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Standard Audiograms for the IEC 60118-15 Measurement Procedure

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Abstract

For the characterization of hearing aids, a new test method has been defined in the new International Electrotechnical Commission (IEC) standard 60118-15. For this characterization, the hearing aid will be set to actual user settings as programmed by standard fitting software from the hearing aid manufacturer. To limit the variation of programming outcomes, 10 standard audiograms, which cover the entire range of audiograms met in clinical practice, have been defined. This article describes how the set of standard audiograms has been developed. This set of standard audiogram has been derived by a vector quantization analysis method on a database of 28,244 audiograms. Using this analysis method, sets of typical audiograms have been obtained of sizes 12 and 60. It turned out that the smaller set could not be used for selecting audiograms as sloping audiograms were absent. Therefore, the larger set has been analyzed to provide seven standard audiograms for flat and moderately sloping hearing loss and three standard audiograms for steep hearing loss.

Keywords

audiogram, hearing aids, standards

Introduction

It has long been known that the existing American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) standards are inappropriate to characterize the advanced features of modern digital hearing aids. The existing measurement standards IEC 60118-0 (IEC, 1983) and ANSI S3.22 (ANSI, 2003) for hearing aids date back several decades and reflect the typical features available in the analog hearing aids of those days. These standards have been updated on several occasions, but this has not taken into account the dramatic increase of processing complexity that has occurred since the introduction of digital signal processing hearing aids in 1996. Many recent hearing aids have a special test program where many valuable features are disabled to establish a test setting in accordance with the classic standards. Such measurements will most often *not* reveal the actual performance of the hearing aid as a user will experience it. Furthermore, the current measurement standards make use of a Reference Test Setting that brings the hearing aid in a prescribed state such that electroacoustic performance and distortion parameters could be measured in a reproducible way. Such Reference Test Settings have in some cases been known to prescribe a combination of device settings and test conditions that yield results that have little relevance for actual hearing aid functioning and that even may be misleading. An example of such a measurement is the AGC (Automatic Gain Control) testing prescribed by ANSI S3.22 (ANSI, 2003). Although this measurement is meaningful for broadband AGC hearing aids, it has no value to expose the characteristics of modern multiband compression hearing aids.

In 2004, the European Hearing Instrument Manufacturers Association (EHIMA) decided to initiate a project on developing new measurement standards for advanced digital hearing aids. The EHIMA Technical Committee was asked to define a project on developing proposals for new measurement standards that would be internationally supported by all important industry stakeholders. Speech amplification was chosen as the first topic for a new measurement procedure and a working group called ISMADHA (International Standards for Measuring Advanced Digital Hearing Aids) was established with participants from all EHIMA member companies.

Modern hearing aids depend on fitting software for adjusting the devices to fit the hearing loss of the user. One of the objectives of the new measurement procedure is that the measurements should portray the performance of the hearing

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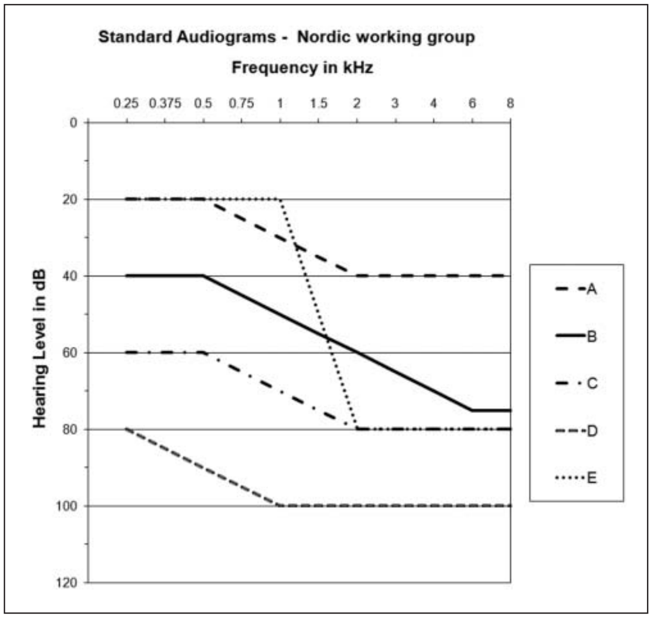

Figure 1. Standard audiograms defined by the Nordic Cooperation on Disability (NSH, 2003): (A) mild sensorineural loss, (B) moderate sensorineural loss, (C) severe sensorineural loss, (D) profound sensorineural loss, and (E) precipitous sensorineural loss

aid as used on an actual user or for specification sheets made by manufacturers as for a typical user. A new measurement standard should therefore be based on programming of the hearing aid with the manufacturers' standard fitting software. The new procedure does not prescribe Reference Test Settings as such. Instead, the device is programmed with the fitting software using the audiogram for a particular user or using a standard audiogram chosen by the manufacturer. The standard programming must be achievable with the standard fitting software and should be as close as possible to the settings normally prescribed. In this way, verification of measurements is facilitated.

Standard Audiograms

The idea of using standard audiograms for hearing aid testing was first suggested by the Nordic Cooperation on Disability (NSH), discussing the possibilities for modernizing hearing aid measurement standards. Initially, a set of five audiograms (see Figure 1) were chosen more or less arbitrarily from general experience with the aim to represent (A) mild sensorineural loss, (B) moderate sensorineural loss, (C) severe sensorineural loss, (D) profound sensorineural loss, and (E) precipitous sensorineural loss (NSH, 2003).

The proposed five standard audiograms were checked against a database of 15,000 audiograms from Stockholm South Hospital. The results were quite surprising and disappointing. Even when allowing one frequency to be outside a ±10 dB band (250 Hz - 6 kHz) around the standard audiograms proposed, only 26% of the 15,000 audiograms could be accounted for by the standard audiograms A to E. These results lead to a discussion on how to develop a set of standard audiograms that would cover the typical range in a better way.

Based on discussion in the ISMADHA working group, it was decided to apply a more statistically based method to produce the desired standard audiograms. The objective was to define a set of audiograms representing typical audiometric configurations for losses ranging from almost normal hearing to profound losses and also including steeply sloping audiograms. A set of audiograms that had a high likelihood of being seen in practice was desirable, but the need to cover the total range of losses was the overriding requirement. After consultations with Arne Leijon (Sound and Image Processing, Royal Institute of Technology [KTH], Sweden), it was decided to apply a vector quantization (VQ) procedure to derive new standard audiograms. Martin Dahlquist was contracted by the ISMADHA project to do the analysis of a suitable large database of audiograms based on the suggestions of Arne Leijon.

Method

This section describes the method that has been applied to generate sets of typical audiograms from which the set of new standard audiograms will be chosen.

Data Source

Pure tone thresholds from 28,244 ears were collected from a database at the Department of Audiology at Stockholm South Hospital. This database includes the 15,000 ears from the initial analysis in the previous section. These thresholds served as input to a VQ method, resulting in a set consisting of a predefined number of "typical audiograms."

Participants

All audiograms from the patients who visited the Department of Audiology at Stockholm South Hospital during the 44-month period from January 1, 2001 to August 31, 2004 were collected. Stockholm South Hospital is one of four major hospitals in metropolitan Stockholm with a referral population of approximately 540,000 from central Stockholm and some of its suburbs. This population consists mainly of ethnic Swedes, but 11% are immigrants.

The audiograms were measured in standard audiometry booths (seven available), in most cases with GN Resound Aurical audiometers. The audiograms were stored in the database of the Auditbase system, and the thresholds were exported to an Excel sheet. The measurement period in this study corresponds to when Auditbase was installed until when the hearing clinic was closed in September 2004 after which the Karolinska University hospital runs this clinic with special criteria for patient selection.

Audiograms from about 19,500 patients were recorded during the 44-month period. As a number of patients were measured multiple times, only the first measurement for each patient was selected. This, together with removing empty and obviously erroneous measurements, reduced the number of measurements to 28,244 ears. Any missing data at singular frequencies were interpolated. For this number of ears, the three-tone average (500 Hz, 1 kHz, 2 kHz) was 40.8 dB (median 41.7 dB) with a standard deviation of 22.2 dB. The average age was 67.5 years (median = 72.9) with a standard deviation of 19.8 years; 54.8% of the patients were female and 45.2% male. The study was approved by the local ethics committee.

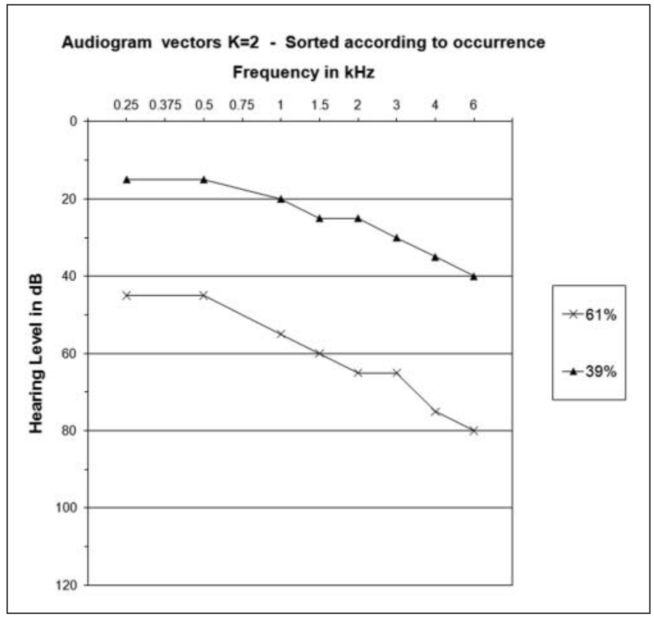

Figure 2. Results of vector quantization of 28,244 audiograms with *K* = 2

Statistical Analysis

"Typical audiograms" were obtained by so-called VQ of the total data set of 28,244 recorded audiograms showing the hearing threshold (in dB HL) at eight audiometric test frequencies 250, 500, 1,000, 1,500, 2,000, 3,000, 4,000, and 6,000 Hz. Each audiogram was stored as a vector containing these eight threshold values.

VQ can be seen as a kind of clustering of vectors. A vector quantizer is defined by a "codebook" containing a set of *K* "code vectors" ($C(1)$, ..., $C(K)$), where *K* denotes the number of desired typical audiograms for a set of typical audiograms. The vector quantizer assigns each input vector to the nearest code vector found in the codebook. The codebook is adapted to a given set of training vectors ($X(1)$, . . ., $X(N)$). In the present application, the training data set contains N = 28,244 eight-dimensional vectors with measured hearing thresholds. The *K* trained eight-dimensional code vectors are presented as the "typical audiograms."

The training is an automatic procedure, often called the "generalized Lloyd" or "LBG" algorithm (Gersho & Gray, 1992; Linde et al., 1980). This algorithm adapts the codebook vectors iteratively to minimize the total sum of distances between training vectors and their corresponding code vectors. As a consequence of this criterion, the distance from a codebook vector to its closest neighboring code vector is usually not uniform. Code vectors tend to be packed more closely together in a region of space where there are many training vectors. In this analysis, the training procedure calculated the Euclidean distance from each measured audiogram to its corresponding "typical" code vector audiogram to which it was allocated, and minimized the sum of these distances for all the measured audiograms. This VQ training algorithm was repeated to find separate codebooks with size K = 2 to 12 and for K = 60.

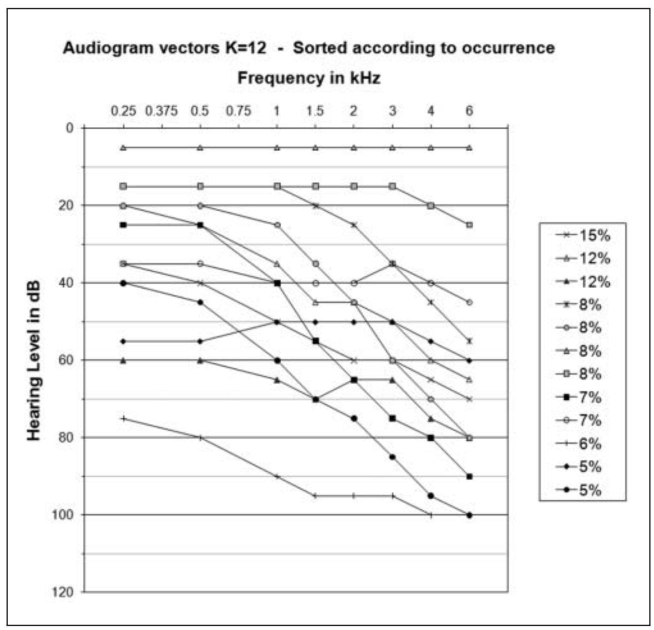

Figure 3. Results of vector quantization of 28,244 audiograms with *K* = 12

Results

In the first round of analysis, values of K = 2 to 12 were applied resulting in sets of "typical audiograms." From this, the sets for K = 2 and K = 12 are shown in Figures 2 and 3, respectively. The percentages indicated at each typical

Table 1. Audiogram Vectors Chosen for the Flat and Moderately Sloping Group

No.	ID	*p* (%)	Rank	HL	Category	250	500	1,000	1,5000	2,000	3,000	4,000	6,000
N_1	A4	1.5	36	10	Very Mild	10	10	10	10	10	20	35	40
N_2	A31	2.6	6	27	Mild	20	20	25	30	35	40	50	50
N_3	A23	3.1	2	42	Moderate	35	35	40	45	50	55	60	70
N_4	A48	2.7	4	58	Moderate/severe	55	55	55	60	65	65	75	80
N_5	A21	2.0	19	75	Severe	65	70	75	80	80	75	80	80
N_6	A22	2.0	16	85	Severe	75	80	85	90	90	95	100	100
N_7	A17	1.5	34	102	Profound	90	95	105	105	105	105	105	105

Note: HL is the average hearing loss for 0.5, 1, and 2 kHz.

Table 2. Proposed Standard Audiograms for the Flat and Moderately Sloping Group

No.	Category	250	375	500	750	1,000	1,500	2,000	3,000	4,000	6,000
N_1	Very mild	10	10	10	10	10	10	15	20	30	40
N_2	Mild	20	20	20	22.5	25	30	35	40	45	50
N_3	Moderate	35	35	35	35	40	45	50	55	60	65
N_4	Moderate/severe	55	55	55	55	55	60	65	70	75	80
N_5	Severe	65	67.5	70	72.5	75	80	80	80	80	80
N_6	Severe	75	77.5	80	82.5	85	90	90	95	100	100
N_7	Profound	90	92.5	95	100	105	105	105	105	105	105

audiogram are the fractions of the total population that is associated with the generated audiogram.

Although many typical audiogram shapes were represented by the vectors of the analysis, no steep sloping losses were found for any of the code sets between 2 and 12. Obviously, the audiograms generated by this method can be seen as a sort of mean value of many audiograms with different shapes. The part of the total population associated with each audiogram vector ranged between 5% and 15% for $K = 12$. This approach still seems to conceal some of the more important audiogram configurations such as the steeply sloping audiograms.

It was then decided to step up the code set value to $K = 60$ so that more different shapes would show up. This resulted in a large set of vectors or audiogram configurations; each only representing a smaller number of the audiograms in the database, but now steeply sloping audiograms could also be identified.

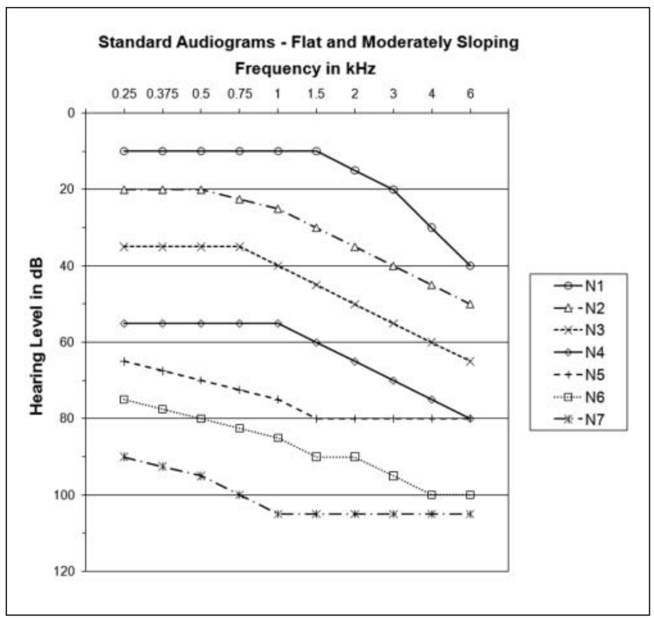

Figure 4. Proposed standard audiograms for the flat and moderately sloping group

Selection of Audiograms

To find audiogram vectors covering the entire range from almost no hearing loss to profound hearing loss, the set was next sorted according to the audiogram value at 250 Hz. The entire data set of the 60 vectors sorted according to this criterion is given in Table A.1 of the appendix. A set of audiogram vectors that represent flat or moderately sloping audiograms was selected based on three main criteria: first, covering the entire range as based on the 250 Hz loss; second, selecting the audiograms with the highest percentage of association; and third, covering all levels of HL as defined by $HL = (HL_{500} + HL_{1k} + HL_{2k})/3$. The selection was limited to seven audiogram configurations ($N_1, \ldots, N_7$) to assure a reasonable differentiation between the configurations. The seven audiogram

Table 3. Audiogram Vectors Chosen for the Steep Sloping Group

No.	ID	*p* (%)	Rank	HL	Category	250	500	1,000	1,500	2,000	3,000	4,000	6,000
S_1	A37	1.3	15	12	Very mild	15	10	10	15	15	30	55	70
S_2	A13	1.2	46	30	Mild	20	15	20	35	55	80	95	95
S_3	A12	1.1	48	57	Moderate/severe	25	35	60	75	75	75	80	85

Note: HL is the average hearing loss for 0.5, 1, and 2 kHz.

Table 4. Proposed Standard Audiograms for the Steep Sloping Group

No.	Category	250	375	500	750	1,000	1,500	2,000	3,000	4,000	6,000
S_1	Very mild	10	10	10	10	10	10	15	30	55	70
S_2	Mild	20	20	20	22.5	25	35	55	75	95	95
S_3	Moderate/severe	30	30	35	47.5	60	70	75	80	80	85

vectors chosen are given in Table 1. To make the audiograms more "standard-like," a few values were edited slightly to straighten out the curves. The audiogram frequencies of 0.375 and 0.75 kHz were added by interpolation. The audiograms chosen were classified according to the degree of hearing loss (Goodman, 1965). The resulting set of proposed standard audiograms is given in Table 2 and in Figure 4.

To identify steeply sloping losses, the maximum difference between the values at 6,000 Hz and 250 or 500 Hz were calculated. If one of the two differences exceeded 60 dB, the audiogram was defined as steeply sloping. From Table A.1, it can be seen that sloping loss audiograms have a low percentage of association. From the 10 steep sloping audiograms that were identified, the best association rate is 1.8% and the total is only 12.3%. For selecting steep audiograms, it makes no sense to sort according to the loss at 250 Hz. Instead, the audiograms were sorted according to the roll-off frequency as defined by the frequency where the loss has dropped by 30 dB relative to the loss at 250 or 500 Hz. The selection was then made from the audiogram configurations with roll-off frequencies close to 1 kHz, 2 kHz, and 3 kHz and that had the highest percentage of association. Note that the obvious candidate for S_2 (A10) has been skipped as that would resemble close to S_3 (A12); the next candidate for S_2 appeared to be A13. The three chosen audiogram vectors are shown in Table 3. To make the audiograms more "standard-like," a few values were edited slightly to straighten out the curves. The resulting set of standard steeply sloping audiograms is given in Table 4 and in Figure 5.

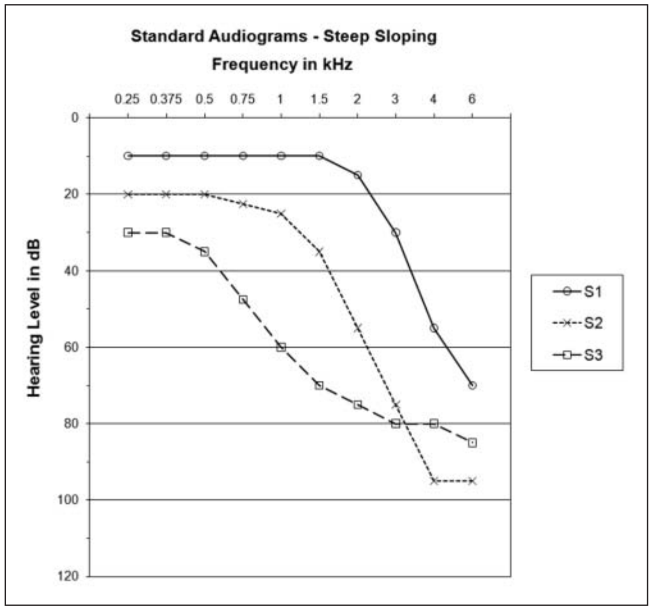

Figure 5. Proposed standard audiograms for the steep sloping group

Discussion

A total of 10 standard audiograms have been proposed for standardization. Although not all chosen audiogram configurations occur with high frequency in the data material, they do cover the entire range from almost normal hearing to profound hearing loss. The three sloping losses are the steepest that could be found among the 60 vectors used in the analysis. Using more vectors may produce even steeper losses, but each vector will then only represent an even smaller subset.

The proposed set of 10 standard audiograms were analyzed using the same procedure as described above in the section "Standard Audiograms" to compare with the set proposed by the Nordic Cooperation on Disability of Figure 1. The results are shown in Table 5.

Allowing for one frequency outside the ±10 dB band around each standard audiogram 46% of the audiograms in the database could be covered. This is an improvement over the 26% for the earlier proposal based on five audiograms.

Table 5. Percentage of Audiograms in Database Being Within a Specified Range Around the Standard Audiograms

Audiogram	All in Range (%)	Max. 1 Outlier (%)
N_1	1.6	4.7
N_2	2.9	7.1
N_3	6.6	15.1
N_4	4.2	9.7
N_5	1.2	3.3
N_6	0.8	1.9
N_7	0.6	1.2
S_1	0.5	1.9
S_2	0.3	1.2
S_3	0.8	3.1
Sum	19.5	49.2
Sum – overlap	19.5	46.0

The proposed set of audiograms are intended to be used for hearing aid measurements in which the effect of fitting the hearing aid or the use of certain features must be demonstrated in an objective way, for instance, for data and application sheets on hearing aids, on hearing aid features, and on fitting methods. For this purpose, one of the audiograms that is typical for the intended use and within the recommended fitting range of that hearing aid should be selected. By providing a range of seven flat and moderately sloping audiograms in all categories of hearing loss and three steeply sloping audiograms, it is expected that a choice can be made in the middle of the application range of a hearing aid, with one or two alternatives more close to the limits of that range. For instance, a hearing aid with modest amplification (e.g., open fit aids) may select audiogram N_2 with alternatives N_1 and N_3; when having a standard hearing aid audiograms N_4 with alternatives N_3 and N_5 may be chosen and for a power hearing aid, audiograms N_6 with alternatives N_5 and N_7 should be chosen. On top of that one sloping audiogram could be added. By restricting the number of selectable audiograms for a hearing aid type, it will be avoided that an audiogram is taken that has been "optimized" to favor the measurement results, for instance, in data and application sheets.

These audiograms are now part of the proposal for the new IEC 60118-15 (IEC, 2009) measurement standard. In this new standard, one of the standard audiograms can be used to program the hearing aid before the actual testing takes place. In cases where the standard audiograms are not appropriate, it is allowed to define another audiogram if that is deemed necessary by the specific application of the hearing aid and when stated in the measurement report.

Appendix

Table A.1 presents the audiogram vectors for the analysis at $K = 60$ for the entire database of 28,244 audiograms. In this table, the vectors are sorted to the loss of 250 Hz. The candidate sloping audiograms are indicated with their cutoff frequency. The selected audiograms for the flat and moderately sloping audiograms are indicated by $N_1, \ldots, N_7$. The selected audiograms for the selected steeply sloping audiograms are indicated by S_1, S_2, and S_3.

Table A.1. Typical Audiogram Vectors Sorted According to the Loss at 250 Hz for the $K = 60$ Analysis

Order No.	Audiogram ID	250	500	1,000	1,500	2,000	3,000	4,000	6,000	*p* (%)	Steep Sloping	Roll-off (kHz)	Selected
1	A40	0	0	0	0	0	0	0	0	3.3	—		
2	A45	5	5	5	10	5	5	10	5	1.6	—		
3	A46	10	5	5	5	0	5	5	15	1.5	—		
4	A44	10	10	10	15	15	15	20	20	2.0	—		
5	A4	10	10	10	10	10	20	35	40	1.5	—		N_1
6	A41	10	10	10	10	10	10	20	45	1.0	—		
7	A5	10	10	15	20	25	30	40	50	1.7	—		
8	A38	10	10	20	35	50	65	75	85	1.1	Yes	1.7	
9	A32	10	10	25	35	45	50	55	60	1.9	—		
10	A3	10	15	20	30	30	30	35	30	1.2	—		
11	A33	15	10	10	20	30	55	65	65	2.0	—		
12	A37	15	10	10	15	15	30	55	70	1.3	Yes	3.2	S_1
13	A42	15	15	10	10	10	5	10	15	2.0	—		

(continued)

Table A.1. (continued)

Order No.	Audiogram ID	250	500	1,000	1,500	2,000	3,000	4,000	6,000	*p* (%)	Steep Sloping	Roll-off (kHz)	Selected
14	A31	15	20	35	50	55	60	65	65	2.6	—		
15	A15	15	20	35	60	70	80	90	95	1.1	Yes	1.2	
16	A36	20	15	20	35	55	60	65	60	1.0	—		
17	A13	20	15	20	35	55	80	95	95	0.7	Yes	1.9	S_2
18	A43	20	20	20	20	20	15	20	20	1.8	—		
19	A1	20	20	25	30	35	40	50	50	2.7	—		N_2
20	A27	20	20	25	35	40	55	65	75	2.3	—		
21	A14	20	20	30	50	65	70	75	80	1.5	Yes	1.5	
22	A25	20	25	35	45	45	50	60	75	2.2	—		
23	A28	20	30	40	45	45	45	50	60	2.4	—		
24	A7	20	30	45	50	45	35	30	25	0.8	—		
25	A8	25	25	25	25	25	25	30	40	1.2	—		
26	A12	25	35	60	75	75	75	80	85	1.2	Yes	0.9	S_3
27	A30	30	25	25	35	45	65	80	90	1.0	Yes	2.8	
28	A24	30	30	40	50	50	60	70	75	2.5	—		
29	A26	30	35	40	50	55	65	75	90	1.8	Yes	2.5	
30	A9	30	35	45	60	65	65	75	75	2.8	—		
31	A34	30	35	45	55	55	50	55	55	2.2	—		
32	A11	30	35	60	80	90	100	105	105	0.9	Yes	1.0	
33	A50	30	45	60	65	65	60	65	65	1.8	—		
34	A39	35	30	25	30	30	40	50	65	1.7	—		
35	A2	35	35	35	35	35	35	35	40	1.3	—		
36	A23	35	35	40	45	50	55	60	70	3.1	—		N_3
37	A10	35	35	45	60	65	80	95	100	1.7	Yes	2.0	
38	A35	35	40	40	40	40	40	45	55	1.8	—		
39	A6	40	40	40	35	25	20	20	25	0.9	—		
40	A48	40	45	50	55	55	55	60	70	2.7	—		
41	A59	40	45	50	60	60	60	70	85	1.9	—		
42	A51	40	55	65	70	70	70	80	95	0.9			
43	A29	45	45	40	40	40	50	65	75	1.3	—		
44	A53	45	50	60	70	70	75	80	80	1.6	—		
45	A49	50	45	50	60	60	60	70	70	2.0	—		
46	A57	50	55	60	60	55	50	55	65	1.5	—		
47	A60	55	50	45	50	50	50	60	60	1.2	—		
48	A56	55	50	50	50	50	60	75	85	1.1	—		
49	A52	55	55	55	60	65	65	75	80	2.0	—		N_4
50	A54	55	55	55	50	45	40	40	45	1.1	—		
51	A47	55	55	60	65	70	70	75	95	1.4	—		
52	A19	55	60	65	75	80	90	100	105	1.7	—		
53	A18	55	65	90	105	105	110	110	110	0.8			
54	A16	60	55	55	60	65	80	90	95	1.1	—		
55	A55	60	65	65	65	65	60	65	70	2.5	—		
56	A21	65	70	75	80	80	75	80	80	2.0	—		N_5
57	A22	75	80	85	90	90	95	100	100	2.0	—		N_6
58	A58	80	75	70	70	65	65	70	75	1.2	—		
59	A20	80	80	75	75	75	75	85	95	1.4	—		
60	A17	90	95	105	105	105	105	105	105	1.5	—		N_7

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