Predictors of Hearing Acuity: Cross-sectional and Longitudinal Analysis

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Background. This study aimed to identify predictors of hearing thresholds (best-ear pure-tone average at 1, 2, and 4 kHz) and hearing deterioration in order to define potential target groups for hearing screening.

Methods. We analyzed data from the Maastricht Aging Study, a Dutch cohort (aged 24–81 years; N = 1,721) that was observed for 12 years. Mixed model analysis was used to calculate each participant’s average hearing threshold deterioration rate during the follow-up period. We built ordinary least square linear regression models to predict the baseline threshold and deterioration rate. Potential predictors included in these models were age, gender, type of occupation, educational level, cardiovascular disease, diabetes, systemic inflammatory disease, hypertension, obesity, waist circumference, smoking, and physical activity level. We also examined the relationship between baseline threshold and the deterioration rate.

Results. Poorer baseline thresholds were strongly associated with faster hearing deterioration. Higher age, male gender, manual occupation, and large waist circumference were statistically significantly associated with poorer baseline thresholds and faster deterioration, although the effects of occupation type and waist circumference were small.

Conclusions. This study indicates that age and gender must be taken into account when determining the target population for adult hearing screening and that the time interval between repeated screenings should be based either on age or on the hearing thresholds at the first screening.

Key Words: Hearing loss—Epidemiology—Risk factors.

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Hearing loss is very common in older adults. The prevalence of hearing impairment (expressed as best-ear pure-tone average at 0.5, 1, 2, and 4 kHz [BEPTA0.5–4kHz > 25 dB]) was reported to be 0.6%, 2.0%, 5.8%, 15.0%, 31.0%, and 63.1% for people aged 20–29 years, 30–39 years, 40–49 years, 50–59 years, 60–69 years, and ≥70 years, respectively (1,2). A high prevalence of hearing impairment has also been associated with male gender (1–5), white race (1,2), low educational level (1–4), low household income (1), manual labor (4), stroke (3), diabetes (3), inflammatory bowel disease (6), rheumatoid arthritis (7), hypertension (2,8), overweight (5), large waist circumference (9), smoking (2,5), and low physical activity (4), as well as with exposure to sunlight (10), noise, chemicals, and ototoxic medication (11). However, the literature also describes contradictory findings.

Factors associated with hearing loss prevalence are expected to be related to hearing loss incidence and progression as well. Cruickshanks and colleagues (12) found that age, gender, and type of occupation, but not occupational noise exposure and educational level, were significantly associated with the 5-year incidence of hearing impairment (worst-ear PTA0.5–4kHz > 25 dB) and that only age was associated with the 5-year progression (hearing threshold deterioration > 5 dB). Mitchell and colleagues (13) reported similar results for the 5-year incidence of hearing impairment in the best ear (BEPTA0.5–4kHz > 25 dB) and the 5-year progression. Longitudinal studies on the hearing threshold deterioration rate only consistently identified age as a significant predictor (3,8,14–16).

This study examined the association between hearing thresholds (BEPTA0.5–4kHz) and a large set of potential predictors in a Dutch cohort between 24 and 81 years old that was observed for 12 years. We also longitudinally examined the association between the hearing threshold deterioration rate and a large array of potential predictors. Some of these...
METHODS

Study population

The total study population consisted of 1,823 participants (aged 24–81 years) from the Maastricht Aging Study (MAAS), a longitudinal study on the determinants of cognitive aging, which started in 1993 (17,18). Data on participants aged 49 years and older were collected at four points in time: at baseline \(T_0\) and at 3 \(T_1\), 6 \(T_2\), and 12 years \(T_3\) after baseline. Data on younger participants were collected at \(T_{0.5}\), \(T_1\), \(T_6\), and \(T_{12}\).

The hearing thresholds of the MAAS participants were initially assessed in a soundproof booth. From January 1994, however, the hearing tests were performed in a quiet room that was not fully soundproof. To overcome eventual bias from this change in measurement setting, we have not used the audiometric data collected before January 1994. Neither did we use the audiometric data of people who reported suffering from Ménière’s disease (they have fluctuating hearing acuity, which was judged to be uninteresting for this study).

For logistical reasons, 85 people did not have their hearing tested after January 1, 1994, and were therefore excluded, as were the 17 people who reported Ménière’s disease at their first hearing test. Thus, 1,721 MAAS participants remained eligible for participation in the cross-sectional analysis. For the longitudinal analysis, 313 more people were excluded, either because their hearing was tested only once \(n = 291\) or because they reported Ménière’s disease at their second hearing test \(n = 22\). Accordingly, 1,408 MAAS participants remained eligible for participation in the longitudinal analysis.

Measures

Pure-tone hearing thresholds were assessed for each ear at frequencies of 0.5, 1, 2, and 4 kHz using a screening audiometer (Interacoustics AS7, Denmark) in combination with circumaural headphones. In this study, we used the thresholds at 1, 2, and 4 kHz. The thresholds were based on ascending responses using up 5 dB, down 10 dB steps with 0 dB as the lowest and 90 dB as the highest stimulus intensity, which is a variation of the Hughson-Westlake method for audiometric testing (19). The participants’ BEPTA \(_{1–4 kHz}\) was calculated at every point in time. Other objectively measured participant characteristics included height, weight, waist circumference, and blood pressure. Individuals with a body mass index of 30 kg/m\(^2\) or more were classified as obese (20). Participants with a waist circumference more than 102 cm (men) or 88 cm (women) were labeled as having a large waist circumference (20). Participants with a diastolic blood pressure above 90 mmHg were considered to be hypertensive. Furthermore, hypertension was diagnosed whenever the systolic blood pressure was greater than 140 mmHg (for adults younger than age 60) or 160 mmHg (for adults aged 60 or older) (21).

Information on the participants’ type of occupation (manual versus intellectual labor), level of education (primary education or lower vocational training versus higher education), presence of cardiovascular disease, presence of diabetes, presence of a systemic inflammatory disease (either rheumatoid arthritis or inflammatory bowel disease), smoking status (current smoker versus ex- or nonsmoker), and physical activity (low versus moderate to high) was obtained by self-report.

Analysis

Ordinary least square (OLS) linear regression models were made to predict BEPTA \(_{1–4 kHz}\) at baseline. Predictors included in the models were: age, age\(^2\), gender, type of occupation, educational level, cardiovascular disease, diabetes, chronic inflammatory disease, hypertension, obesity, waist circumference, smoking, and physical activity level. The strength \((B\)-estimates\) and statistical significance \((p\)-values\) of the associations between baseline BEPTA \(_{1–4 kHz}\) and the predictors (baseline values) were examined in univariate models first, and thereafter in a full multivariate model that included all predictors. Next, we excluded nonsignificant predictors \((p > .05)\) from the full multivariate model one by one (backward selection). The adjusted \(R^2\) \((R^2_{adj})\) of the resulting “final” multivariate model and the univariate models were compared with each other. The \(R^2_{adj}\) reflects the proportion of the total interindividual variance in baseline BEPTA \(_{1–4 kHz}\) that is explained by the baseline values of the predictor(s) in the model, with an adjustment for the number of predictors in the model so that an increase in the number of predictors does not necessarily result in an increase in \(R^2_{adj}\).

We started the longitudinal analysis by examining the pattern of hearing threshold deterioration over time. Two linear mixed models were made to determine whether the change in BEPTA \(_{1–4 kHz}\) hearing levels over time followed a linear or an exponential pattern during the 12-year follow-up period. The models included random and fixed effect variance components for the intercept and slope (either time or time\(^2\)) with an unstructured covariance matrix. By specifying a model with a random intercept and a random slope, a linear (in case of time) or a quadratic (in case of time\(^2\)) regression line was fitted for each individual separately. The goodness of fit of linear mixed models is expressed by the Bayesian Information Criteria (BIC) value, where lower BIC values
indicate better model fit. We compared the BIC value for the model with time with the BIC value for the model with time\(^2\) to assess whether the actual pattern of BEPTA\(_{1–4\text{kHz}}\) hearing levels over time is best described by a linear or by a quadratic model.

Next, we calculated the average hearing deterioration rate for each individual, based on the regression line that was predicted by the linear mixed model with time. With OLS linear regression, we examined the relationship between baseline BEPTA\(_{1–4\text{kHz}}\) and the deterioration rate. Furthermore, OLS linear regression models (univariate models and a full and final multivariate model) were made to predict the individuals’ average hearing deterioration rate based on the baseline values of the following nonaudiometric predictors: age, age\(^2\), gender, type of occupation, educational level, cardiovascular disease, diabetes, chronic inflammatory disease, hypertension, obesity, waist circumference, smoking, and physical activity level. We inspected the predictors’ B-estimates and p-values as well as the proportion of the interindividual variance in hearing deterioration rates explained by the predictor(s) in the model (\(R^2_{\text{adj}}\)).

All analyses were done for the total population, and for the young (24–42 years), middle-aged (43–62 years), and older (63–81 years) adults separately.

**RESULTS**

**Participants**

The baseline characteristics of the participants who were included in the cross-sectional (\(N = 1,721\)) and longitudinal analysis (\(N = 1,408\)) are given in Table 1 (total population) and Supplementary Table S1 (separately per age group). Of the 1,408 people who were included in the longitudinal analysis, 411 (29%) had their hearing tested twice, 701 (50%) had their hearing tested three times, and 296 (21%) had their hearing tested four times within a follow-up period of 3 to 12 years. For 149 people (11%), the time span between the first and the last audiometric assessment was 3 years; for 379 people (27%) it was 6 years; for 109 people (8%) it was 9 years; and for 771 people (55%) it was 12 years. The mean length of follow-up was 9.5 years.

**Predictors of the Baseline Hearing Threshold (Cross-sectional Analysis)**

Table 2 shows the final multivariate model for the total population; the univariate models and the full multivariate model can be found in Supplementary Table S2. In all models for the total population, age was by far the strongest predictor of baseline BEPTA\(_{1–4\text{kHz}}\). We found a positive quadratic relationship between baseline BEPTA\(_{1–4\text{kHz}}\) and baseline age (Figure 1). The model with age and age\(^2\) explained 48.7% (95%CI = 45.3–52.1) of the total interindividual variance in BEPTA\(_{1–4\text{kHz}}\). Inclusion of other statistical significant predictors—that is, gender, type of occupation, and waist circumference—raised the explained variance to 50.9% (95%CI = 47.5–54.2; final multivariate model). Gender was the second strongest predictor of baseline BEPTA\(_{1–4\text{kHz}}\) in the final multivariate model with men having 4.2 dB (95%CI = 3.2–5.1) poorer hearing thresholds than women.

<table>
<thead>
<tr>
<th>Table 1. Baseline Population Characteristics</th>
<th>Cross-sectional Analysis ((N = 1,721))</th>
<th>Longitudinal Analysis ((N = 1,408))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, median (range), in years</td>
<td>52.7 (24.0–84.7)</td>
<td>51.3 (24.0–83.7)</td>
</tr>
<tr>
<td>BEPTA, median (IQR), in dB</td>
<td>11.7 (5.0–23.3)</td>
<td>10.0 (5.0–21.7)</td>
</tr>
<tr>
<td>BEPTA &gt; 25 dB, n (%)</td>
<td>380 (22.1)</td>
<td>269 (19.1)</td>
</tr>
<tr>
<td>Male gender, n (%)</td>
<td>868 (50.4)</td>
<td>731 (51.9)</td>
</tr>
<tr>
<td>Manual occupation, n (%)</td>
<td>832 (49.6)</td>
<td>664 (48.2)</td>
</tr>
<tr>
<td>Low educational level, n (%)</td>
<td>651 (37.9)</td>
<td>511 (36.3)</td>
</tr>
<tr>
<td>Cardiovascular disease, n (%)</td>
<td>289 (16.8)</td>
<td>207 (14.7)</td>
</tr>
<tr>
<td>Diabetes, n (%)</td>
<td>70 (4.1)</td>
<td>51 (3.6)</td>
</tr>
<tr>
<td>Chronic inflammatory disease, n (%)</td>
<td>175 (10.2)</td>
<td>93 (9.6)</td>
</tr>
<tr>
<td>Hypertension, n (%)</td>
<td>325 (18.9)</td>
<td>258 (18.3)</td>
</tr>
<tr>
<td>Obesity, n (%)</td>
<td>341 (19.8)</td>
<td>263 (18.7)</td>
</tr>
<tr>
<td>Large waist circumference, n (%)</td>
<td>480 (27.9)</td>
<td>369 (26.2)</td>
</tr>
<tr>
<td>Smoking, current, n (%)</td>
<td>478 (27.8)</td>
<td>377 (26.8)</td>
</tr>
<tr>
<td>Low physical activity, n (%)</td>
<td>773 (45.1)</td>
<td>635 (45.1)</td>
</tr>
</tbody>
</table>

**Notes:** BEPTA = best-ear pure-tone average (1, 2, and 4 kHz); IQR = interquartile range.

<table>
<thead>
<tr>
<th>Table 2. Final Multivariate Linear Regression Models to Predict the Best-Ear Pure-Tone Average (1, 2, and 4 kHz) at Baseline</th>
<th>Total population ((24–81\text{ years}; N = 1,721))</th>
<th>Young adults ((24–42\text{ years}; N = 556))</th>
<th>Middle-aged adults ((43–62\text{ years}; N = 628))</th>
<th>Older adults ((63–81\text{ years}; N = 537))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age(^*)</td>
<td>0.129 (0.057)</td>
<td>0.298 (0.045)</td>
<td>0.520 (0.069)</td>
<td>0.869 (0.108)</td>
</tr>
<tr>
<td>Age(^{2})*</td>
<td>0.008 (0.001)</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Male gender</td>
<td>4.168 (0.489)</td>
<td>&lt;.001</td>
<td>4.351 (0.774)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Manual occupation</td>
<td>2.089 (0.494)</td>
<td>&lt;.001</td>
<td>1.797 (0.773)</td>
<td>.02</td>
</tr>
<tr>
<td>Cardiovascular disease</td>
<td>2.813 (1.158)</td>
<td>.015</td>
<td>2.813 (1.158)</td>
<td>.015</td>
</tr>
<tr>
<td>Hypertension</td>
<td>3.376 (1.087)</td>
<td>.002</td>
<td>3.376 (1.087)</td>
<td>.002</td>
</tr>
<tr>
<td>Large waist circumference</td>
<td>1.374 (0.559)</td>
<td>.014</td>
<td>1.481 (0.740)</td>
<td>.046</td>
</tr>
</tbody>
</table>

**Note:** B-estimates can be interpreted as the difference in the baseline hearing threshold (in dB) per unit change in the predictor.

\(^*\)Age (in years) is centered to the age of the youngest participant in each of the models.
Table 2 also shows the results of the final OLS linear regression models for the three age groups separately. Age was still the strongest predictor of baseline hearing thresholds but the proportion of variance in BEPTA$_{1-4\text{kHz}}$ explained by age was low: 8.5% (95%CI = 4.1–12.9) in young adults, 9.9% (95%CI = 5.5–14.3) in middle-aged adults, and 9.4% (95%CI = 4.7–14.1) in older adults. Inclusion of other statistical significant predictors raised the explained variance to 10.8% (95%CI = 6.0–15.6) in young adults, 15.2% (95%CI = 10.0–20.4) in middle-aged adults, and 18.4% (95%CI = 12.3–24.5) in older adults. Gender was the second strongest predictor of baseline BEPTA$_{1-4\text{kHz}}$ in the final multivariate model for middle-aged and older adults, but we did not find a gender effect in the youngest age group. Adjusted for all other significant predictors, middle-aged and older men had, respectively, 4.4 dB (95%CI = 2.8–5.9) and 7.9 dB (95%CI = 5.6–10.2) poorer hearing thresholds than middle-aged and older women. The hearing thresholds of middle-aged and older men were comparable to the hearing thresholds of women who were respectively 8.4 years (95%CI = 5.5–11.3) or 9.1 years (95%CI = 6.5–11.8) older. A third strong predictor was type of occupation, with older adults with manual labor having 4.8 dB (95%CI = 2.5–7.2) poorer hearing thresholds than older adults with intellectual labor.

Predictors of the Hearing Threshold Deterioration Rate (Longitudinal Analysis)

**Pattern of hearing deterioration.**—The BIC value for the model with time (BIC = 28,749) was lower than the BIC value for the model with time$^2$ (BIC = 29,224), which means that the pattern of hearing deterioration over time is better represented by a linear function than by a quadratic function. Thus, the study participants’ BEPTA$_{1-4\text{kHz}}$ changed at a constant rate during the 12-year follow-up period. The overall median hearing deterioration rate was 7.3 dB/decade (interquartile range [IQR] = 5.3–10.9). For young adults, it was 5.1 dB/decade (IQR = 4.2–6.1); for middle-aged adults, it was 7.6 dB/decade (IQR = 6.0–10.0); and for older adults, it was 12.3 dB/decade (IQR = 9.5–14.6).

**Deterioration rate in relation to the baseline hearing threshold.**—The hearing deterioration rate was linearly related to baseline BEPTA$_{1-4\text{kHz}}$ (Figure 2). In a univariate model, baseline BEPTA$_{1-4\text{kHz}}$ explained 79.5% (95%CI = 77.6–81.4) of the total interindividual variance in the hearing deterioration rate. The proportion of variance explained by baseline BEPTA$_{1-4\text{kHz}}$ was 45.8% (95%CI = 39.2–52.4) in young adults, 60.7% (95%CI = 55.6–65.8) in middle-aged adults, and 75.5% (95%CI = 71.2–79.8) in older adults.

**Deterioration rate in relation to nonaudiometric factors.**—Table 3 shows the final multivariate model for the total population; the univariate models and the full multivariate model can be found in Supplementary Table S3. In all models for the total population, age was by far the strongest nonaudiometric predictor of the hearing threshold deterioration rate. The hearing deterioration rate was quadratically related to baseline age (Figure 3). The model with age and age$^2$ explained 54.8% (95%CI = 51.3–58.3) of the total interindividual variance in the hearing deterioration rate. Inclusion of other statistical significant nonaudiometric predictors—that is, gender, type of occupation, and waist circumference—raised the explained variance to 56.6% (95%CI = 53.2–60.0; final multivariate model). Gender was the second strongest nonaudiometric predictor of the deterioration rate in the final multivariate model with men having a 1.1 dB/decade (95%CI = 0.8–1.4) faster deterioration than women.

Table 3 also shows the results of the final OLS linear regression models for the three age groups separately. Age...
was still the strongest nonaudiometric predictor of the deterioration rate but the proportion of variance explained by age was low: 9.8% (95%CI = 4.7–14.9) in young adults, 14.5% (95%CI = 9.1–19.9) in middle-aged adults, and 8.9% (95%CI = 3.5–14.3) in older adults. Inclusion of other statistically significant nonaudiometric predictors raised the explained variance to 12.6% (95%CI = 7.0–18.2) in young adults, 20.7% (95%CI = 14.8–26.6) in middle-aged adults, and 16.4% (95%CI = 9.5–23.3) in older adults. Gender was the second strongest nonaudiometric predictor of the hearing deterioration rate in the final multivariate model for middle-aged and older adults but not for young adults. Adjusted for all significant nonaudiometric predictors, the deterioration rate was, respectively, 1.3 dB/decade (95%CI = 0.9–1.7) and 1.8 dB/decade (95%CI = 1.2–2.5) higher in middle-aged and older men than in middle-aged and older women.

**DISCUSSION**

Consistent with other studies, we found that higher age and male gender were significantly associated with poorer baseline hearing levels (1–5). The positive quadratic relationship we found between age and the deterioration rate has also been described in earlier studies (3,22). Age explained 8.9% of the interindividual variance in the deterioration rate in adults ≥63 years in this study, which is comparable to the 9% described by Gates and Cooper (16) and by Viljanen and colleagues (23) for adults aged ≥58 years.

Poorer hearing at baseline (BEPTA<sub>1–4 kHz</sub>) was significantly associated with faster hearing deterioration in the subsequent 3–12 years. The baseline hearing levels explained 79.5% of the interindividual variance in the deterioration rate. To our knowledge, only two earlier studies have examined the association between baseline pure-tone average thresholds and the deterioration rate (14,16). No significant association with the deterioration rate was found for PTA<sub>0.5–4 kHz</sub> (14) and PTA<sub>0.5–2 kHz</sub> (16), but poorer baseline PTA<sub>0.5–4 kHz</sub> was found to be related to slower deterioration (16). In these two studies, the analyses were performed for the left and right ear separately. The mean age of our population was lower, our study population was much larger, and our follow-up period was twice as long. These differences may explain the discrepancy in results between the previous and current studies. Poorer baseline hearing levels (in comparison to age-matched peers) may reflect a high genetic susceptibility to hearing loss, which would explain the faster deterioration we found in adults with poorer baseline hearing levels. Cross-sectional twin studies recently revealed that interindividual differences in hearing levels are primarily attributed to genetic variation: for example, Viljanen and colleagues (23) found that genetic effects accounted for 75% (95%CI = 67–81) of the total variance in BEPTA<sub>1–4 kHz</sub> for older women and Wingfield and colleagues (24) found that genetic effects explained 65%–66% (95%CI = 45–74) of the total variance in both BEPTA<sub>0.5–2 kHz</sub> and BEPTA<sub>1–4 kHz</sub> for older men.

We found a great overlap between the predictors of baseline BEPTA<sub>1–4 kHz</sub> and the predictors of the hearing deterioration rate (even 100% agreement in the nonstratified models), which is not surprising, given the strong relationship between baseline BEPTA<sub>1–4 kHz</sub> and the deterioration rate. Gender, type of occupation, cardiovascular disease, waist circumference, and obesity were related to the hearing deterioration rate in at least one of the age groups, but...
their effect was consistently small (maximum 1.8 dB/decade). This is the first longitudinal study to examine the relationship between the hearing threshold deterioration rate and chronic inflammatory disease, obesity, waist circumference, and physical activity level. Studies on the relationship between cardiovascular disease, smoking, and diabetes at baseline have consistently reported that these factors are not related to the hearing threshold deterioration rate (3,8,14,15). Studies on the deterioration rate in BEPTA \(0.5\text{–}4\text{kHz}\) have not detected a gender difference (3,13,14), although gender differences in the single frequency deterioration rate have been reported (22,25,26). Previous longitudinal studies (3,8,12–15) also found inconsistent results for type of occupation, educational level, and hypertension.

This study has several limitations. First, the audiometric measurements did not take place in a fully soundproof booth. Consequently, ambient noise—which is usually low frequent noise—might have biased the hearing thresholds at the lower frequencies. For this reason, we excluded the 0.5 kHz measurement, but we cannot rule out that the 1 kHz measurement was biased for some participants. Another limitation is the ethnicity of the participants, who were mainly white Caucasian. This limits the generalizability of the results because hearing thresholds are known to differ between races (1,2). A third study limitation is that we were unable to include information about noise exposure in the model. Cross-sectional studies have consistently reported an association between noise exposure and hearing loss (11), but it is difficult to accurately estimate noise exposure (eg, exposure time, frequency, noise intensity, use of ear protection) and to capture it in one or two parameters that can be used in a prediction model. However, previous longitudinal studies have not found a significant relationship between noise exposure and the hearing threshold deterioration rate (14,15,25); neither did noise exposure confound the effects of other predictors (3). A final study limitation is that we did not collect information on ototoxic medication use, exposure to ototoxic chemicals, or a family history of hearing loss.

We chose to use the best-ear hearing thresholds instead of the worst-ear hearing thresholds because best-ear hearing thresholds were thought to be more closely related to hearing disability, adherence to screening advice, and hearing aid use. However, future studies that are aimed at the causal relationships between environmental factors and hearing loss (eg, in order to develop interventions to prevent hearing impairment and further deterioration) are advised to use the worst-ear hearing thresholds, because those have been reported to be more influenced by environmental factors than the best-ear hearing thresholds (24).

In conclusion, our results indicate that primarily age and gender must be taken into account when determining the target population for an adult hearing screening program and that the time interval between repeated screenings should be based either on age or on the hearing thresholds at the first screening.

**Supplementary Material**

Supplementary material can be found at: [http://biomedgerontology.oxfordjournals.org/](http://biomedgerontology.oxfordjournals.org/)

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**References**


