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An individual fitting algorithm for digital hearing aids by the modified critical bands and loudness scaling

Jeong-Guon Ih (1) and Kyung-Hoon Park (2)

(1) Centre for Noise and Vibration Control, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea
(2) Agency for Defence and Development, Jinhae, Korea

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ABSTRACT

It is very important to apply the individual fitting algorithm for the hearing aids to the hearing impaired patient. This is in particular true for equipping the modern sophisticated digital hearing aids. Existing threshold-based fitting methods adopting a pure tone stimulus yield the same target gains when individual hearing thresholds are identical. Consequently, the loudness perception of an individual does not precisely reflected into the fitting data sometimes, thus a tedious re-fitting adjustment procedure should be done after an initial fitting. Other loudness-based fitting methods, employing fractional octave-band tone stimulus, often result in excessive gains at low frequencies and too many measurements for loudness level setting. In this study, as an attempt to alleviate the aforementioned problems, a new psychoacoustic fitting method is suggested. Subjects with normal hearing are tested and the loudness perception to a certain level of band-limited white noise at the modified 14 critical bands is classified by five categories. In this way, a standard database as the target fitting value is constructed by processing the test results in the statistical manner. A hearing impaired patient is subject to the same test procedure and the perceptual response data are used for estimating the individual hearing characteristics. Measured hearing loss data are compared with the database of standard normal hearing and, then, the target gains for five loudness categories are obtained for compensation. Comparisons were made between proposed and existing fitting methods for some patients. The results revealed that many patients felt better auditory performance after wearing hearing aids fitted by the present method than the existing algorithms even after the empirical re-adjustment.

INTRODUCTION

Individual target-gain setting is utmost important to make a maximum use of up-to-date digital hearing aids (HA) capability. The expected result of such hearing compensation as a function of frequency for a patient is clear speech communication, good sound quality, comfortable hearing, and natural audible environment. Existing HA fitting algorithms can be abruptly classified into two types: threshold-based methods and loudness normalization methods.

The threshold-based fitting methods adopt the half-gain rule [1], which states that the hearing impaired person would feel most comfortable when a gain corresponding to about half of his/her threshold level is given for amplification. The methods such as POGO2 [2], NAL [3] or Fig6 [4], adopting pure tone stimuli, can calculate the target gain quickly and are beneficial to the infants or very old peoples due to the fact that they do not need individual subjective test. However, these methods yield the same target gains when individual hearing thresholds are identical. Consequently, the loudness perception of an individual shall not be precisely reflected into the fitting data, thus a tedious re-fitting adjustment procedure should be followed by an initial fitting. The other group of fitting methods based on the loudness feeling includes LGOB [5] or ScalAdapt [6] algorithms. These methods set the HA gains calculated from the normalized loudness for the given sound level and frequency, that can generate the same loudness response as the normal hearing. They employ fractional octave-band tone stimuli like octave or 1/3-octave band tones with rather fine loudness scales. These fitting methods are useful because an individual fitting to the patient is directly possible by considering both threshold value and loudness response by the subjective test. However, they often result in excessive gains at low frequencies and too many subjective measurements for loudness level setting.

In this study, as an attempt to reduce the severity of the aforementioned problems, a new modified psychoacoustic fitting method is suggested. Subjects with normal hearing are tested and the loudness perception to a certain level of band-limited white noise at the modified 14 critical bands is classified by five categories. In this way, a standard database as the target fitting value is constructed by statistically processing the test results for normal hearing. The same procedure as the testing for normal hearing is applied to the impaired individual to obtain the target gain. Loudness normalization is conducted to obtain the gain by comparing the loudness sensation of normal hearing with that of a person with hearing loss.

CONSTRUCTION OF PSYCHO-ACOUSTICAL FITTING ALGORITHM (PAFA)

Preparation of stimulus sound signals

Usually, sound signals like pure tone, octave or 1/3-octave band tones have been used for the audiological test. However, the human auditory system relies on the critical bands (CBs) for analyzing the wide band sounds [7], which are related to the continuous speech, music, and the other sounds from the living environment. The spectra of these wide band sounds which are meaningful in a life can be described by the CBs for the recognition and perception. From this reason and also due to the necessity in measuring the loudness for psychoacoustical reason, the fitting algorithm in this study utilizes the CBs directly rather than using the proportional bands.

The present PAFA method starts from the selection and modification of critical bands of human auditory system in the frequency range of 0.l-9.5 kHz, which encompasses nearly all important spectral components of sounds in relation to the voice, speech, music, and the other sound signals from human activities. There are total 21 CBs within this frequency range. Among them, the CBs substantially related to the speech articulation are not changed, but the CBs influential to the speech intelligibility in a non-critical way are merged into wider bands than the original CBs: the number of bands is now reduced to 14 as shown in Table 1. It is known that about 70% of speech clarity is involved with the frequency range of 0.5-2 kHz and 25% at 2-8 kHz range [8].

Table 1. Modified critical bands: frequency ranges, center frequencies, thresholds, and uncomfortable levels (UCL)

Band No.	Freq. range (Hz)	Center freq. (Hz)	Threshold (dB)	UCL (dB)
1	100-200	150	18.0	105.0
2	200-510	350	8.5	95.0
3	510-630	570	3.5	94.0
4	630-770	700	1.5	93.0
5	770-920	840	1.0	92.0
6	920-1080	1000	0.5	90.0
7	1080-1270	1170	0.0	89.5
8	1270-1480	1370	-0.5	89.0
9	1480-1720	1600	-1.0	89.0
10	1720-2000	1850	-1.0	88.5
11	2000-2700	2350	-3.0	88.0
12	2700-3700	3200	-4.5	88.5
13	3700-5300	4500	-4.0	89.0
14	5300-9500	7400	0.5	92.0

Loudness assessment for normal hearing people

Audiometric test was done in a very quiet room using the head set (Sennheiser HD 25), to which the sound signal was provided by the notebook computer equipped with a sound card (U24) through the headphone monitor (Theaterphone HSM 6240). Initial calibration of the sound signal was conducted with a dummy head (Head Acoustics HMS 3). The white noise was generated with a 44.1 kHz in sampling rate having 16-bit resolution by a commercial code (Cool Edit Pro 2.0). Then, a bank of band pass filter (Chebychev I) was applied to the signal to make 14 band tones as listed in Table 1. These CB band tones were given to the subjects for a second.

Subjects with normal hearing were chosen based on ISO 389. In the previous studies [5,6,9-11], about 10-20 subjects with normal hearing were involved in the hearing test to obtain the average data of the loudness perception. In this study, 43 Korean subjects, comprised of 23 males and 20 females who are all in twenty some years old, were employed in the test to reduce the data deviations.

The purpose of the subjective test was to determine the extent of sound magnitude of each modified CB, which corresponds to a loudness perception class among 5 categories: ‘very soft,’ ‘soft,’ ‘comfortable,’ ‘loud,’ ‘very loud.’ To avoid any confusion in the concept of the loudness perception category, the information on the standard perception for each category was clearly instructed to the subjects. Loudness magnitude corresponding to the ‘very soft’ perception category is a very low sound level barely exceeding the hearing threshold, but one can somehow identify the character of sound. ‘Soft’ perception category is defined as a low sound level that needs a small amount of amplification to be felt as comfortable. ‘Comfortable’ category is associated with the natural, pleasant, and comfortable auditory feeling to the sound from TV, radio, or other A/V players. ‘Loud’ feeling will be felt for a group of sound levels that interferes the speech communication, so a proper amount of sound level reduction is required. ‘Very loud’ category includes the high sound levels that are perceived very uncomfortable, which is felt like a shouting sound, although one can still endure it for a short time.

The test screen given to the subjects is shown in Figure 1. At each modified CB, the subject could position the slide bar to adjust the sound level corresponding to each loudness perception class among 5 categories. The modified CB was given in a random order to avoid similar response for the adjacent bands. Also, to each modified CB sound, the amplitude range for varying the position of the slide bar was set differently for all categories, so a monotonically increasing pattern from ‘very soft’ to ‘very loud’ was avoided. The other aspect which should be considered seriously was the test order of loudness perception. Finishing the measurement for a modified CB and moving to the next CB, if the last test was for the ‘very loud’ feeling in the former CB and the next test was for the ‘very soft’ feeling in the new CB, underestimation of sound level, i.e., selection of high level of sound, could be caused by the masking effect of the former ‘very loud’ sound. To refrain from such an unreliable condition, increasing and decreasing stimulus patterns were alternated in the experiment. The purpose and the test method were well instructed to the subjects before the measurement.

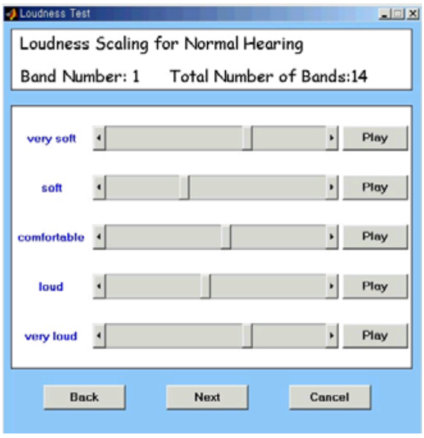


Figure 1. Test screen for the loudness assessment for normal hearing people

The total number of sounds to be tested by a subject was 70, which needed about 45 minutes on average. During 45 minutes, 20 minutes were used for the training before the assessment and about 25 minutes were spent for the main test. To avoid tiredness and subsequent loss of concentration of the subject, occasional stoppage of the test were allowed, in particular, at least 10 s were forced to stop the test after exposed to a loud level.

Loudness classification for normal hearing

The scaled data collected from 43 subjects with normal hearing were used for the loudness classification for normal hearing, which will be used for the comparison standard. Mean and 95% confidence interval (CI) were calculated employing the t-test; z-test could not be used because any prior experimental result did not exist. Meaningful result from the t-test can be obtained when the number of samples is greater than about 30 or the distribution of samples represents the normal distribution [12]. Our subjective test results fitted to both conditions for the effective t-test. Also, one can find that the statistical theory of requiring squared number of samples (n^2) for testing n cells holds for our study; in our case, n=5 and n^2=25, from which the number of subjects, 43, is enough for the confidence of the test.

For each loudness perception category, the test data were statistically treated for 14 CBs according to the sex of the subjects with normal hearing. Calculated statistical data were: standard deviation (SD); lower 95% CI level (CIL); upper 95% CI level (CIU); lower quartile (P25); upper quartile (P75); minimum value (Min); maximum value (Max). Then, the combined data for both sexes were also statistically processed in the same way. The result revealed that an average person with normal hearing feels the 'very soft' loudness at 24.9 dB in sound pressure level (SPL), 'soft' sensation at 44.2 dB, 'comfortable' at 62.5 dB, 'loud' at 76.9 dB, and 'very loud' at 84.3 dB. In the viewpoint of 95% CI, 'loud' sensation got a minimum value of 3.2 dB, 'soft' a maximum value of 4.7 dB, and the other loudness sensations had similar magnitudes in between these deviations. Although the uncertainty in perceiving the loudness, that invokes inconsistent evaluation of the test subjects due to unclear definition of the perception, is the largest for 'soft' sound category, maximum deviation of 4.7 dB at this category is still smaller than 5 dB that is the just noticeable level difference (JNLD) of the impaired hearing. The results showed that there was no significant difference in the responses between male and female, which is a convenient feature in the HA fitting.

The psychophysical responses of all 43 subjects on the loudness perception category as a function of CB were plotted as data scattergrams and Figure 2 shows two such graphs for 'soft' and 'comfortable' sensations as examples. Compared to the 'comfortable' loudness sensation, the category 'soft' contains a lot of outliers. Figure 3 depicts an example of the CB response being felt as 'loud' sensation of 43 subjects with normal hearing to the given SPL stimuli. In this figure, the interquartile ranges show the data span of 50% of the subject responses and the 95% CI of the mean value after the t-test. One can observe that the 95% CI corresponds to about 5 dB range regardless of the sensation category. All results are summarized in Figure 4, which illustrates the equal sensation contours as a function of CB for the average people with normal hearing. In this figure, one can observe that the loudness sensation decreases at the very high frequency band, while for small loudness sensation, like 'very soft' and 'soft' categories, the low frequency sound levels are high similar to the equal loudness contour in ISO226, which is based on the pure tone stimulus [13]. It seems that loudness sensations are most sensitive at 1.85-3.2 kHz bands (CB=10-12 Bark). The shaded zones indicate the 95% CI range, which provides useful tolerance for the actual HA fitting practice.

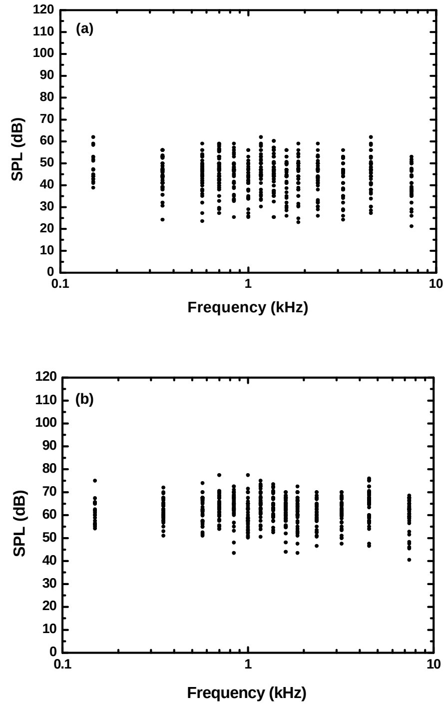


Figure 2. Scattering of the sensation SPL of 43 subjects with normal hearing for the given loudness sensation category and the CB: (a) 'soft' feeling, (b) 'comfortable' feeling

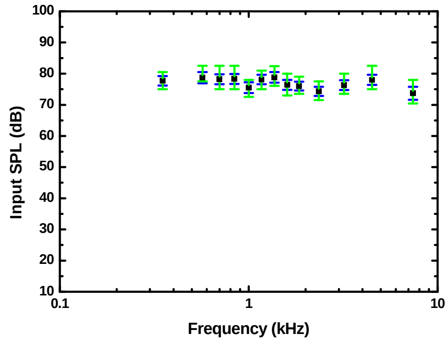


Figure 3. CB response being felt as 'loud' sensation of 43 subjects with normal hearing to the given SPL stimuli: ■, mean value; I, interquartile range for the raw data; I, 95% CI for the mean

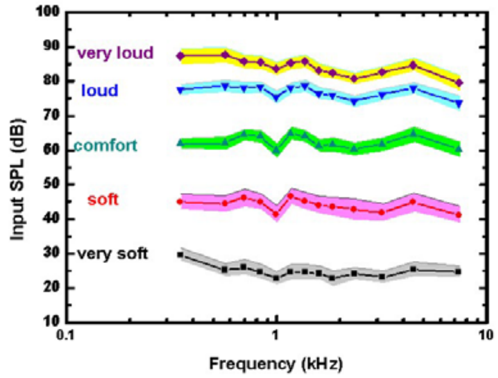


Figure 4. Equal sensation contours as a function of CB for the average people with normal hearing. Shaded areas indicate the 95% CI ranges for loudness sensation categories

Loudness assessment of hearing impaired people

More concern and care in the audiometric test are needed for the hearing impaired patients than the normal hearing people. After familiarizing with the subject personally, a full instruction to the test purpose and procedure was given and the subjects were trained to enhance the data reliability. False positive response of the subject to hide his/her hearing loss to a smaller level could be avoided by informing the purpose of the test to treat him/her in an appropriate manner. False negative response of the subject to overstate his/her level of hearing loss could be avoided by explaining the real purpose of the test to make him/her positive to the test.

The responses of the subject to the banded sounds, which were used for identifying the loudness response of the people with normal hearing, were obtained in this test. The purpose of loudness assessment for a subject with hearing loss was to compare his/her response with the average response reference of the normal hearing people. Then, the necessary gain for each CB was attained individually. One can recall that the fitting algorithms based on the loudness threshold yield the approximated gain from the statistical processing of the clinical results over the hearing impaired persons. However, the present method enables an individual fitting of the hearing impaired person with reference to the average loudness perception of the normal hearing people, so the fitting effort based on the classification of the hearing loss types is never required.

In testing for the hearing impaired person, uncomfortable level (UCL) spectra were not measured because the UCL of the hearing impaired patient is often higher than the normal hearing people and one cannot usually reach UCL due to the limited maximum sound level reproduced being around 120 dB. However, the hearing threshold spectra were measured for the same modified 14 CBs as used for the normal hearing people. First, the band tone of 1 s duration at the 5th modified CB, centred at 1 kHz with the bandwidth of 160 Hz, was selected for the test and, then, higher CBs were tested in the ascending order followed by the descending order test from the 5th CB again. Except the case of a severe hearing loss at a specific band due to very long time exposure to the excessive noise at that band, the amount of hearing losses of two adjacent CBs would not be very different from each other. Therefore, for a quick finding of the threshold level of a CB, the tracking method starting from the threshold level at the reference band, which was adjacent to the CB of concern, was employed. The hearing threshold data of the hearing impaired person were used as the boundary value of the 'very soft' sensation category in the loudness perception test for the hearing impaired person. The same test method to obtain the loudness perception values for the normal hearing people was conducted for the testing of the hearing impaired person.

Target gain setting in the PAFA method

Figure 5 shows the clinical test result of a 62-year old lady, who has an experience of wearing the HA. When the different hearing loss characteristics exist at two ears, each ear should be tested for a time by using the two-channel controller of the headphone monitor. However, this subject possessed similar hearing thresholds for both ears, so the same signal was given to both ears simultaneously for the loudness perception test. One can observe the equal loudness sensation contours in Figure 5(a). Level difference between normal hearing and impaired hearing for a CB results the target gains to be provided to the hearing impaired person to feel the same loudness sensation among five categories of loudness perception, which can be found in Figure 5(b). If the sensation level of the hearing impaired person is larger than that of the normal hearing people, the target gain is just the difference between two levels; however, in the reverse situation, there is no need to provide any gain to the hearing impaired person. The latter condition happens due to the recruitment phenomenon, such that the hearing impaired person responds to the large magnitude sound stimulus in a similar perception as the normal hearing person feels, but, for the small magnitude sound, the patient exhibits a large hearing loss.

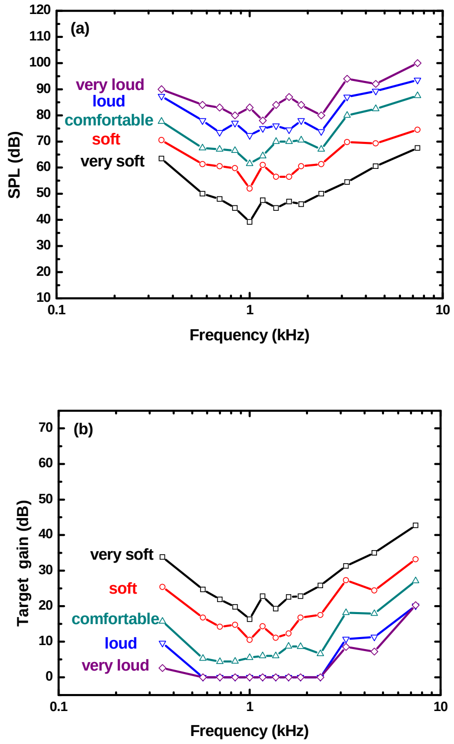


Figure 5. Clinical data of a hearing impaired person. (a) Equal loudness sensation contours, (b) resultant target gains for the five-class loudness perception category: —□—, very soft; —○—, soft; —△—, comfortable; —▽—, loud; —◇—, very loud.

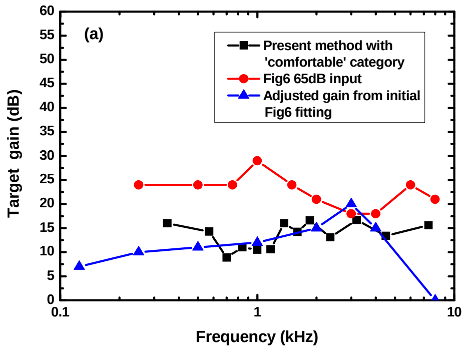
PRACTICE EXAMPLES

To compare the performance of the present fitting method, i.e., PAFA method, with the existing popular method, viz., Fig6 method [4], a clinical test was conducted for 10 hearing impaired patients. All subjects wore HA and the average age of them, 7 males and 3 females in 72-88 years old, was 75.8. Subjects have worn the HAs for 8.6 hours per day and they had been wearing the HAs at least for 1 year and 4 months. The subject wore one of three types of HA, i.e., ITE, ICE, and CIC types [14], for whom the Fig6 method was adopted for the initial fitting.

Even though the patient's HA is fitted with Fig6 method, the gain values are not sometimes satisfactory because the stimuli are conveniently the pure tones that produce, in general, larger hearing loss estimation compared to the banded stimuli, in particular below 2 kHz. This means that the target gain for the fitting of HA by Fig6 is excessive than is needed actually. From this reason, the patient can complain about the discomfort if the laborious re-adjustment of the fitting for each frequency is not followed after initial fitting. The reason of such overestimation of the target gain is also due to the fact that the threshold data of the patient is obtained from the statistical average of the thresholds of the patients having similar amount of hearing loss. If the spectral pattern of the hearing loss of the patient is not too different from this average threshold, there is little problem; however, if not, a serious problem happens. Consequently, the current practice of the fitting is that, after initial gain setting by Fig6 method, the gain is reduced by 5-10 dB, depending on the experience of the practitioner, and then refitting is carried out to satisfy the customer. This is usually a tedious task and both the audiologist and the patient would feel cumbersome. Figure 6(a) shows the comparison of three fitting results to a patient by using the 65 dB input stimuli, either pure tone or band tone depending on the fitting method. In the range of 500-4000 Hz, one can find that the gain obtained by interactively adjusting the initial gain by applying the Fig6 method is similar with that obtained by the application of the present PAFA method. The result from the present method corresponds to the 'comfortable' loudness sensation category, which corresponds to the average loudness magnitude in speech communication.

Another fitting example for a different patient is shown in Figure 6(b). In this case, the audiometric test for the hearing loss revealed that the spectral loss amounts are similar for both pure tone and band tone excitations. However, as can be seen in Figure 6(b), the initial gain obtained by the Fig6 method is very different from that by the present PAFA method except for 1-4 kHz range. The patient complained that the HA generated howling, which was actually due to the excessive gain in the low frequency range by about 7 dB below 1 kHz. After fitting with the present method, all the patients who had the same problem were satisfied with the sound.

The degree of satisfaction with the PAFA method was also tested by using the COSI (client oriented scale of improvement) questionnaires. The result showed that the fitting by the present method was felt well in conversation in quiet places than that of empirically re-adjusted Fig6 method.



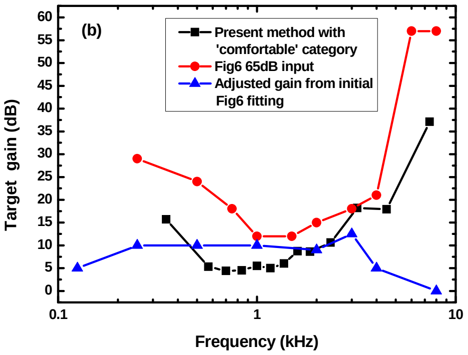


Figure 6. Audiometric target gains for patients obtained by 65 dB input using three fitting methods: original Fig6 method, adjusted Fig6 fitting value to patient response, present PAFA method tuned at 'comfortable' sensation category.

CONCLUSIONS

In this paper, a new psychoacoustical fitting method for the hearing aids is proposed. To this end, first, the modified 14 critical band tones were fed to 43 subjects with normal hearing and five classes of loudness sensation category were employed in the assessment. The results were statistically processed to be used as the reference data for the prescription of target gains for the hearing impaired patients. The same procedure was applied to the impaired individual to obtain the target gain. Loudness normalization process was practiced by comparing the loudness sensation of average normal hearing with that of a hearing impaired person. The proposed PAFA fitting method was compared with the existing Fig6 method practicing to the impaired individual that had the dissatisfaction. It was clearly observed that the present PAFA method yielded a better matched gain to the hearing sensitivity than Fig6 method and the method reduced dissatisfaction profoundly compared to the Fig6 algorithm. Test results reveal that the proposed PAFA method can be directly used in the digital fitting of hearing aids, of which the auditory performance is at least equal to or slightly better than the empirically re-adjusted Fig6 fitting using the tedious trial-and-error method.

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