# Adaptive Expert System for Digital Hearing Aids Gain recommendations using Linear and Non Linear Prescriptive Procedures

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*Abstract:* The core object of the work is to design and develop an adaptive expert system, which could perform audiological investigations of hearing impaired subjects, to identify the hearing loss level and to recommend the most appropriate gain values for different frequency bands of a digital hearing aid. We have tested 353 subjects in the age group of 18 to 72; of these, 289 were males and 64 were females and a hearing aid was recommended for 159 subjects. These subjects were fitted with a digital hearing aid, with a first fit formula selected based on the audiogram of the subject, from any one of the standard linear and non linear prescriptive procedures. The standard procedures are formulas from the National Acoustic Laboratory (NAL), Prescription Of Gain Output (POGO), and the Desired Sensation Level (DSL). The recommendations were verified for satisfaction among the hearing aid users with the value of the Speech Discrimination Score (SDS); only 28 were satisfied with NAL-R, 25 were satisfied with POGO II, 23 were satisfied with NAL-NL2 and 12 were satisfied with DSL I/O. The unsatisfied subjects obtained satisfaction, by changing the gain value with the expertise of audiologists, stored in the expert system. Based on the suggested gain values and additional data from the expert audiologists, the gain formula could be made distinct for different language and living conditions.

*Key-words:* Expert system, Speech intelligibility, Hearing threshold, Real ear insertion gain, Hearing aids, Speech discrimination score, Pure tone average

## 1 Introduction

Human hearing may deteriorate because of different reasons [1]. Hearing impairment can be solved easily by fixing a hearing aid, because it is a non invasive procedure. The objective of the computer based audiological investigations, is to perform them in an efficient manner in arriving at the hearing sensitivity of individuals [2]. To provide better satisfaction among the hearing aid users, the gain recommendations are made by the expert system. At first, the knowledge domain consisting of the expert's opinion and diagnostic methods was created. Provision is made to update the knowledge data base as and when required, thus making the system adaptive. The expert system effectively carries the expert's knowledge to the required people. In the case of hearing aid usage, the gain prescription is a mapping or a formula that uses an individual's characteristics in amplification settings. The individual characteristics are usually the hearing threshold, Most Comfortable Level (MCL), Uncomfortable Level (UCL), and loudness contour data being used for the prescription of gain. Initially, it was possible to program a hearing aid with the purpose of normalizing the loudness over a wide range of levels, so that the hearing aid user will perceive the same loudness as a normal hearing person. Another important consideration during the prescription of gain is to maximize speech intelligibility. After the hearing aid has been programmed with the initial recommended gain, fine tuning according to the requirements of the user is usually done. It is desirable to minimize the need for fine tuning because it requires considerable effort from the user as well as from the audiologists. Therefore, it is important that the prescribed gain is as close to the optimal gain of the patient as possible.

The digital hearing aid of modern days uses different frequency bands in an audible range of sound. REIG is the additional gain required with the hearing aid usage, to get a clear perception of sound by the hearing impaired patients. The Integrated Real ear measurement improves the accuracy of fitting initially, and subsequently, when the hearing aid is fine tuned to achieve better speech intelligibility to the patient [3, 4]. Most of the hearing aid users are comfortable with lesser gain than what is actually prescribed for them. Gerling states that "prescribing the same gain for all individuals, simply because they have the same hearing thresholds, will result in inaccuracies of too little as well as too much gain"[5]. Over the past several years many prescriptive fitting formulas have been developed and tested to fit hearing aids. Prescriptive formulas have been developed for linear instruments and also for Wide Dynamic Range Compression (WDRC) hearing aids. The National Acoustics Laboratory of Australia developed the NAL-R formula for hearing aid models with linear circuits [6]. With the development of non linear hearing aids, a suitable prescriptive procedure was needed to provide multiple gain curves for different input levels. Depending on the patient's practical feedback and preference, the final gain settings will vary from these initial settings. With an increase in the number of prescriptive formulae, the quality of service can be defined as the extent to which a particular fitting procedure will give satisfaction to the hearing aid users. The prescriptive procedure NAL-R, is the extensively tested and validated prescriptive procedure for linear amplification because of its successful recommendations [7-9]. Prescriptive procedures NAL-R and POGO II were developed in 1986 and 1988 respectively to get greater accuracy with the linear instruments [10].

The increased use of conventional and programmable nonlinear hearing aid circuits requires new prescriptive methodologies to consider nonlinearity in hearing aids. They further assist clinicians in their ability to fit these products easily and accurately. Further formulae created, using these approaches are the DSL I/O [11], IHAFF [12, 13], FIG6 [14-17], NAL-NL1 [18] and NAL-NL2 [19]. The advantages and limitations of the various prescriptive fitting approaches can be obtained from different sources [20]. Analyzing all the parameters and standards used in the prescriptive procedures, the present work considers an appropriate procedure for the specific hearing impairment. The speech discrimination score is obtained by the speech audiometric test, after incorporating the suitable prescriptive procedure suggestions in the digital hearing aid. The procedure which gives the best score will be considered an appropriate procedure for that type of hearing loss. An expert system has a unique structure that emulates the decision making ability of a human expert, i.e., the audiologist. It has an interference engine inbuilt, designed to produce a decision by logical reasoning, based on certain rules given in the knowledge base. The knowledge base is framed with a set of IF and THEN rules, formed by experimenting with different type of hearing impaired subjects [21].

## 2 Material & Methods

### 2.1 NAL - R formula.

Byrne and Tonnisson [6] formulated the NAL formula, and later it was revised by Byrne and Dillion [7] in an attempt to prescribe a frequency response that gives a clear understanding of speech, even if the hearing aid user adjusted the volume control level to his/her satisfaction. It is customary to provide too little low frequency gain, relative to the mid and high frequency gain. To overcome this difficulty and add more benefits and applications to the NAL procedure, Byrne and Dillion proposed a revised version, the NAL-R. The specific NAL-R formula for the calculation of real-ear insertion gain (REIG) is presented in table 1.

Table 1: NAL - R formula for Real Ear Insertion Gain

| Frequencies in Hz | Formula |
|---|---|
| 250,500,1K,1.5K,2k,3k, 4k,6k | 0.15*PTA + 0.31* Hearing threshold at a particular frequency + conversion factor = Required REIG in dB |

Pure Tone Average (PTA) is the average of the hearing threshold measured at frequencies of 500Hz, 1 kHz and 2 kHz. The conversion factors are -17,-8, -3,+1,+1,-1,-2,-2 for the frequencies of 250Hz, 500Hz,1kHz,1.5kHz, 2kHz, 3kHz, 4kHz, and 6kHz respectively. The NAL formula includes 10dB reserve gain [22].Two other modifications to the NAL-R formula have been suggested for those with severe sensorineural hearing impairment [9, 23]. Modification 1 is made if the PTA value exceeds 60 dB. The difference value i.e. PTA-60 is multiplied by 0.116 and added to the REIG value [20]. The second modification arises if the value of the hearing threshold at 2 kHz exceeds 90dB. Based on the hearing threshold value, this modification suggests an increase in the gain for low frequencies, and reduction in the gain for high frequencies. This adjustment alters the hearing aid response of a person with severe hearing loss who requires more low frequency energy and less high frequency energy for decreasing the feedback problems [24, 25]. If the threshold measured at 2 KHz exceeds 90 dB, then the value given in table 2 is added with the particular frequency gain.

Table 2. NAL -R adjustment when the hearing threshold at 2 KHz exceeds 90 dB.

| HL at 2 kHz dB HL | Frequency in kHz. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | .25 | .5 | .75 | 1 | 1.5 | 2 | 3 | 4 | 6 |
| 95 | 4 | 3 | 1 | 0 | -1 | -2 | -2 | -2 | -2 |
| 100 | 6 | 4 | 2 | 0 | -2 | -3 | -3 | -3 | -3 |
| 105 | 8 | 5 | 2 | 0 | -3 | -5 | -5 | -5 | -5 |
| 110 | 11 | 7 | 3 | 0 | -3 | -6 | -6 | -6 | -6 |
| 115 | 13 | 8 | 4 | 0 | -4 | -8 | -8 | -8 | -8 |
| 120 | 15 | 9 | 4 | 0 | -5 | -9 | -9 | -9 | -9 |

## 2.2. POGO II formula for calculating Real Ear Insertion Gain

The gain preferences of persons with hearing impairment are highly considered in the designing of the POGO formula [26]. POGO was derived from Lybarger's 1/2 Gain Rule, with a correction factor suggested for low frequencies, to enhance the speech intelligibility. An enhanced version of this procedure called POGO II, modifies the gain; if the hearing threshold at a particular frequency is greater than 65 dBHL, then the gain is increased by half the amount of that for the hearing loss that exceeds 65 dB, explained in step 2 [14].

Step 1: To calculate REIG, the hearing threshold at the particular frequency is divided by 2 as given in table 3.

Step 2: If the hearing threshold at a particular frequency is greater than 65dB, 65dB is subtracted from the hearing threshold, then half of it is added to the value calculated in step 1. Otherwise the gain is calculated as explained in step 1.

A low frequency conversion factor -10 dB and -5 dB is added to the REIG value for 250Hz and 500Hz respectively [27,28]. These two formulae have been widely used in calculating the gain values for linear digital hearing aids.

Table 3: POGO II Gain Calculations

| Frequency in Hz | Formula |
|---|---|
| 250,500,1K, 1.5K,2k,3k, 4k,6k | Hearing threshold * 0.5 = REIG in dB<br>If the hearing threshold is greater than 65dB then the required REIG in dB = [Hearing threshold *0.5 + 0.5 * (Hearing threshold – 65)] |

## 2.3. Desired Sensation Level (DSL) procedure

The DSL method differs from the previous procedures NAL-R and POGO II in several aspects. First, it prescribes real ear aided gain rather than real ear insertion gain. Real ear aided gain is the SPL near the ear drum minus the SPL at some reference point outside the head. Real ear insertion gain is the effective gain obtained by the signal, because of the hearing aid usage.

### 2.3.1. Desired Sensation Level Input / Output (DSL I/O) Procedure

The DSL I/O procedure is evolved from the DSL procedure, first used as a prescriptive method for children [29, 30]. The objective is to achieve the desired sensation level of the amplified signal for multiple level inputs. DSL [I/O] can also be used as an effective method of achieving Loudness Equalization. The DSL [I/O] program provides frequency-specific output targets for multiple input signal levels, based upon speech, not on tones. The I/O approach divides the input dynamic range into three regions: 1) input levels below the compression threshold, or Imin; 2) input levels that will exceed the compression threshold when amplified, or Imax; and 3) the levels between these two limits. If the input signal level is equal to or less than Imin, linear gain is applied to the signal (i.e., below the compression threshold). If the signal level is equal to or greater than Imax, the output is limited to Omax (output limiting). For input signals between 'Imin and Imax, I/O formula applies compression to the signal. The calculation procedure is shown in table 4.

Table 4. Desired Sensation Level Input / Output Formula for calculating the Real Ear aided Gain

| Input conditions | Output (Real Ear aided Gain Formula) |
|---|---|
| I < I min = (Linear Gain) | O = O min |
| I min < I < Imax (Linear Compression) | O= (I-Imin/Imax-Imin)* (O max-Omin) + Omin |
| I > I max (Output Limiting) | O = Omax |

## 2.4. FIG 6 Procedure

The Fig 6 Procedure is a loudness-based fitting formula, designed to accommodate the types of hearing losses described by Killion and Fikret-Pasa [31]; indeed the name of this approach is derived from the loudness growth concept presented in Figure 6 of that article. Killion added a loudness-based fitting formula to the array of prescriptive fitting procedures. In its current form, it is a spreadsheet approach to estimating the level-dependent gain and frequency response of nonlinear hearing aids. Since these aids can change their gain and frequency response depending upon the input level, the FIG 6 procedure can be utilized to calculate the gain and frequency response for low-level 45 dB SPL, moderate level 65 dB SPL, and high level 95 dB SPL sounds [32]. The formula for the FIG6 is presented in table 5.

Table 5. Gain calculations in FIG 6 procedure

| | |
|---|---|
| Low level input (45 dB SPL) | Gain for low level sounds<br>1. G= 0 for 0 to20 dBHL<br>2. G = HL-20 for 20 to 60 dB HL<br>3. G = HL-20 - 0.5*(HL-60) for HL >= 60 dB. |
| Moderate level input ( 65 dB SPL) | Gain at MCL<br>1 G=0 for0to20dBHL<br>2. G = 0 .6 *(HL-20) for 20 to 60 dB HL<br>3. G=0.8*HL-23 for HL>=60 dB. |
| High level input ( 95 dB SPL) | Gain for high-level sounds<br>1. G=0 for 0 to 40 dBHL<br>2. G = 0 .1 * (HL-40) A 1 .4 for HL >= 40 dB. |

## 2.5. NAL-NL2 Procedure

The NAL-NL2 is the second generation prescriptive procedure of the National Acoustic Laboratories, for fitting wide dynamic range compression (WDRC) instruments. Like the NAL-NL1, NAL-NL2 aims at making speech intelligible, and the overall loudness comfortable. This aim is mainly driven by the belief that these factors are the most important for hearing aid users, but is also driven by the fact that less information is available about how to adjust the gain to optimize other parameters that affect prescription, such as localization, tonal quality, detection of environmental sounds, and naturalness [33, 34]. The objective is achieved by combining a speech intelligibility model and a loudness model in an adaptive computer-controlled optimization process. Adjustments have further been made to the theoretical component of NAL-NL2 directed by the empirical data collected during the past decade with NAL-NL1. One loop uses the intelligibility model to find the gain-frequency response that maximizes speech intelligibility. The second loop uses the loudness model to calculate the loudness that would be perceived by the hearing-impaired person with the selected gain-frequency response [35, 36]. The adaptive process was used to derive the optimal gain-frequency responses for 240 audiograms, covering a wide range of severity and slopes, each at seven speech input levels from 40 to 100 dB SPL.

## 2.6. Expert system architecture

The expert system is framed with the input from the knowledge base and case specific data, as shown in the architecture in figure 1. In the designed system, the knowledge base was from the expert audiologists who are involved in the hearing aid fitting procedure. During the course of their professional career, they might have made many fitting trials with different types of hearing impaired subjects.

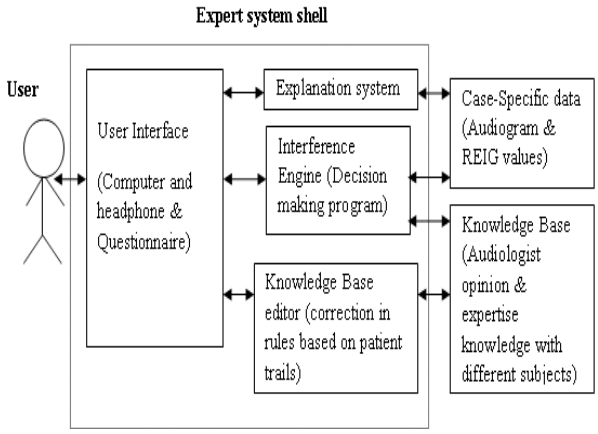


Fig.1. Expert system architecture

The audiograms and REIG values are stored and used as case specific data. The audiograms were classified with the hearing impairment types and the REIGs corresponding to that type of hearing loss were considered. The knowledge base editor edits the rules subsequently, with the effective trials made with the subjects of hearing loss, not in the original data base. The Interference engine section consists of the decision making program, decides the REIG values to be suggested for the subject under trial, based on the knowledge base rules and case specific data. The User interface section links the subject and the expert system effectively. Head phones connected to the computer were used to interface the subject with the expert system, and a questionnaire was prepared to interact with the hearing impaired subjects to make the decision process effective.

## 2.7. Testing sequence

The pure tone audiometric test and speech audiometric test are used, to assess the performance of the entire auditory system. In the pure tone audiometric test, the tone frequencies ranging from 125Hz to 8000Hz are used to test the patient and the tone has dB value ranges from -10dB to +110 dB are generated with the help of Matlab software, so that the accuracy of the test tone is very high. Similarly, the test words used to test the patient in the speech audiometric test are also recorded and stored as wave file.

Step 1: If the user wants to perform the audiometric test, he or she should enter his or her personal data on the patient data screen.

Step 2: If the user wants to see or verify any relevant data or information regarding the audiometric tests they may select the appropriate option.

Step 3: In the audiometric test option, at first the user has to select the pure tone audiometric test.

Step 4: After finishing the pure tone audiometric test the user has to perform the speech audiometric test. If both these test results fail to predict the comparable results, go to step 3.
Step 5: Based on these test results and data, the gain recommendations based on standard prescriptive procedures are made, if the subject has been identified as an eligible patient to wear a hearing aid.
Step 6: If the recommendation does not provide satisfaction to the hearing aid users, then the audiologist has to make more trials with the patient, and make necessary changes in the gain, so as to maximize the SDS value, which in turn will enable the successful usage of the hearing aid.
Step 7: If the patient is satisfied with these values of gain then they are stored in the data base. This will be used in due course for successful fine tuning of the formula.

### 2.8. Audiological investigations

#### 2.8.1. Pure tone audiometric test

Pure tone audiogram test includes air-conduction test and bone-conduction test. The purpose of air-conduction test is to find the hearing sensitivity at various frequencies. Matlab program generates the test signals with the corresponding dB ranges from -10dB to +110 dB and different frequencies 125Hz, 250Hz, 500Hz, 1000Hz, 1500Hz, 2000Hz, 3000Hz, 4000Hz, 6000Hz and 8000Hz for pure tone audiometric test. Pure tone audiometric test with masking is done only when the difference between the air conduction threshold of bad ear with that of bone conduction threshold of good ear is greater than or equal to 10dB gets attenuated. The loss of sound energy during the air conduction test, when the stimulus is passing from test ear to the cochlea of the non-test ear is called as Inter-aural Attenuation (IA) and it ranges from 45 to 80dB.Cross hearing is a serious concern in case of bone conduction test than it is for air conduction because both the cochleae are equally stimulated. Therefore to get a reliable test results the non-test ear is not to be involved in the testing procedure by delivering suitable noise signal to it. The masking noise should be loud enough to prevent the tone reaching and stimulating the non-test ear, but at the same time it should not mask the signal given to the test ear which may be called as over masking [37].Thus, an audiologist should select appropriate masking signal level in dB.

#### 2.8.2. Speech audiometric test

Speech discrimination is the subject's ability to identify the words presented to them through head phones. In this procedure presentation of 50 selected monosyllabic words. The speech discrimination score (SDS) is the percentage of words correctly identified. The pathology of the inner ear, the auditory nerve, and the central auditory pathways are the reasons that affect this score. The ability of an individual to discriminate speech cannot be predicted by the pure-tone audiogram test. An individual may hear a sound well enough, but the neural signals may be altered to the extent, that the sound is unintelligible. Subjects suffering only from conductive hearing loss will be able to identify words, if the sound is loud enough. Subjects with sensorineural hearing loss have a marked dip in the SDS value, without a proportionate loss of pure-tone or speech sensitivity. It is to be noted, that there is a predictable relationship between the patient's PTA and SDS.

### 2.9. Gain Recommendations

The pure tone thresholds of various frequencies are used for the calculation of real ear insertion gain. Initially it is based on the standard formulae stored in the expert system. If the subject does not get satisfaction with the recommendations, the audiologist has to change the gain settings with his experience, till the patient is satisfied by maximizing the SDS value. After the patient's satisfaction the gain settings are saved in the data base. This data will be very useful in developing a standard formula for different language and living conditions.

## 3 Results and Discussion

In four different specialty hospitals, 353 subjects were tested for the prediction of hearing loss, using the computerized audiometer inbuilt in the adaptive expert system, and also with the conventional audiometer model 2001 Digital clinical diagnostic audiometer from Arphi Electronics, under the same testing conditions. The audiograms taken by both modalities are compared for validation. As a proof of validation, audiograms of a subject with mild hearing loss taken with both modalities are shown in fig 2.

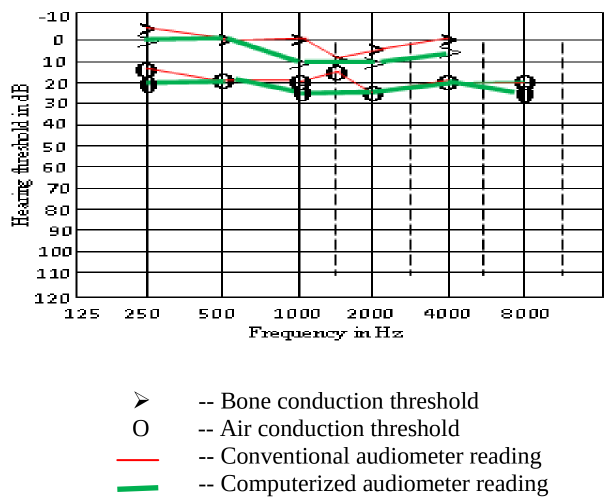


Fig. 2. Comparison of the audiograms of a subject with mild hearing loss

The results of the computerized audiometer inbuilt in the adaptive expert system are marked in thick green color, whereas the conventional audiometer readings are marked in thin red color. The pure tone average arrived at, using computerized audiometer is 23.33, whereas it is 21.66 when the same subject is tested with the conventional audiometer. The interpretation of the computerized audiometer results is same as that of the conventional audiometer results, except for a marginal difference in the value of PTA.

### 3.1. Calculation of REIG

The subjects are also tested with the speech audiometric test using the computerized audiometer, and the SDS is calculated. The minimum threshold of hearing, obtained with the pure tone audiogram test is used to find the REIG required for the digital hearing aid.

Audiometric thresholds of above the mentioned individual, are given below.

Frequency: .25k .5k 1k 1.5k 2k 3k 4k 6k

Threshold: 50 45 65 65 70 60 50 45

Step 1: 0.15 *PTA= 0.15 * (45 + 65 + 70)/3 = 9

The REIG calculated, using the NAL-R formula is given in table 6.

Table 6. NAL – R real ear insertion gain calculations

| Frequency in Hz | Formula | Conversion factor | REIG |
|---|---|---|---|
| 250 | 9 + 0.31(50) = 24.25 | -17 | 7.25 |
| 500 | 9 + 0.31(45) = 22.95 | -8 | 14.95 |
| 1000 | 9 + 0.31(65) = 29.15 | -3 | 26.15 |
| 1500 | 9 + 0.31(65) = 29.15 | +1 | 30.15 |
| 2000 | 9 + 0.31(70) = 30.70 | +1 | 31.70 |
| 3000 | 9 + 0.31(60) = 27.60 | -1 | 26.60 |
| 4000 | 9 + 0.31(50) = 24.50 | -2 | 22.50 |
| 6000 | 9 + 0.31(45) = 22.95 | -2 | 20.95 |

The same patient's hearing aid can be programmed with the help of the gain recommendations, calculated using the POGO II formula. The prescription of the real ear insertion gain using the POGO II formula is calculated as given in the steps below, and is shown in table 7.

Step 1: For calculating the required REIG, the hearing threshold is divided by 2. In this case except 2 kHz all the frequencies have less than 65dB; so the correction factor is required only for 2 kHz. But a low frequency factor of -10dB is added with the 250Hz hearing threshold/2, and -5dB is added with the 500Hz hearing threshold/2 to get REIG.

Step 2: For 2 kHz, the REIG calculation is varied, because the minimum threshold of hearing exceeds 65dB. In this case, it is 70dB. It is divided by 2, i.e., 35dB and the difference between 65dB from 70dB is divided by 2, and it is 2.5dB, which is added to the 35dB, and the final suggested REIG for 2 kHz is 37.5dB. Step 1 is followed for the remaining frequencies.

Table 7. POGO -II real ear insertion gain calculations

| Frequency in Hz | Formula | Conversion factor | REIG |
|---|---|---|---|
| 250 | 25.0 + 0 | -10 | 15.0 |
| 500 | 22.5 + 0 | -5 | 17.0 |
| 1000 | 32.5 + 0 | 0 | 32.5 |
| 1500 | 32.5 + 0 | 0 | 32.5 |
| 2000 | 35.0 + 2.5 | 0 | 37.5 |
| 3000 | 30.0 + 0 | 0 | 30.0 |
| 4000 | 25.0 + 0 | 0 | 25.0 |
| 6000 | 22.5 + 0 | 0 | 22.5 |

The patient is not satisfied with the recommendations of REIG for various frequencies using POGO II formula and NAL-R formula, and hence, the expert audiologist makes some corrections in the gain settings for arriving at the satisfaction of the subject concerned, and the gain recommendations of the standard formulae, and expert audiologist's recommendations are given in table 8 for comparison. The recommendations of REIG for various frequency ranges, using the POGO II and NAL-R formulae for the same test results of a patient, and also the final suggestions by the audiologist, are plotted as shown in fig 3.

Table 8. Comparison of the gain suggestions of the standard formulae and the expert audiologist

| Frequencies in Hz | NAL-R Gain | POGO II Gain | Suggested Gain |
|---|---|---|---|
| 250 | 7.25 | 15.0 | 12.5 |
| 500 | 14.95 | 17.0 | 18.0 |
| 1000 | 26.15 | 32.5 | 28.5 |
| 1500 | 30.15 | 32.5 | 33.5 |
| 2000 | 31.70 | 37.5 | 34.0 |
| 3000 | 26.60 | 30.0 | 28.5 |
| 4000 | 22.50 | 25.0 | 26.0 |
| 6000 | 20.95 | 22.5 | 24.5 |

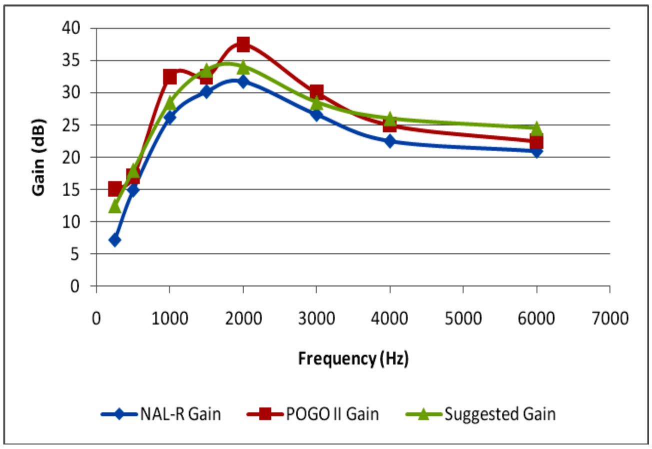


Fig. 3. Comparison of NAL-R, POGO-II and the suggested recommendations of REIG

A similar type of gain calculations and gain suggestions for a subject with mild hearing loss is made by the careful alignment of the gain by the expert audiologist, to give a clear speech perception, as given in table 9 and the value is plotted in Fig 4.

Table 9. Gain suggestions for a subject with mild hearing loss

| Frequency in Hz | NAL-R Gain | POGO II Gain | Suggested Gain |
|---|---|---|---|
| 250 | -5.0 | 2.5 | 1.0 |
| 500 | 4.0 | 7.5 | 5.0 |
| 1000 | 13.6 | 15.0 | 14.0 |
| 1500 | 12.0 | 12.5 | 15.0 |
| 2000 | 13.6 | 15.0 | 10.0 |
| 3000 | 12.0 | 12.5 | 14.0 |
| 4000 | 12.0 | 12.5 | 12.0 |
| 6000 | 12.0 | 12.5 | 12.0 |

The gain calculations for all the 159 subjects were analyzed. In almost all the cases, the variation required for the high frequency ranges as against the gain suggested by the system is very less. In the low frequency region a mild variation is required. In the mid frequency region, where the majority of the speech frequencies are available, much variation in the suggested gain is required in this region. Two different types of hearing aid fitting procedures (NAL-R formula and POGO II formula) have been compared. The main outcomes were the improvement of speech intelligibility scores in quiet and noisy conditions. Data were related to the real ear insertion responses that were measured after fitting. For analytic purposes, subgroups were composed according to the degree of hearing loss, characterized by unaided speech intelligibility in quiet, previous experience with hearing aids, unilateral or bilateral fittings, and the type of hearing aid.

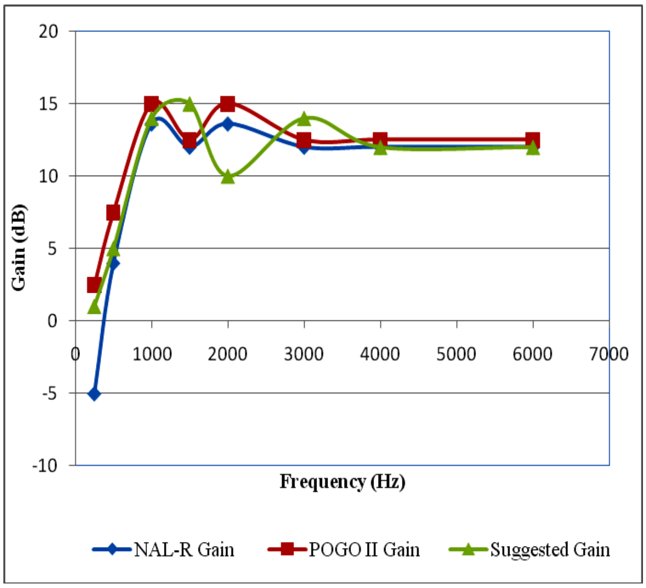


Fig. 4. Gain recommendation comparison for a subject with mild hearing loss

In the subsequent evaluation period, non linear prescriptive procedures like the DSL I/O, IHAFF, FIG6, NAL-NL1 and NAL-NL2, were also used for gain suggestions. Differences between the responses prescribed by different prescriptive procedures were verified for subjects with different types of hearing loss. The gain prescriptions by NAL-NL1, DSL I/O, IHAFF and FIG 6 procedures for a subject with 40dB flat hearing loss for an input level of 50 dB SPL are shown in figure 5.

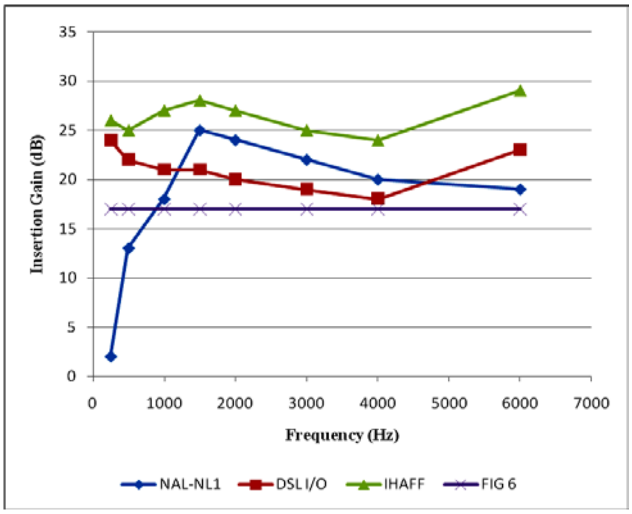


Figure 5. Insertion gain at the input level of 50 dB SPL for each of the four selection procedures for a subject with flat 40dB hearing loss

The IHAFF and DSL I/O procedures prescribe more or less the same gain for all the frequencies for this subject, who has a flat hearing loss. The FIG 6 procedure prescribes a constant level of gain for all frequencies at different input levels. NAL – NL 1 prescribes less gain for low frequency signals compared to all other procedures. For mid frequency and high frequency regions, the gain preferred is more than that prescribed by the other procedures. The NAL-NL1 procedure normally will not suggest high gain for the frequencies with high loss, because of the decreased ability of the ear to extract information at those frequencies. For a low input level, NAL-NL1 may not prescribe much gain to get audibility, at the frequencies where the loss is high, or the frequencies at which speech is least important for intelligibility. The DSL I/O prescribes a more appropriate gain-frequency response for mild level inputs than the NAL formula. We found equal improvement of speech intelligibility in quiet, while, fitting according to the NAL-R formula resulted in a somewhat better performance, as expressed by the speech-to-noise ratio, in comparison to the POGO II formula in the case of linear hearing aids. In the 159 subjects tested and found to be suitable to use hearing aids 28 received satisfaction with NAL-R, 25 with POGO II, 23 with NAL-NL2 and 12 with DSL I/O. The remaining people received satisfaction only after adjusting the gain settings by experienced audiologists. These successful gain settings were stored in the data base, for formulating a revised formula to give complete satisfaction among the hearing aid users, irrespective of their age, sex and living environment. The system will give an adaptive solution for all these kind of variations, because it is developed with the feedback received from the patients.

# 4 Conclusion

An Adaptive Expert System was designed and developed, to perform audiological investigations like the pure tone and speech audiometric test. All the subjects considered for study were tested with both the conventional 2001 digital diagnostic audiometer, and also with the computerized audiometer inbuilt in the expert system. The accuracy of the computerized audiometer was found to be 94.87%. It also recommends more accurate REIG values, so that the hearing impaired person gets satisfied with the performance of the hearing aid. The expert system has sound knowledge base rules formed using the experienced hearing aid fitting trials of the audiologists, with different types of hearing impaired subjects. If any corrections are made by the experienced audiologists in the suggested gain values by the expert system, they are stored. They will be used to strengthen the knowledge base, and used for fine tuning the REIG formula. This would not only reduce the number of fitting trials but also lead to the recommendation of superior technical specifications, with regard to the design of hearing aid. The procedures based on speech intelligibility play an important role in getting satisfaction to the hearing aid users like NAL-NL1 and NAL-NL2. This additional specialized attention certainly would bring better satisfaction among the hearing aid users. The different types of hearing loss suffered by the subjects, and the satisfied gain values for a particular subject, have to be analyzed for further fine tuning of the formula used for the calculation of REIG. The formula can be made distinctive to any language and different living conditions.

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