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Hearing Thresholds at High Frequencies: Age as a Predictor of Values

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Abstract

Introduction The audiological evaluation has the main objective of determining the integrity of the auditory system. Pure tone audiometry is a standardized behavioral procedure that aims to investigate auditory thresholds to describe auditory sensitivity. Despite being recognized since the mid-1960s, high frequency audiometry is still little used and explored in clinical practice, and its use is more considered as an audiological monitoring tool or as a research tool.

Objective To analyze the audiological thresholds of high frequency audiometry in normal hearing individuals, and to verify the predictive capacity of age in the auditory thresholds of high frequency audiometry.

Methods This is a retrospective, cross-sectional, and quantitative study that was approved by the Research Ethics Committee under number 5.039.583/21. The procedures were: clinical evaluation, pure tone audiometry, acoustic immittance measurements, and high frequency audiometry. All data collected from the exams were tabulated in an Excel spreadsheet and analyzed using appropriate statistical tests in the Statistical Package Social Sciences software.

Results A total of 980 medical records were analyzed. The right and left ears presented similar tonal hearing thresholds for the frequencies of 12 kHz and 16 kHz. The threshold variance of 29.8% in the 12 kHz frequency can be explained by the variance of age, while, for the frequency of 16 kHz, this percentage is of 46.4%.

Conclusion For 12 kHz hearing thresholds, an increase of 1 year leads to a 0.66 dBHL increase in hearing threshold. For 16 kHz hearing thresholds, an increase of 1 year leads to a 1.02 dBHL increase in hearing threshold.

Keywords
- hearing
- audiometry
- hearing loss

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Introduction

The entire auditory system can be evaluated through behavioral and electrophysiological measures. The audiological evaluation has the main objective of determining the integrity of the auditory system[1] and must be guided by validated and scientifically recognized procedures and techniques, which aim to guarantee the quality of the exam and patients' safety.[2]

Pure tone audiometry (PTA) is a standardized behavioral procedure that aims to investigate auditory thresholds to describe auditory sensitivity, comparing the obtained values with normality standards, using pure tone as a reference.[2] This procedure is commonly called conventional audiometry and it tests frequencies between 250 and 8,000 Hz.[3] The audiological result obtained from this evaluation must contain the type, degree, configuration, and laterality of hearing loss, if it has been identified, according to the adopted literature.[2]

However, human hearing is in a frequency range that extends from 20 to 20,000 Hz, which demonstrates that conventional pure tone audiometry (PTA), by itself, is not effective for the assessment of the entire frequency range. Therefore, it is suggested to carry out high frequency audiometry (HFA), since the thresholds of frequencies from 9,000 to 20,000 Hz can also be investigated depending on the equipment that has been used.[2]

Despite being recognized since the mid-1960s, HFA is still rarely used and explored in clinical practice, and its use is more considered as an audiological monitoring tool or as a research tool.[4] The use of HFA often allows for the early identification of hearing alterations caused by factors such as age, ototoxicity, or the presence of tinnitus, as these frequencies are the first to be affected in most diseases that affect the inner ear.[1] It also makes it possible to provide additional information for individuals with complaints of difficulty in understanding speech in noisy environments, as high frequencies are necessary for the decoding of speech signals, discrimination of consonant sounds, and speech recognition.[4,5]

Because there is a possible variability in relation to age, to describe the HFA results, it is suggested the identification of the equipment, the type of the transducer, and the stimulus used, as well as the classification adopted, since there is still no universal standardization for these thresholds.[2,6] Additionally, the great variability of application methodologies and the lack of consensus regarding calibration standards still make their use difficult in clinical routine.[7] Despite this, evidence indicates that there is a decrease in auditory sensitivity with the increase in the analyzed frequency, which may be a common trend.[8]

Thus, the present study's main objective is to analyze the audiological thresholds of HFA in normal hearing individuals and to verify the predictive capacity of age in this procedure's auditory thresholds.

Methods

This is a retrospective, cross-sectional, and quantitative study that was approved by our institution's Research Ethics Committee under the number 5.039.583/21.

The research was performed through analysis of the medical records of individuals treated between the years 2017 and 2019, with the following inclusion criteria: having been evaluated by PTA and HFA, with thresholds in PTA within the parameters of normality according to the classification by Loyd and Kaplan.[2]

The PTA and HFA were performed in a clinical environment, with trained audiologists with more than 5 years of experience in the area.

Procedures

The following aspects were analyzed in the patients' medical records:

- Appointment with an ear, nose, and throat (ENT) doctor before the examinations. If cerumen was found, it was previously removed when the patient was submitted to evaluation.
- PTA: to determine the auditory thresholds at frequencies from 250 to 8,000 Hz by air and at frequencies 500 to 4,000 Hz by bone (when necessary), for each ear, in a soundproof booth, meeting ANSI S3.1-1991 environmental noise level. Patients were positioned and instructed to raise their hand when hearing the acoustic stimulus, even if it was of low intensity. Afterwards, the headphones were positioned by the audiologist, for an adequate placement that would not interfere with the accuracy of the exam due to the resonance characteristics of the external acoustic meatus, as well as to avoid the possibility of collapsing. The equipment used was an Audiometer AC40 (Interacoustics, Middelfart, Denmark) and earphones type TDH39 (Telephonics Corporation, New York, NY, USA), both properly calibrated.
- Speech tests: the speech recognition threshold (SRT) and index of speech recognition (ISR) tests were performed for each ear. The patient was instructed to repeat the words presented by the audiologist as they understood them. The equipment used was an Audiometer AC40 and earphones type TDH39, both properly calibrated.
- HFA: the frequencies of 12 kHz and 16 kHz were analyzed for each ear. The assessment was performed in a soundproof booth (meeting the ANSI S3.1-1991 environmental noise level standard). Patient orientation was the same as in PTA, with the exception that the sounds presented would be higher. The earphone was carefully placed. The equipment used was an Audiometer AC40 and earphones (KOSS R-80, Milwaukee, WI, USA), both properly calibrated.
- Acoustic immittance measurements were used to verify the mobility condition of the tympanic membrane, ossicular chain, and middle ear. Patients were instructed that they would feel a slight pressure inside the ear and some loud noises, but they should remain silent and avoid moving. The equipment used was a properly calibrated Otoflex 100 (Natus Medical Inc., San Carlos, CA, USA). There was no need for an acoustic booth for this procedure.

Data Analysis

All data collected from the exams were tabulated in an Excel (Microsoft Corp., Redmond, WA, USA) spreadsheet and analyzed using appropriate statistical tests in the Statistical Package Social Sciences (SPSS, IBM Corp. Armonk, NY, USA) software, version 25.0. The statistical significance value adopted was 5% ($p \leq 0.05$). To calculate the 95% confidence intervals (95% CI), the corrected and accelerated bias method was used based on 2,000 bootstrap samples. The values in square brackets in the tables indicate the upper and lower limits of the 95% CI.

The description of the study sample was performed through measures of central tendency and dispersion. The statistical analysis of verification of hearing thresholds by separate ears and the relationship of these thresholds with the age factor was done. The analysis of thresholds according to gender was not performed, as recent previous studies have shown no difference between genders.[9,10]

Results

For a better understanding of the results, they were subdivided into three sections, related to the characterization of the study sample, the analysis of the audiometric thresholds of HFA, and the analysis of the predictive capacity of age in relation to the thresholds, respectively.

Section 1–Characterization of the Study Sample

A total of 980 medical records were analyzed, of which 642 (65%) were female and 338 (35%) were male. ►**Table 1** presents the measures of central tendency and dispersion of the age variable of the analyzed subjects.

Section 2–Analysis of Audiological Thresholds of HFA between Ears

►**Table 2** presents the measures of central tendency and dispersion of pure tone thresholds for frequencies of 12 kHz and 16 kHz according to the ear, as well as their comparison using the Student *t*-test for paired samples (parametric), because the sample number is large enough to allow the direct use of parametric tests due to the central limit theorem. The effect size of the difference between the ears was measured using the Cohen D coefficient. The total number of each ear for each frequency is different from what was described as a sample in the methods section, because only thresholds with all responses were considered. Ears that had no response were discarded for this analysis.

The results in ►**Table 2** demonstrate that there was a statistically significant difference between the ears for the pure tone hearing threshold at the frequency of 12 kHz. However, the analysis of the effect size (ES) suggests that the observed difference is negligible, and there is an overlap between the 95% CI. These factors, along with the fact that the *p*-value obtained through traditional hypothesis tests can be underestimated due to the large number of participants, suggest that both ears present similar behavior in relation to the pure tone threshold at the frequency of 12 kHz. At the frequency of 16 kHz, no statistically significant differences were observed between the ears. Thus, the right and left ears presented similar tonal hearing thresholds for the frequencies of 12 kHz and 16 kHz.

Section 3–Predictive Capability

►**Table 3** presents the simple linear regression models designed to verify the predictive capacity of age in relation to pure tone thresholds at frequencies of 12 kHz and 16 kHz. The models had age as an independent variable and the pure tone threshold of each frequency as a dependent variable. Due to the fact that no differences were observed between the ears in relation to the thresholds, they were unified to increase sample number and power. Ears that showed no response were excluded from the linear regression models.

Table 1 Characterization of the study sample in relation to age

Variable	n	Mean	SD	Median	Min.	Max.
Age (years)	980	35.88 [34.99–36.82]	14.06	36.0 [35.–37]	5	70

Abbreviations: Max., maximum; Min., minimum; SD, standard deviation.

Table 2 Descriptive values and comparative analysis of the ears in relation to pure tone thresholds

Variable	Ear	n	Mean	SD	Median	Min.	Max.	*p*	ES
Thresholds – 12 kHz (dBHL)	RE	973	19.55 [18.54–20.62]	16.62	15.0 [15.0]	0.0	75.0	**0.029***	0.05
	LE	975	18.84 [17.83–19.94]	17.07	10.0	0.0	110.0		
Thresholds – 16 kHz (dBHL)	RE	782	28.95 [27.53–30.2]	19.71	25 [25–30]	0.0	60.0	0.173	0.029
	LE	798	28.82 [27.49–30.16]	19.47	30 [30]	0.0	60.0		

Abbreviations: ES, effect size; LE, left ear; Max., maximum; Min., minimum; RE, right ear; SD, standard deviation. **Notes:** The Student *t*-test was used for paired samples. * Statistically significant value at the 5% level ($p \leq 0.05$).

Table 3 Simple linear regression models of age as a predictor of pure tone threshold at frequencies of 12 and 16 kHz

Frequency	n		b	B	p
12 kHz	1,948	Constant	−4.3 [−6.02–−2.58]	–	< **0.001***
		Age	0.66 [0.61–0.7]	0.55	< **0.001***
16 kHz	1,580	Constant	−4.5 [−6.41–−2.6]	–	< **0.001***
		Age	1.02 [0.97–1.07]	0.68	< **0.001***

Notes: r^2 for 12 kHz = 0.298 ($p < 0.001^*$); r^2 for 16 kHz = 0.464 ($p < 0.001^*$). * Statistically significant value at the 5% level ($p \leq 0.05$).

The results in ►**Table 3** demonstrate that the simple linear regression models were significantly better than the means of the dependent variables in the task of predicting the pure tone threshold at the frequencies of 12 kHz and 16 kHz. It was observed that 29.8% ($r^2 = 0.0298$, $p < 0.001$) of the tonal auditory threshold variance for the frequency of 12 kHz can be explained by the variance of age, while for the frequency of 16 kHz, this percentage is of 46.4% ($r^2 = 0.464$, $p < 0.001^*$).

The values of the nonstandard coefficient b for the constant and independent variable suggest that, for 12 kHz, the relationship between age and pure tone auditory threshold is represented by the ►**Fig. 1**, and given by the equation (y is the pure tone hearing threshold value, in dBHL, and x is the age value, in years):

$$y = -4.30 + 0.66x$$

And for 16 kHz, this relationship is represented by ►**Fig. 2**, and given by the equation:

$$y = -4.50 + 1.02x$$

Thus, these mathematical relationships propose that, for 12 kHz, the increase of one year of age leads to an increase of 0.66 dBHL in the pure tone auditory threshold. For 16 kHz, the increase of one year of age leads to an increase of 1.02 dBHL in the pure tone threshold.

Investigation of the Predictive Ability of Age in Relation to the Probability of Presence of Response in the Frequencies of 12 and 16 kHz

►**Table 4** presents the binary logistic regression models designed to verify the predictive capacity of age in relation to the probability of presence of response at frequencies of 12 kHz and 16 kHz. The models had age as an independent variable and the presence or absence of a response for each frequency as a dependent variable. Due to the fact that no differences were observed between the ears in relation to tonal auditory thresholds, they were unified to increase the sample number and sample power.

The results in ►**Table 4** demonstrate that, for the frequency of 12 kHz, the binary logistic regression model did not have a statistically significant improvement after adding age as an independent variable. Therefore, age was not a predictor of presence or absence of response to the 12 kHz frequency.

For the frequency of 16 kHz, it was observed that the binary logistic regression model had a statistically significant improvement after adding age as an independent variable. The values of the nonstandard coefficient b for the constant and for the independent variable suggest that, for 16 kHz, the relationship between age and the probability of having a missing response is given by the equation:

$$P(A) = \frac{1}{1 + e^{-(6.29+0.12x)}}$$

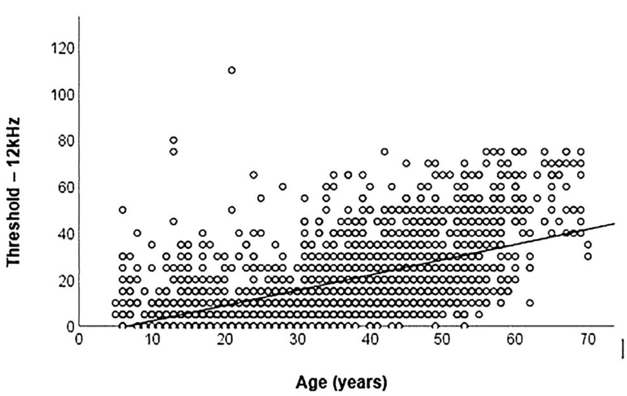

Fig. 1 Pure tone hearing threshold for 12 kHz as a function of age and linear model fitted to the data.

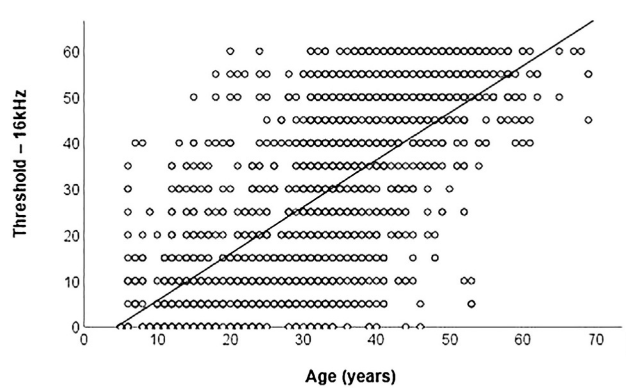

Fig. 2 Pure tone hearing threshold for 16 kHz as a function of age and linear model fitted to the data.

Table 4 Binary logistic regression models of age as a predictor of the presence of response for frequencies of 12 and 16 kHz

Frequency	n		b	OR	*p*	r^2	
						Cox-Snell	Nagelkerke
12 kHz	1960	Constant	−11.62 [−15.02–−8.21]	–	< **0.001***	0.02	0.20
		Age	0.14 [0.08–0.2]	1.15 [1.08–1.22]	< **0.001***		
16 kHz	1960	Constant	−6.29 [6.90–−5.68]	–	< **0.001***	0.22	0.35
		Age	0.12 [0.1–0.13]	1.12 [1.11–1.14]	< **0.001***		

Abbreviation: OR, odds ratio. **Notes:** Model fit quality – 12 kHz: $\chi^2 = 2.82$, $p = 0.945$; 16 kHz: $\chi^2 = 41.42$, $p < 0.001^*$. * Statistically significant value at the 5% level ($p \leq 0.05$).

Where P(A) is the probability of having a missing response, x is the age in years and e is the Euler number (≈ 2.718). Similarly, the probability of having a present response is given by the equation:

$$P(P) = 1 - P(A)$$

Where P(P) is the probability of having a present response and P(A) is the probability of having a missing response.

The odds ratio (OR) showed that the increase of 1 year in age increases the chance of a missing response by 1.12 times in relation to the previous age value.

Discussion

According to the profile of the sample, it can be seen that the average age of the individuals was 35 years. Considering that the survey was performed for over 3 years, a higher frequency of young adults was observed. This can be explained by the fact that, normally, older individuals are more likely to have hearing thresholds outside the normal range, and, therefore, would not meet the inclusion criteria of this study. It is known that hearing begins to deteriorate in the fourth decade of life and presbycusis affects a large number of individuals.[11,12]

It was observed that more than half of the medical records analyzed were composed of assessments by female individuals (65% of the sample). These data are consistent with findings from other studies, in which authors had a 67% female and 33% male sample.[10] Researchers claim that the higher occurrence of women in clinical audiology trials may be due to the fact that women seek health care more frequently.[4,13] Despite this, no consensus was found in the literature regarding the better hearing quality of women when compared with men; in fact, recent previous studies showed no difference between the genders. Thus, the analysis of the research on thresholds according to the gender variable was not performed.[9,10]

Considering the analysis performed in ►**Table 2**, which compares the thresholds by ears and frequencies, it was observed that only the frequency of 12 kHz had a statistically significant difference. It has been shown that the right ear has a higher threshold than the left ear. However, the analysis of the effect size obtained suggests that the observed difference is negligible, as well as an overlap of the 95% CI. These factors, along with the fact that the *p*-value obtained through traditional hypothesis tests can be underestimated due to the large number of participants in the sample, suggest that both ears present similar behavior in relation to the pure tone threshold at the frequency of 12 kHz. At the frequency of 16 kHz, no statistically significant differences were observed between the ears. Thus, the HFA thresholds obtained for both the 12 kHz and 16 kHz frequencies were not different when compared between the right and left ears. That is, both ears had similar tonal hearing thresholds for the frequencies tested, as in other studies that performed this analysis.[9] This is still not a consensus in the literature, as the research by Oppitz et al. demonstrates that the right ear has higher audibility thresholds than the left ear, with statistical significance in certain HFA thresholds.[4]

In section three of the results, we presented the possibility of predictive capacity to HAF thresholds in the frequencies of 12 kHz and 16 kHz related with age, and their relationship with the presence or absence of responses in these frequencies. This study demonstrated it is possible to predict thresholds and find a response parameter, thus making its applicability more palpable and recommended in the clinical practice of auditory diagnostic assessment. It is already known that HFA are relevant to the audiological monitoring process of individuals, but they are still scarcely used in clinical routine. According to numerous studies, HFA should be part of the battery of tests for individuals with tinnitus complaints,[14] with constant exposure to noise,[15–17] and use of ototoxic drugs.[5]

It was possible to observe that the sensitivity to high frequencies was shown to decrease with increasing age. Such findings corroborate those in the literature and indicate that the HFA can be used clinically for early diagnosis of auditory aging, as shown in ►**Figs. 3** and **4**, through the statistical analysis of this research.

According to the analysis of the answers and statistical tests applied, the age explains 29.8% of cases of threshold variance for 12 kHz, and 46.4% for 16 kHz. Other variables must be taken into account, such as diseases, personal habits, and genetic issues, among others.

Thresholds for 12KHz (n= 1948)	
Equation y =-4,30 + 0,66x (Y = threshold and X=age)	
Age (years)	Threshold (dBHL)
10	0
20	10
30	15
40	20
50	30
60	35
70	40
80	50

Fig. 3 Summary chart of expected thresholds for 12kHz.

Thresholds for 16KHz (n=1580)	
Equation y =-4,50 + 1,02x (Y = threshold and X=age)	
Age (years)	Threshold (dBHL)
10	5
20	15
30	25
40	35
50	45
60	65
70	65
80	75

Fig. 4 Summary chart of expected thresholds for 16kHz.

Our hypothesis was that age has a relevant impact on the presence or absence of responses at high frequencies, which may be due to the anatomy itself and the dynamics of the cochlea's functioning, the so-called cochlear tonotopy. Some studies suggest that at high frequencies there is greater hearing sensitivity, with increasing age, than at low frequencies.[18] Such findings corroborate the literature and indicate that high-frequency audiometry can be used for clinical diagnosis, as it can distinguish hearing sensitivity between young people and adults with normal audiological results in conventional audiometry. Although this is proven, in this study it was observed that age explains a certain percentage of the HFA threshold value, which is also a consequence of other aspects of life such as habits, genetic predispositions, and preexisting diseases.

This research reinforced the possibility of using HAF in clinical practice, as well as the importance of evaluating high frequencies for a broader care of the individual. However, it must be observed that this study was limited to only the analysis of two high frequencies. Other studies should be performed to confirm the findings in other frequencies that can also be evaluated and corroborate the importance of centers performing their biological calibration.

Conclusion

According to the data collected, the statistical tests performed, and the analyzes performed, it was possible to verify that there was no significant difference between the right and left ear for the auditory thresholds of 12 kHz and 16 kHz frequencies.

For 12 kHz hearing thresholds, a 1 year increase leads to a 0.66dBHL increase in hearing threshold. Age was not a predictor of the presence or absence of a response. The age factor explains 29.8% of the cases. For 16 kHz hearing thresholds, a 1 year increase leads to a 1.02dBHL increase in hearing threshold. Age was a predictor of presence or absence of response: increasing age by 1 year increased the chance of nonresponse by 1.12 times compared with previous age; this factor explains 46.4% of the cases. For future studies, other variables such as diseases, personal habits, and genetic issues, among others, must be taken into account.

Authors' Contribution

Laura Franco Chiriboga: contributed to data collection, as well as research development and data analysis, and writing of the article. Karolina Pessote Sideri: contributed to the analysis of data and preparation of the article. Carla Salles Chamouton: contributed as a reviewer of the article. Júlia Nayara Silva Oliveira: contributed to acquisition of data. Luis Miguel Chiriboga Arteta: contributed with the conception and design.

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Conflict of Interests

The authors have no conflict of interests to declare.

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