sample. Several previous studies show a greater number of steeply sloping losses (Chang et al. 2019; Lee et al. 2010). To better quantify this variation we can gauge the approximate slope of the profiles by looking at the difference between their best and worst thresholds. The maximum difference between the best and worst frequency in the current study sample is approximately 25 dB for the whole sample. One possibility is that there were a greater number of conductive and mixed hearing losses in this sample than seen in previous studies. These losses tend to have a flatter shape and were excluded in some previous studies (Chang et al. 2019; Lee et al. 2010). When excluding conductive and mixed hearing losses in the current study, similar flatter patterns emerge, with a maximum of 30 dB variation between the best and worst threshold (see 7 profiles graphs in Figure 1). Comparatively Bisgaard et al.'s analysis which used a similar methodology has several profiles with a 60–65 dB drop across the frequency range, and several more with an approximately 40 dB difference (Bisgaard, Vlaming, and Dahlquist 2010). Other studies have multiple profiles with over 40 dB difference between the best and worst audiometric threshold (Chang et al. 2019; Lee et al. 2010).

The flatter patterns observed in the present data could be the result of population level differences in the shape and level of hearing loss seen in LMICs. Limited existing data examined variations in the shape of hearing loss seen across global populations. The audiometric pattern resulting from various underlying pathologies is known to vary significantly (Schlauch and Nelson 2014; Squires, Colombo, and McKinney 2019). We also know that the causes of hearing loss in LMICs are likely to differ, proportionally, from their high-income counterparts (Monasta et al. 2012). Higher levels of infectious disease-related hearing loss, ototoxicity, and noise-induced hearing impairments are expected to be seen in these populations. Thus, the flatter patterns likely result from proportional variations in the causative mechanisms of hearing loss in LMICs.

An alternative explanation for the observed differences in lower-income regions could be related to help-seeking behaviours in LMIC populations, rather than population-level differences. The lack of steeply sloping audiometric patterns and the higher proportion of more severe levels of hearing loss might be

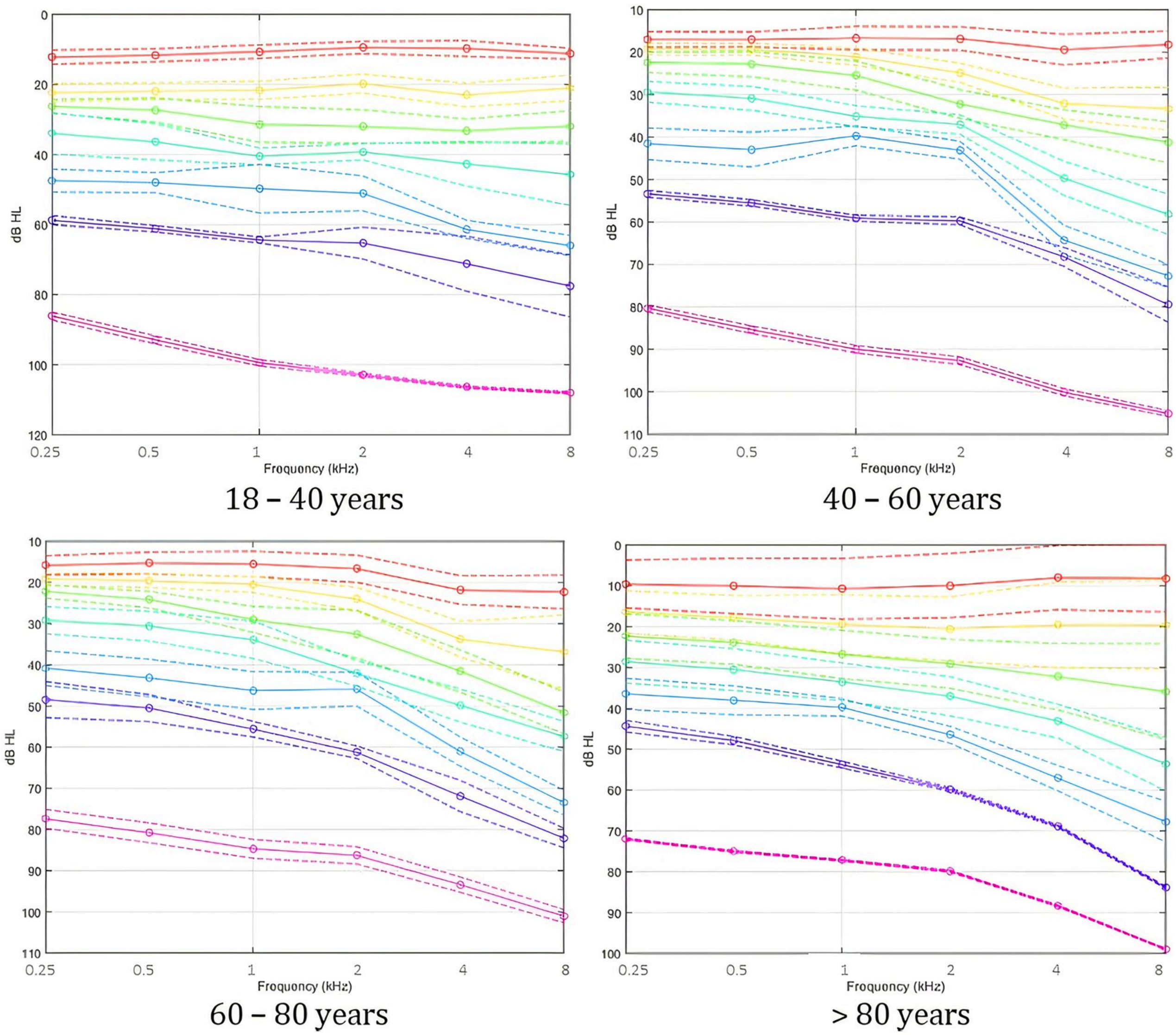

Figure 2. Audiometric patterns for 7 profiles by age category. Colours represent each of the different profiles.

due to individuals with less severe or sloping patterns being less likely to seek help compared to those with more severe, flatter losses. Previous data suggests that help seeking does relate to the severity of loss, but not necessarily the pattern of loss (Meyer and Hickson 2012). There are indications that cultural (e.g. attitudes to hearing loss in the elderly) and practical barriers to access (e.g. cost) can reduce the likelihood of help seeking in adults with hearing loss (Taylor et al. 2023).

A related explanation and limitation of our study is that there could be a sampling bias due to the characteristics of our partner organisations. Although our partners included a mix of a small local clinic and larger hospital-based centres, many were larger specialist centres. Referral pathways may direct those with milder sloping losses to smaller, local clinics (where they exist) and this could potentially be reflected in our data.

In this study, we focused on collecting representative clinical samples from each of the sampled regions rather than representative population samples. This approach is efficient when compared to a population-based study but is representative only of those seeking help for hearing problems. Large scale, high quality, region specific, hearing surveys are required to overcome the gaps in the literature. However, even with efficient design and delivery models (Bright et al. 2019; Saliba et al. 2017), conducting these surveys remains costly. Indeed, such comprehensive population data could resolve one key limitation of this study, the clinical sample collected here was not matched to data collected in other studies in terms of age composition, gender, or other demographic characteristic. This makes comparisons across studies complicated.

A final limitation relates to the machine learning approach utilised in this study. A vector quantisation approach was undertaken here as it has previously been used successfully to classify audiometric data (Bisgaard, Vlaming, and Dahlquist 2010). Several other methods have been utilised in the literature (Elkhouly et al. 2023; Ellis and Souza 2021; Lee et al. 2010), and it is not clear which method provides a more robust representation of the data at present.

Figures 3 and 4 present hearing loss categories and average hearing thresholds respectively, mapped against GNI per capita. A clear association between the four-frequency average hearing threshold (4FA) and GNI is evident. The relationship between health outcomes and measures of income per capita are well

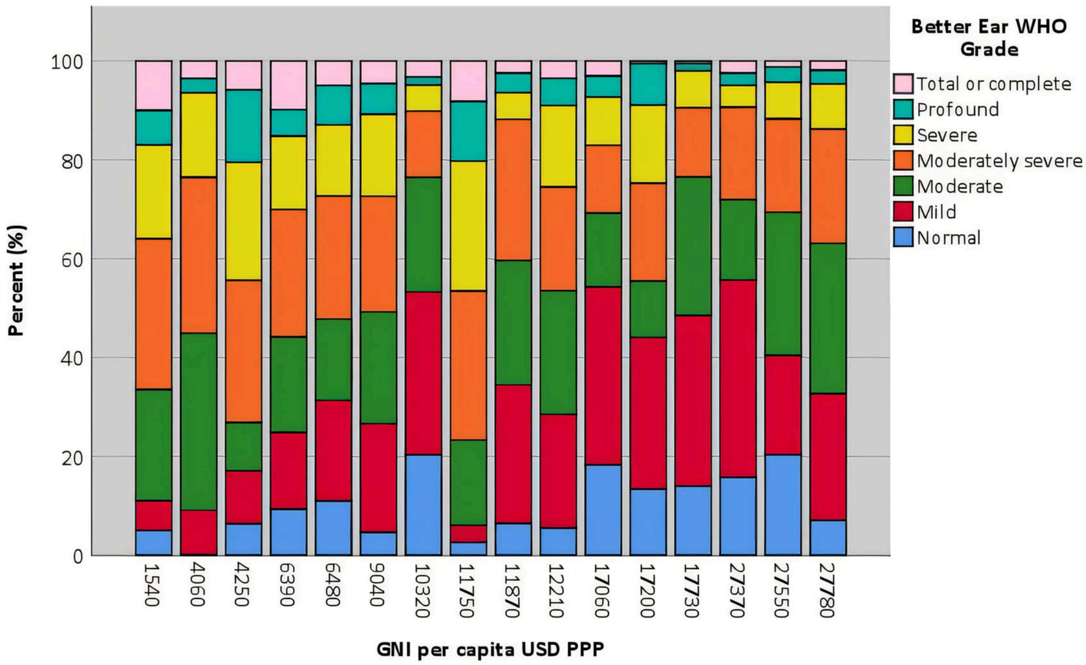

Figure 3. Better ear World Health Organisation (WHO) grade of hearing loss by region Gross National Income (GNI) per capita USD (Purchasing Power Parity (PPP), 2018 Atlas method).

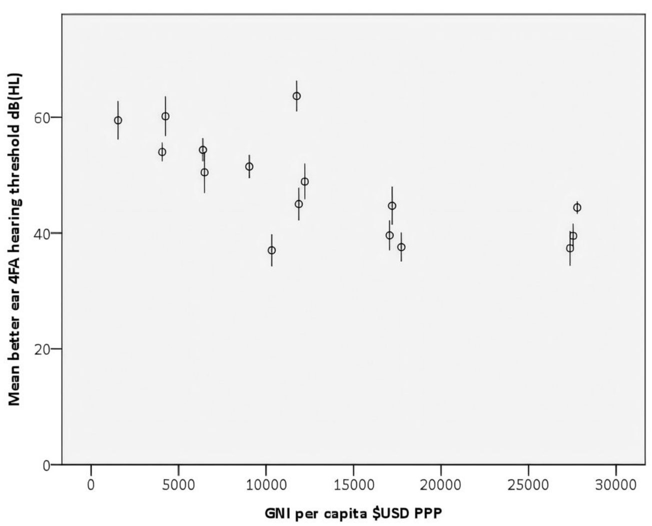

Figure 4. Better ear four frequency average (4FA) hearing threshold dB (HL) with 95% CI by region Gross National Income (GNI) per capita USD (Purchasing Power Parity (PPP), 2018 Atlas method).

reported in the literature (Schell et al. 2007), as is the relationship between the prevalence of hearing loss and GNI (World Health Organization 2013). However the specific relationship between GNI and the severity of hearing loss has not been reported in the literature to our knowledge. Our findings suggest that a greater proportion of more significant levels of hearing loss exists in lower-income regions, which aligns with several population-based studies (Newall et al. 2020; Wang et al. 2010). It is possible that these findings also reflect differences in help seeking behaviour and access as previously noted. As noted above, as the data in the current study is not population based, sampling bias could have influenced the apparent relationship seen here.

Our study advances the understanding of hearing loss in low-and middle-income countries and suggests that economic development can play a crucial role in improving hearing health outcomes in these regions. The findings of varied patterns and severity of hearing loss in those seeking help have important implications for the development of effective interventions and policies to address hearing loss in these regions. Scalable hearing rehabilitation technologies and delivery methodologies could be custom designed to suit the needs of these populations. Specifically, over-the-counter (OTC) or pre-programmed hearing aids could be developed with flatter amplification profiles more suitable to LMIC requirements. Early investigations of OTC hearing aids in an LMIC context suggested that they did not meet the required amplification standards (Chan and McPherson 2015; Cheng and McPherson 2000). Newer devices offer the potential for more efficacious outcomes, but to our knowledge have not been well studied in an LMIC context (Manchaiah, Swanepoel, and Sharma 2023). Rehabilitation programs in LMICs would also have to include devices capable of dealing with more severe hearing loss, with pathways and consideration made for the many who have unaidable losses.

Conclusions

In this study we provide evidence that the patterns of hearing loss seen in LMICs are distinct from those in high income regions, having a flatter profile on average. These results are likely to reflect proportional differences in causes of hearing loss in these regions. We also show that there is a correlation between hearing thresholds and measures of economic development in LMICs. These results should help to guide plans for the prevention and rehabilitation of hearing loss in low-and middle-income regions.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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