

The Value of Routine Real Ear Measurement of the Gain of Digital Hearing Aids

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Abstract

The main aims of this study were: (1) to determine whether routine real ear insertion gain (REIG) measurement is necessary in fitting digital hearing aids; and (2) to assess the extent to which modifying the frequency-gain response of an aid can lead to better matches to the target in cases where the target gain was not initially achieved. The target formula was selected as NAL-NL1 in the programming software of four types of digital hearing aids. REIG measurements on 42 ears showed that 64% of cases failed to come within ± 10 dB of the target at one or more of the following frequencies: 0.25, 0.5, 0.75, 1, 1.5, 2, and 4 kHz. After adjusting the frequency-gain response of the aids, based on the REIG results, 83% of cases came within ± 10 dB of the target. The target was met more often, both before and after adjustment, for aids with seven gain “handles” than for aids with four gain “handles.” The results indicate that REIG measurements can and should be used to achieve more accurate fittings but that accurate adjustments are difficult with some aids.

Key Words: Real ear insertion gain, digital hearing aid, slope of audiogram, pure tone average, real ear unaided gain

Abbreviations: BTE = behind the ear; CAMEQ = Cambridge prescription method based on loudness equalization; CAMREST = Cambridge prescription method based on loudness restoration; DSL = desired sensation level; MHAS = Modernizing Hearing Aid Services; NAL = National Acoustic Laboratories; NAL-NL1 = National Acoustic Laboratories’ non linear fitting procedure, version 1; NAL RP = National Acoustic Laboratories Revised, Profound; NHS = National Health Service; PTA = pure-tone average; REAR = real-ear aided response; RECD = real-ear coupler difference; REDD = real-ear dial difference; REM = real ear measurement; REIG = real-ear insertion gain; REOG = real-ear occluded gain; REUG = real-ear unaided gain

Sumario

Los propósitos principales de este estudio fueron: (1) determinar si las mediciones rutinarias de ganancia de inserción en oído real (REIG) son necesarias para adaptar auxiliares auditivos digitales; y (2) evaluar el grado en que la modificación de la respuesta de ganancia por frecuencia de un auxiliar puede llevar a mejores ajustes en los casos donde la ganancia meta no le logró inicialmente. La fórmula meta fue seleccionada como la NAL-NL1 en el software de programación de cuatro tipos de auxiliares auditivos digitales. Las mediciones del REIG en 42 oídos mostró que el 64% de los casos fallaron en acercarse a ± 10 dB de la meta, en una o más de las siguientes frecuencias:

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0.25, 0.5, 0.75, 1, 1.5, 2, y 4 kHz. Luego de ajustar la respuesta de ganancia por frecuencia, con base en los resultados del REIG, 83% de los casos se acercaron a ± 10 dB de la meta. La meta fue alcanzada más a menudo, tanto antes y después del ajuste, para auxiliares con siete ajustes de ganancia que para auxiliares con cuatro ajustes. Los resultados indican que las mediciones de REIG pueden y deberían ser utilizadas para lograr adaptaciones más exactas, pero que tales ajustes exactos son difíciles en algunos auxiliares.

Palabras Clave: Ganancia de inserción por oído real, auxiliar auditivo digital; pendiente del audiograma, promedio tonal puro, ganancia no amplificada de oído real

Abreviaturas: BTE = retroauricular; CAMEQ = método de prescripción de Cambridge con base en ecualización de la sonoridad; CAMREST = método de prescripción de Cambridge con base en restauración de la sonoridad; DSL = nivel deseado de sensación; MHAS = Modernizando los Servicios de Auxiliares Auditivos; NAL = Laboratorios Nacionales de Acústica; NAL-NL1 = Procedimientos no lineales de adaptación de los Laboratorios Nacionales de Acústica, versión 1; NAL RP = Laboratorios Nacionales de Acústica, Revisado, Profundo; NHS = Servicio Nacional de Salud; PTA = promedio tonal puro; REAR = respuestas amplificadas de oído real; RECD = diferencia del acoplador en oído real; REDD = diferencia en el dial en oído real; REM = medición en oído real; REIG = ganancia de inserción en oído real; REOG = ganancia ocluida en oído real; REUG = ganancia no amplificada en oído real

The initial fitting of hearing aids is often based on a prescription target, usually derived from audiometric thresholds. Examples are NAL(R) (Byrne and Dillon, 1986), NAL-NL1 (Dillon, 1999; Byrne et al, 2001), DSL[i/o] (Cornelisse et al, 1995), CAMEQ (Moore et al, 1999), CAMREST (Moore, 2000), and the “DSL multistage input/output algorithm” (Scollie et al, 2005). At least some of these targets are based on empirical measurements showing that fitting according to the target leads to greater speech intelligibility in quiet or in noise and/or better subjective quality than fittings that deviate significantly from the target (Byrne, 1986; Byrne and Cotton, 1988; Moore et al, 2001). Also, fitting according to a target can optimize the audibility of speech for a given overall loudness (Moore and

Glasberg, 1998). Therefore, it would seem desirable to meet the target as closely as possible.

Measurement of real ear insertion gain (REIG) is a reliable and accurate procedure for determining how well a hearing aid is adjusted to match a prescription target, and for adjusting a hearing aid so as to improve the match (Seewald et al, 1999). REIG is defined as “the SPL at the eardrum when aided minus the SPL at the eardrum when unaided” (Dillon, 2001). Following the modernizing of hearing aid services (MHAS) in the UK, REIG measurements are widely used in fitting of digital hearing aids in the majority of audiology departments in the National Health Service (NHS). However, the recommendation that REIG should be measured is not always followed in the UK or else-

where, and some authors have reported that relatively few audiologists and hearing aid dispensers routinely use real ear measurements (REMs) to verify hearing aid fitting (Mueller, 2003; Kirkwood, 2004). The value of routine REIG measurement in the fitting of analog hearing aids has been investigated in several studies (Swan and Gatehouse, 1995; Harrowven, 1998; Norman and James, 2000).

Swan and Gatehouse (1995) investigated the necessity of measuring REIGs to identify inadequate hearing aid prescriptions through a prospective study of 319 new analog hearing aid users with a mean pure tone average (PTA) hearing threshold at 0.5, 1, 2, and 4 kHz of 47 dB (SD=11). The insertion gain recommended by the National Acoustic Laboratories (NAL) fitting method (Byrne and Dillon, 1986) was chosen as the target. The fitting was considered acceptable if the difference between the REIG and the NAL target was less than 10 dB at all frequencies from 0.25 to 4 kHz. Their results revealed that 76% of fittings were not acceptable. The PTA and the overall slope of the audiogram did not differ significantly for cases whose fittings failed to achieve the NAL target and those that met the target. However, the former, called here the "fail group," had significantly poorer hearing at 4 kHz and had significantly more steeply sloping audiograms between 2 and 4 kHz than the "pass" group. This suggests that patients with more steeply sloping audiograms and more severe high-frequency hearing losses are more difficult to fit well. Sixty-eight patients from 241 in the fail group attended an additional fitting session. After appropriate changes in the tubing, filters, horn, and hearing aids, 62% came within 10 dB of the NAL target at all frequencies. Swan and Gatehouse concluded that the routine use of REIG in all analog hearing aid fittings would result in many patients having a more accurately fitted hearing aid.

In recent years many technical advances have been applied to hearing aids, and digital hearing aids have

become increasingly popular. These offer many advantages over analog hearing aids (Levitt et al, 1990; Wouters et al, 2002). In particular, since digital hearing aids offer more possibilities for controlling the frequency-gain characteristic, some authors have questioned whether it is still essential to perform REM in routine hearing aid fitting, or whether the first fit program of digital hearing aids can be relied upon to provide gain consistent with a given prescription formulae (Hawkins and Cook, 2003; Aarts and Caffee, 2005).

Hawkins and Cook (2003) investigated the accuracy of hearing aid fittings predicted by the manufacturer's software, using 12 subjects. Their results revealed that the fitting software overestimated actual real-ear gains, particularly at higher frequencies. The measured insertion gain at and above 2 kHz consistently fell short of the predicted insertion gain. Aarts and Caffee (2005) further examined the predictive accuracy of the real-ear aided response (REAR) values provided by one hearing aid manufacturer's fitting software, for a nine-channel digital hearing aid, using 79 ears. They found that the REARs predicted by the manufacturer's fitting software were inaccurate for almost all subjects. They concluded that one of the causes of the discrepancy between predicted and measured REAR values is the use of average real-ear unaided gain (REUG) in the hearing aid fitting software. The REUG represents the amount of natural amplification of the open ear resulting from the resonances of the concha and ear canal in the frequency range 0.25–4 kHz. In practice, the REUG varies significantly across individual ears, especially in terms of the location and magnitude of the primary resonance peak (Weiner and Ross, 1946).

The studies described above only assessed the discrepancy between gains predicted by the manufacturers' software and gains actually measured. They did not assess the extent to which fitting could be made more accurate by adjustment of the hearing aids. Also, they did not explore the influence of sev-

eral factors that might affect the deviation from the target values. The aims of the present study were: (1) to investigate the number of fittings which came within ± 10 dB of the NAL-NL1 (Dillon, 1999) insertion gain target through the first fit or quick fit program of four types of digital hearing aids when the NAL-NL1 prescription was selected as the gain formula in the programming software of the aids; (2) to assess the extent to which modifying the frequency-gain response of the aids led to a better match to the target for those who did not initially achieve the target gains; (3) to determine the pass/fail rate for different types of hearing aids and different earmolds; (4) to determine the extent to which the REUG is related to the difference between the measured REIG and the insertion gain target, which is denoted here "target mismatch."

METHOD

Subjects and Audiograms

Forty-two ears of a consecutive sample of 24 patients (12 female, 30 male) who were considered for provision of digital hearing aids in the period April to June 2006 at the Audiology Department (clinic B), Ealing Hospital, London, were included in this study. Pure tone thresholds were measured in a sound-attenuating room following the British Society of Audiology recommended procedure (2004), using an Aurical audiometer with Madsen HB7 (TDH 39P) headphones and Radioear B71 bone vibrator. The Aurical was calibrated in November 2005. Air conduction thresholds were measured at 0.25, 0.5, 1, 2, 4, and 8 kHz. The mean PTA for the frequencies 0.5, 1, 2, and 4 kHz was 53 dB HL (SD= 16). This study was performed in accordance with the Helsinki declaration on medical ethics issues.

Hearing Aids and Ear Molds

The hearing aids used were 16 Spirit 3 (Oticon, known in some parts of the world as "Tego Pro"), eight Prisma 2 Pro (Siemens), three Prisma 2 DSP+ (Siemens),

and 15 Danalogic 6 (GNReSound, known in some parts of the world as "Pixel"), chosen based on the patients' audiograms and the recommended fitting range of the hearing aids. If two or more hearing aids were suitable for an individual case, then the hearing aid was chosen based on its availability from stock in the clinic or randomly. Spirit 3 is a six-channel hearing aid. It has six gain "handles" with center frequencies at 0.25, 0.75, 1.5, 2.5, 4.5, and 7 kHz, and crossover frequencies are adjustable. Prisma 2 Pro and Prisma 2 DSP+ are four-channel aids with three individually adjustable crossover frequencies at 0.35/0.55, 0.71/1.12/1.8, and 2.25/2.8/3.5 kHz. Danalogic 6 has 17 channels, but the software includes only seven gain "handles" at 0.25, 0.5, 1, 2, 3, 4, and 6 kHz.

Twenty-two hearing aids were fitted using non-occluding ear molds (eight Oticon Corda, nine Starkey skeleton open molds with D/F Ring, and five GNReSound flex-tube), five using all soft shell molds, two using non-allergic shells, six using skeleton acrylic soft tips and 1 mm vents, three using skeleton acrylic soft tips and 2 mm vents, and four using skeleton acrylic soft tips and no vents. Skeleton molds had standard size 13 tubing. Oticon Corda and GNReSound flex-tube had narrow tubing. The inner diameters of the narrow and standard tubing are about 0.7 and 1.9 mm, respectively, while the outer diameters are about 1 and 3.3 mm, respectively.

Fitting Procedure

The fitting session usually lasted about one hour. Twenty-five minutes of that was allocated to programming the aid and performing REM, 30 minutes to auditory rehabilitation, and 5 minutes to journal entry. The target gains used here were based on the NAL-NL1 fitting method (Dillon, 1999). This is a non-linear version of the NAL-R method (Byrne and Dillon, 1987). NAL-NL1 is one of the most widely used methods for fitting compression hearing aids to adults. Its aim is to maximize speech intelligibility for a specified loudness level, as calculated using a loudness model (Moore and Glasberg, 1997). The factors taken into account for

calculating the insertion gain at each frequency are hearing level and air-bone gap at that frequency, three-frequency average hearing level, and the overall speech input level (Byrne et al, 2001). For medium input levels, the gains prescribed by NAL-NL1 are similar to those prescribed by NAL(R), and there have been studies showing that subjects prefer gains and frequency responses based on NAL(R) as opposed to gains and/or frequency responses that deviate significantly from those prescribed by NAL(R) (Byrne, 1986; Byrne and Cotton, 1988).

The hearing aids were programmed following the recommended procedures and guidelines of the hearing aid manufacturers. The aids were programmed using the most recent version of the manufacturers' propriety software contained in the NOAH 3 platform (Genie 6 for Spirit3, Connex 5.2 for Prisma 2 Pro and Prisma 2 DSP+, and Aventa 2.10 for Danalogic 6). A PC housed the NOAH 3 software as well as the Madsen Aurical REM module (version 2.50) used for REM.

Siemens and Oticon recommend use of the NAL-NL1 formula for the fitting of their aids, and then verification against the NAL-NL1 insertion gain target. The Connex 5.2 software has four acclimatization levels (level four corresponds to the most experienced), and it is recommended that the aids are set to level four if it is desired to achieve the NAL-NL1 prescription target; the gain may then be modified based on the patient's preferences and experience with the hearing aid. The Genie 6 software has three acclimatization levels, and it is recommended that the aids are set to level three to achieve the NAL-NL1 prescription. Siemens and Oticon do not recommend changing the programming of the aid following initial fitting unless REM reveals gross deviations from the target insertion gain. If necessary, adjustments to the programming should then be made to achieve a closer fit to insertion gain target, as long as the patient finds the sound acceptable and comfortable. These adjustments to the programming can be made while the insertion gain is active on screen, using the two NOAH modules (Connex/Genie/Aventa and REM) together. GNReSound recommends use of either

audiogram+ or NAL-NL1 targets for the fitting of the aids.

For all hearing aids, NAL-NL1 was selected as the target formula, and the hearing aid features were selected in the software as follows: expansion off, noise reduction off, feedback cancellation off, voice activity detection off. Type of tubing (number 13 or thinner tubing) and vent size (1 mm, 2 mm, and open) were also selected as appropriate in the fitting software. REIG was measured following the MHAS guidelines using an Aurical (Madsen) system as follows: NAL-NL1 was selected as the REIG target, then the NAL-NL1 insertion gain target was generated by specifying multi-channel limiting, four-channel compression (the maximum number of channels allowed by the NAL-NL1 software), compression threshold (CT) for a wideband signal equal to 52 dB SPL for Prisma 2 Pro, Prisma 2DSP+, and Danalogic 6 and 57 dB for Spirit 3, reference position on head surface, head orientation at 45°, bilateral or unilateral as appropriate, tubing on number 13 (there was no option for thinner tubing in the REM module), vent size as appropriate, input level at 65 dB, real-ear coupler difference (RECD) on predicted, real-ear unaided gain (REUG) on predicted, real-ear dial difference (REDD) on predicted, transducer type on supra-aural headphone and hearing instrument as BTE. Several of these settings do not influence the outcome of the REM, but they are mentioned here as they are part of the procedure specified by the MHAS guidelines. It should be noted that the NAL-NL1 software sometimes does not give a recommendation for gain at certain frequencies if the hearing loss is large. This happened most often at 4 kHz but sometimes at other frequencies. In such cases, the manufacturers' software usually assigned a gain at the "missing" frequency that was equal to the gain at the next lowest frequency.

Otoscopy always preceded REM, to check that the ear canal was healthy and not obstructed by cerumen. The probe tube was calibrated using a pure tone sweep at 65 dB SPL. To perform calibration, the probe tube was placed close to the reference microphone aperture in the REM headset, and the headset was held

0.5 m in front of the loudspeaker and with the microphone and probe tube facing the loudspeaker. The calibration was checked by holding the headset in the same position and running a REUG measurement using a 65 dB SPL modulated speech noise stimulus. The calibration was considered as accurate if the measured REUG response was 0 dB at all frequencies. If not the calibration was repeated. The patient was positioned so that the ear under test was at 45° to the loudspeaker, 0.5 m from the loudspeaker, and level with the center of the loudspeaker. The patient was instructed to sit as still as possible during recording. The thinner (1.1 mm) microphone probe tube (with a black-colored marker) was used. The marker was set 27 mm from the end of the probe tube, and the probe tube was inserted until the marker was at the tragus. For all subsequent measurements, the signal was a 65 dB SPL modulated speech-shaped noise. With the probe tube in place, the REUG was recorded. Then the hearing aid was placed behind the ear, and the earmold was inserted into the ear, leaving the probe in place. With the hearing aid switched off, the real ear occluded gain (REOG) was recorded. Then the aid was switched on, and the real ear aided gain was recorded. From this, the REM software calculated the REIG.

The difference between the REIG and the NAL-NL1 target was recorded as the first fit target mismatch at 0.25, 0.5, 0.75, 1, 1.5, 2, 3, and 4 kHz. The fitting was considered acceptable if the difference between the REIG and the NAL-NL1 target gain was less than 10 dB at all frequencies. If the NAL-NL1 software did

not give a recommended gain at a specific frequency, then that frequency was ignored for the purpose of deciding whether a fitting was acceptable or not. If a fitting was not acceptable, the frequency-gain response was modified using the gain “handles” in the hearing aid software, and by adjusting cross over frequencies if appropriate, to achieve a closer fit to the insertion gain target, following the manufacturers’ recommended procedure. The REIG was then remeasured. The difference between the final REIG and the NAL-NL1 insertion gain target was recorded as the final target mismatch.

RESULTS

Proportion of Fail Cases and Effect of Adjustment

Of the 42 fittings, 27 (64%; 73% for females, 60% for males) failed to come within ± 10 dB of the NAL-NL1 insertion gain target at one or more frequencies between 0.25 and 4 kHz. As shown in Table 1, the proportion of fails was greater at high frequencies than at low frequencies, and was highest (40%) at 3 kHz. After adjusting the frequency-gain response of the hearing aids, 35 fittings (83%; same percentage for males and females) met the target, and seven fittings still failed to meet the target. With adjustment, it was always possible to meet the target for frequencies from 0.5 to 2 kHz. However, the target was not met for two fittings at 0.25 kHz and five fittings at 3 kHz, in all cases because the measured REIG was below the target REIG at those frequencies.

Table 1. Total Number of Cases for Each Frequency (cases for which NAL-NL1 recommended a target REIG), Number of Cases That Failed at Each Audiometric Frequency, and Percentage of Cases That Failed, Both before and after Adjustment

Frequency, kHz	0.25	0.5	0.75	1	1.5	2	3	4
Number of cases	36	40	42	42	42	41	35	26
Number of fails, before	3	4	4	6	11	8	14	8
Percentage of fails, before	8.3	10.0	9.5	14.3	26.2	19.5	40.0	30.8
Number of fails, after	2	0	0	0	0	0	5	0
Percentage of fails, after	5.6	0	0	0	0	0	14.3	0

Comparison of Audiogram Configurations between the Fail and Pass Groups

The mean slope of the audiogram between 2 and 4 kHz was 11 dB/oct (SD=10) for the pass group and 21 dB/oct (SD=19) for the fail group, and the difference was statistically significant ($t=-2.23$, $df=39.79$, $p<0.05$). The slope of the audiogram between 2 and 4 kHz for the fittings which initially came within 10 dB of the target (15 ears) was always less than 35 dB/oct. All fittings for the cases (six ears) with slope over 35 dB/oct initially failed to meet the target (these cases were fitted with completely open molds). However, poor fits were not associated only with steep slopes, since there were 21 cases out of 36 with slopes less than 35 dB/oct which initially failed to meet the target.

The overall slope of the audiogram between 0.25 and 4 kHz was 8 dB/oct (SD=6) for the pass group and 7 dB/oct (SD=6) for the fail group, and the difference was not statistically significant ($t=0.346$, $df=40$, $p=0.731$). The PTA (average of 0.5, 1, 2, and 4 kHz) was 57 dB (SD=13) for the pass group and 50 dB (SD=19) for the fail group, and this difference was also not statistically significant ($t=1.32$, $df=37.84$, $p=0.192$).

Open Fittings versus Occluding Molds

For patients with good high-frequency hearing combined with mild low- and mid-frequency hearing losses, non-occluding earmolds were fitted, because these result in better sound quality, reduced occlusion effect, better externalization and localization of sound, and more comfortable listening (Byrne et al, 1996; Upfold et al, 1997). They may also make it easier to obtain the target frequency-gain response. However, as described below, the fail rate was slightly higher overall for fittings with non-occluding earmolds (68%) than for fittings with occluding earmolds (60%), perhaps because the former were used for patients with more steeply sloping losses.

Of 13 hearing aids fitted using Corda and Flex tube (completely open molds

with thinner tubing), eight hearing aids (62%) initially failed to meet the target at mid- and high frequencies, and two of them failed to meet the target after modifying the frequency gain response in the final REIG examination. These two aids did not provide the 28 dB insertion gain at 3 kHz which was prescribed by NAL-NL1 even after increasing the gain by 10 dB at 3 kHz (because of the risk of feedback it was not possible to increase the gain even more at 3 kHz). Of the 13 subjects who were fitted with completely open molds, four were prescribed with 5–8 dB of gain at 0.25 kHz, and the rest did not require any gain at 0.25 kHz. However, in the four cases that did require gain at 0.25 kHz, REIG measurements showed at most 4 dB gain at that frequency even after increasing the programmed gain at 0.25 kHz by 5–8 dB. This is explained by the fact that, for sounds delivered by a hearing aid, the vent provides a low-cut to the frequency response and wider vents or open molds move the insertion gain toward 0 dB at low frequencies (Upfold et al, 1997; Dillon, 2001; Kates, 2005).

Of nine aids fitted using open molds with standard number 13 tubing (Starkey skeleton open molds D/F Ring), seven (78%) initially failed to meet the target at mid- and high frequencies, and one of them failed to meet the target after modifying the frequency-gain response. In the last case, the aid could not provide the 18 dB gain at 3 kHz which was prescribed by NAL-NL1. This hearing aid did not have a gain “handle” for 3 kHz, although it had gain “handles” at 2.5 and 4.5 kHz. Therefore, it was not possible to increase the gain specifically at 3 kHz because it led to over-amplification at 2 and 4 kHz.

Of 20 aids with occluding molds, 12 (60%) failed initially to meet the target at low, mid-, or high frequencies, and four of them failed to meet the target after modifying the frequency-gain response. In the last four cases, the aids could not provide the prescribed gain at high (4 kHz) and low (0.25 and 0.5 kHz) frequencies while meeting the target gain at midfrequencies (0.75, 1, 1.5, 2 and 3 kHz). The hearing aids used for these four fittings were four-channel aids, and increases in gain at high or low frequencies or changing the

cross-over frequencies led to over-amplification at midfrequencies, so it was not possible to meet the target gain at low and high frequencies while preserving the gain at midfrequencies.

Values of Target Mismatch and Relation to REUG

Table 2 shows the maximum mismatch at each frequency, the mean and standard deviation of the mismatches, and the mean and standard deviation of the absolute values of the mismatches (i.e., the mean and SD ignoring the direction of the mismatches). A negative value indicates a measured REIG below the target generated by NAL-NL1. For the initial fittings, the mean values were consistently negative, indicating that the REIG was systematically lower than estimated using the manufacturers' software. The mean error was especially large at 3 kHz (-10.2 dB) and 4 kHz (-8.2 dB). Following adjustment, the means of the mismatches decreased, as expected. However, for the frequency of 3 kHz, the mean mismatch remained relatively high, at -5.4 dB (SD =

6 dB), reflecting the fact that it was not possible to achieve the target gain at 3 kHz for some of the aids.

For the initial fittings, the mean of the absolute values of the mismatches was equal (but opposite in sign) to the mean of the mismatches at 0.25 and 4 kHz. This reflects the fact that all of the mismatches at these two frequencies were negative; the REIG values were all below the target values. At 0.25 kHz this was usually a result of the use of non-occluding earmolds, as discussed earlier, and it happened despite the fact that non-occluding earmolds had been specified in the manufacturers' software. The consistent negative mismatches at 4 kHz reflect the trend that has been reported in previous studies for the REIG at high frequencies to be lower than set in the manufacturers' software (Hawkins and Cook, 2003). For frequencies from 0.5 to 2 kHz, the initial mismatches were sometimes positive and sometimes negative. The maximum mismatches for the initial fits were positive at 0.75 and 1 kHz, reflecting the fact that the REIG at those frequencies was sometimes markedly higher

Table 2. For Each Frequency, the Number of Cases (cases for which NAL-NL1 recommended a target REIG), Maximum Mismatch, Mean and SD of the Initial and Final Mismatches, and Mean and SD of the Absolute Values (abs) of the Initial and Final Mismatches

Frequency (kHz)	Number of cases	Fitting	Max (dB)	Mean (dB)	SD (dB)	Mean of abs (dB)	SD of abs (dB)
0.25	36	Initial	-20	-3.9	6	3.9	6
		Final	-20	-2.9	5	3.5	5
0.5	40	Initial	-14	-2.7	5	3.5	4
		Final	-10	-0.7	3	1.9	3
0.75	42	Initial	18	-1.4	6	4.3	4
		Final	-8	0.1	3	2.2	2
1	42	Initial	20	-4.0	7	7.7	5
		Final	-10	-2.2	3	2.6	3
1.5	42	Initial	-24	-6.0	8	7.8	6
		Final	-20	-2.6	4	3.1	4
2	41	Initial	±16	-4.0	7	6.5	4
		Final	6	-0.8	3	1.9	2
3	35	Initial	-30	-10.2	7	10.5	7
		Final	-22	-5.4	6	5.8	6
4	26	Initial	-16	-8.2	5	8.2	5
		Final	-10	-3.0	4	4.0	3

Note: A negative number indicates that the REIG was below the target. For the initial fitting at 2 kHz there were two mismatches that were equally large, but opposite in sign, so the maximum is shown as ±16.

than indicated by the manufacturers' software. For the final fittings, the maximum mismatches were all negative except at 2 kHz.

The means of the absolute values of the mismatches represent the typical magnitude of the deviation from the target at each frequency, regardless of sign. These means always became smaller following adjustment, often by a factor of two or more. For example, at 1.5 kHz the mean of the absolute values of the mismatches was 7.8 dB for the initial fitting and 3.1 after adjustment. This indicates the value of making adjustments based on REMs.

The frequency response of the unaided ear plays a crucial role in determining insertion gain, because the response for the unaided ear is subtracted from the response for the aided ear (Fikret-Pasa and Revit, 1992). If the client's ear canal resonance does not correspond to average values in terms of center frequency and magnitude, this could result in mismatch to the target REIG and to unwanted peaks and dips in the REIG (Upfold and Byrne, 1988; Mueller, 2001).

To determine the extent to which individual variability of ear canal resonance is related to the target mismatch, we assessed the correlation between the following two quantities: (1) the difference between the measured REUG and the average REUG incorporated in the aid's software at 2, 3, and 4 kHz, and (2) the target mismatch at 2, 3, and 4 kHz.

The average REUG values usually incorporated in the hearing aid software are 12 dB at 2 kHz, 17 dB at 3 kHz, and 15 or 14 dB at 4 kHz (personal communications with companies). The correlation was not significant at any frequency: for 2 kHz, $r = -0.118$, $p = 0.468$; for 3 kHz, $r = -0.124$, $p = 0.471$; for 4 kHz, $r = 0.056$, $p = 0.785$. This lack of correlation indicates that it is not possible to predict the degree of mismatch from the extent to which the individual's REUR differs from the average REUG incorporated in the aid's software.

It should be noted that, for some prescription methods, such as DSL[i/o] (Cornelisse et al, 1995), CAMEQ (Moore et al, 1999) and CAMREST (Moore, 2000), the sound level at the eardrum, as measured using the real ear aided response

(REAR), is considered more important and more relevant than the REIG. If the target is specified as the REAR, then it becomes unnecessary to measure the REUR; what is important is to achieve the appropriate sound levels at the eardrum. However, individual differences in ear canal geometry, such as the residual volume in the ear canal, and factors such as vent dimensions, can strongly affect the REAR. This provides another reason to perform REM.

Pass/Fail Rate for Different Digital Hearing Aids

Figure 1 shows the percentage of aids of each type for which the target was met on the first fitting (black bars) and after adjustment (final fitting: light gray bars). The proportion of aids meeting the target following initial fitting was highest for the Danalogic 6 and lowest for the Prisma 2DSP+. Following adjustment, the target was met for all of the fittings with Danalogic 6, but a substantial proportion of fittings failed to meet the target for the other three types of aids. This is probably related to the fact that the Danalogic 6 has more channels and more adjustable "gain handles" than the other aids.

DISCUSSION

According to MHAS guidelines for fitting digital hearing aids, tolerances to the prescription rationale of ± 5 dB at 0.25, 0.5, 1, and 2 kHz, and of ± 8 dB at 3 and 4 kHz should be achieved in all cases. However, the criterion used here for adequacy of hearing aid fitting was that the REIG at all frequencies should be within ± 10 dB of the target. We chose this criterion to be able to compare our results with those of others. Despite the laxity of this criterion in comparison to the guideline, 64% of the initial fittings failed to achieve it. This result is consistent with the results of other studies (Hawkins and Cook, 2003; Mueller, 2003; Aarts and Caffee, 2005). After modifying the frequency-gain response of the aids, 17% (seven aids) still did not meet the target. Two of the aids that failed to meet the target were fitted using completely open molds and,

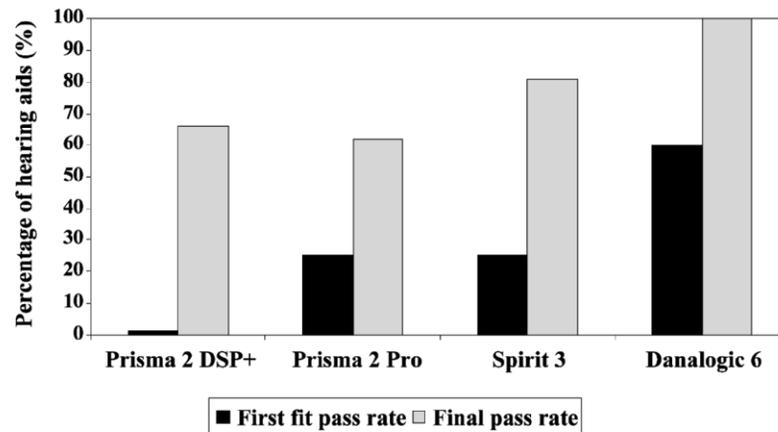


Figure 1. The percentage of fittings that came within ± 10 dB of the NAL-NL1 target in the frequency range 0.25 to 4 kHz using the first fit program of the aids (black bars) and after adjustments in frequency-gain response (light gray bars), for four different types of digital hearing aids.

given the risk of the feedback, it was not possible to increase the gain at the failed frequency of 3 kHz. For the remaining five aids that failed to meet the target, it was not possible to increase the gain at some frequencies while preserving the gain at others. This problem occurred for the aids with four gain “handles” and not for the aids with seven gain “handles.” For the hearing aids with seven gain channel “handles,” it was possible to increase the gain at a specific frequency with only a minor effect on the gain at neighboring frequencies. Given the fact that 100% of the fittings using the hearing aids with seven gain “handles” came within ± 10 dB of the insertion gain target after adjustment, it seems that the chance of meeting the prescription target is higher for hearing aids with more adjustable “handles” (and more channels).

For patients who were fitted with completely open molds, the REIG measurements did not show more than 5 dB of gain at low frequencies. This is consistent with the results of Upfold et al (1997) suggesting that, when a non-occluding earmold is used, it is necessary to increase the hearing aid’s programmed low-frequency gain to provide the same insertion gain as when a closed earmold is used. In many cases, it may be impossible to increase the programmed gain sufficiently to provide useful gain at low frequencies (Moore et al, 2005; Kates, 2005).

The proportion of mismatches and the magnitudes of the mismatches were both greatest at 3 and 4 kHz (Tables 1 and 2),

and the mismatches at these frequencies, at least for the initial fittings, were nearly always negative. This is consistent with the results of Hawkins and Cooke (2003). They obtained insertion gain measures for 12 patients. Their results showed that there were clear differences between the measured gain and insertion gain simulated by the hearing aid software. At 3 and 4 kHz, the measured insertion gain was always below the simulated insertion gain. At 4 kHz, 50% of cases had insertion gains that were more than 10 dB below simulated values. In our study, the mean mismatch for the initial fitting at 4 kHz was -8.2 dB, a value comparable to that found by Hawkins and Cooke. The large negative mismatches at 3 and 4 kHz may occur partly because manufacturers of hearing aids have difficulty in producing the increase in gain around 3–4 kHz that is required to compensate for the loss of the ear canal resonance when a mold is placed in the ear canal.

More generally, hearing aid software may not adequately adjust the hearing aid to achieve a target if the average REUG, microphone location effect, and vent and tubing effects incorporated in the hearing aid software are different from the individual values (Dillon and Keidser, 2003). Unusual shapes or sizes of ear canals may result in especially large discrepancies between the target and measured REIG values (Sanborn, 1998).

As noted earlier, it is debatable

whether attention should be focused on achieving the correct REIG. Most fitting procedures have as their goal for a given hearing loss a specific target spectrum for speech, as measured at the eardrum and characterized by the REAR measured with a speech-shaped noise or with real speech. For example, in connection with the CAMEQ fitting method, Moore et al (1999) stated that "In the case of the Cambridge formula, the aim is to achieve a spectrum at the eardrum that leads to a flat specific loudness pattern for speech presented at a free-field level of 65 dB SPL. Therefore, to get the appropriate gains for a specific individual ear, it is preferable to perform real-ear measurements using a probe microphone system, and to express the target gains as gains at the eardrum." In other words, the REAR is more relevant than the REIG, and to achieve the appropriate REAR values, REMs are needed. Similarly, the DSL[i/o] fitting procedure, both in its original version (Cornelisse et al, 1995) and in the more recent version (Scollie et al, 2005), specifies targets in terms of sound pressure level at the eardrum for a given type of input.

CONCLUSIONS

For a representative sample of digital hearing aids fitted using the manufacturers' first fit or quick fit program, 64% of fittings failed to come within ± 10 dB of the NAL-NL1 insertion gain target at one or more of the audiometric frequencies between 0.25 and 4 kHz. The mean slope of the audiogram between 2 and 4 kHz was significantly greater for fittings which failed to meet the target than for those which met the target. The degree of target mismatch at 2, 3, and 4 kHz was not correlated with the difference between the individual's REUG and the average REUG incorporated in the aid's software. There was no marked difference in the percentage of fittings that failed to meet the target between those using open molds and those using occluding molds. After adjustment, 100% of the fittings for the aids with seven gain "handles" came within ± 10 dB of the target, but this was true for only 62% of fittings for hearing aids with four gain "handles."

This suggests that the chance of meeting the prescription target after adjustment is higher for hearing aids with more gain "handles." Adjustments based on REIG measurements led to clear improvements in the match to target, the pass rate rising from 64% using the first fit program of the hearing aid's software to 83% using REIG measurements. The adjustments typically resulted in the magnitudes of the mismatches (absolute values in dB) decreasing by a factor of two or more. These outcomes suggest that routine REM measurement is useful for achieving more accurate matches to prescriptive targets.

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