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British Society of Audiology and British Academy of Audiology

Guidance on the use of real ear measurement to verify the fitting of digital signal processing hearing aids

July 2007

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1. Scope

This document provides guidance for clinical audiologists¹ who are fitting digital signal processing (DSP) hearing aids. It assumes prior knowledge, and it aims to provide a starting position from which audiologists may develop their skills and experience. Wherever possible, the guidance is based on evidence, but where the evidence base does not exist, guidance is based on best practice as agreed between “experts” at the time of writing. As more evidence comes to light, this guidance will inevitably change. Guidance differs from recommendation in that it is less prescriptive, and deviations from it are acceptable under certain circumstances.

The term real-ear measurement (REM) is used by audiologists to cover a range of different measurements of the real-ear acoustical characteristics of hearing aids. In clinical Audiology, the purpose of real-ear measurement is to compare and verify the real-ear acoustical characteristics of a hearing aid with a prescription target. This document also provides some guidance on the use of prescription targets.

The document does not attempt to address the issue of counselling that is an integral part of hearing aid fitting. The relative importance of technology-centred care (“matching target”) compared with patient-centred care is beyond the scope of this document, and is left to the discretion of the audiologist.

In some parts of the document, using signals of 80 and 90 dB SPL is recommended. Such high intensity sounds can cause discomfort, particularly if they are sudden and unexpected. They can also aggravate tinnitus. High exposure levels can occur when carrying out aided REMs with these sorts of input levels. When carrying out REMs at such levels, great care is needed to prepare the patient, make sure they know how to communicate any discomfort, and be ready to act immediately if distress is apparent. It may be appropriate to start at lower levels and increase the intensity if it causes no discomfort. The document does not address staff training for conducting REMs, however, this type of work does require an experienced audiologist, or audiologist under supervision, (as deemed appropriate by Head of Department).

The document is in two parts. The first, described in section 6 of this document, is based on guidelines produced as part of the Modernising Hearing Aid Services (MHAS) project in England. It applies mainly to adults with mild to moderate sensorineural hearing loss who are being fitted with hearing aids. It assumes the current prescription rationale from the National Acoustic Laboratories (NAL-NL1) (Dillon, 1999), although fitting to other generic, well researched and documented rationales (e.g. Desired Sensation Level (DSL) i/o^2 , Cornelisse et al, 1995, or Camfit, Moore et al, 2001) is acceptable.

The second part, described in section 7 of this document, is based on guidelines from the Modernising Children’s Hearing Aid Services (MCHAS) project in England, and applies to children with mild to moderate sensorineural hearing loss who are being fitted with hearing aids. Recommendations for children include use of the DSL i/o prescription or NAL-NL1, and involves the use of real-ear aided response (REAR) rather than real-ear insertion gain (REIG). Unlike the guidance for typical adults, it may also involve the use of real-ear-to-coupler differences (RECDs).

Some guidance is also included here on adults and children with severe and profound hearing losses and with a conductive component to their hearing loss, although at the time of writing,

¹ The term audiologist in this context includes NHS Audiologists and Registered Hearing Aid Dispensers.

² The version of DSL i/o in common use in the UK at the present time is DSL i/o 4.1

there is no agreement on best clinical practice for fitting DSP hearing aids to these groups of patients.

The guidance for adults within this document does not necessarily apply to children with hearing aids who reach adulthood and transfer into adult services. Their care must be tailored according to their previous hearing aid management, but with due consideration of the principles contained within this document. Of utmost importance is that these young adults are not changed from one prescription to the other, without good reason, see National Deaf Children's Society Quality standards for more details.

This document is compatible with the British Standard: BS ISO 12124: 2001, Acoustics – Procedures for the measurement of real-ear acoustical characteristics of hearing aids. Guidance contained within this document is not manufacturer-specific.

2. Introduction

The recommendation from MHAS / MCHAS and from BSA / BAA is that all patients should undergo real-ear measurement, as appropriate, at their fitting appointment, along the lines suggested by Gatehouse et al, (BAAS newsletter, 2001, issue 36).

"...Where a fitting rationale contains an acoustical target, each hearing aid should be verified by REM using an input stimulus appropriate for the hearing aid under test. Tolerances to the prescription rationale of +/- 5 dB at frequencies of 250, 500, 1000 and 2000 Hz, and of +/- 8 dB at 3000 and 4000 Hz should be achieved in all cases. In addition the slope in each octave should be within +/- 5 dB/octave of the target...."

These tolerances are fairly loose, and depending on the degree of hearing loss often closer matches to targets can be achieved. However, more data on repeatability of REMs are needed before these recommended tolerances are changed.

Real-ear insertion gain differs from 2 cc coupler gain by clinically significant amounts and there is also evidence (Hawkins and Cook, 2003) showing that the hearing aid gain prescribed by a manufacturer's first fitting algorithm differs from targets generated by prescription rationales. Real-ear measurement is the only way to view the actual performance of a particular hearing aid and earmould on a particular patient. However, there is agreement that audiologists may not aim to "reach target" if patient response/opinion indicates otherwise. Fitting to target is a good starting point in the verification process, and for DSP hearing aids today, there are other features that may provide important benefit to patients besides gain and compression. For children however, who cannot provide subjective responses, it is appropriate to place more emphasis on matching target.

In summary, the reasons for using REM as part of the fitting process include:

- Differences do exist between coupler and real-ear measurements
- Patient benefit is greater if the target is well matched (Baumfield and Dillon, 2001, Mueller, 2005)
- A baseline measure from which to work is good practice, especially if the patient switches to a different aid later on.
- REM allows the effects of fine tuning to be seen.
- REM provides graphical confirmation to the audiologist that the intended prescription/processing strategy has been implemented by the hearing aid software. REM therefore helps the audiologist to understand the whole process.
- REM is useful in counselling the patient and family members around what they can and cannot hear.

- REM is useful to verify the function of advanced features, such as directional microphone and noise reduction technologies.

3. Background information

3.1 Why adults and children need different approaches

Children need to be considered differently from adults and there is still some uncertainty as to what constitutes normal hearing in infants (Ching et al, 2001). Acoustical differences between the ear canals of children and adults impact on both audiometric data and on hearing aid amplification. Thresholds recorded using the dB HL scale will vary depending on transducer type and age of the child, even though hearing sensitivity has not changed. This is because the dB HL scale is based on adult data. In order to avoid these measurement errors when prescribing amplification, thresholds may be expressed in sound pressure level at the tympanic membrane (dB SPL). They are then displayed on a SPLogram (rather than an audiogram which uses dB HL) and direct comparisons between hearing thresholds, hearing aid output and the long term average speech spectrum (LTASS) can then be made³. These measurement errors are generally smaller for adults, and may be minimal in adults with average ear canal size and resonance.

A more obvious difference between adults and children is that children are less likely to tolerate probe tube insertion for extended periods of time. An RECD can be measured in a few minutes and applied to coupler data to derive hearing aid output at the child's tympanic membrane. This avoids the child having to be present while fine tuning the hearing aid.

3.2 Choice of real-ear insertion gain or real-ear aided response

Real-ear insertion gain (REIG) differs from real-ear aided response (REAR) in that it takes into account the individual's real-ear unaided response (REUR), i.e. the natural "amplification" in the patient's open, or unoccluded ear canal.

There are advantages and disadvantages of using each measurement; one advantage of REIG is that placement of the probe tube is less critical than that required for REAR. The increase in SPL at the tympanic membrane can be measured at a mid-canal point as long as the probe is in the same place for the unaided and aided conditions of the REIG procedure (Dillon, 2001). This is particularly relevant to audiologists with no/little experience of probe tube measurement.

A patient whose REUR is close to the average is more likely to prefer amplification that takes his own REUR into account, i.e. prefers REIG, (Palmer, 1991). If the REUR is dissimilar to the average, as with cases of abnormal middle ears (e.g. mastoidectomy, perforation) or in children then it seems inappropriate to use REIG. A patient with a REUR that differs greatly from the average prefers amplification based on REAR (Palmer 1991).

Historically, REIG measures have been used in adults, and much of the literature, especially from NAL, uses REIG. REIG is currently recommended for use with adults, except those with abnormal middle ears/ REURs, (see Dillon, 2001, p248 for further explanation). Use of REAR is acceptable practice with adults and is the recommended practice with children, being the method of choice in DSL i/o.

3.3 Choice of prescription

A generic target is preferable to a manufacturer-specific target, as it is a validated evidence based procedure which will minimise the difference that a patient might hear when changing

³ There is some evidence to suggest that measuring thresholds in adults in dB SPL rather than dB HL leads to greater accuracy in hearing aid fittings (Saunders and Morgan, 2003).

aids from one manufacturer to another (Keidser et al, 2003). With the aim of updating patients' DSP aids regularly, it is likely that patients will change from one manufacturer to another over time.

For adults, the preferred prescription target is NAL-NL1. There is evidence to suggest that for some hearing losses DSL i/o prescribes more high frequency gain than preferred in adult users, (Moore et al 2001). More research, however, is needed in this area. For example, Parsons and Clarke suggest that directive counselling can ensure acceptance of DSL with adult fittings (Parsons and Clarke, 2002).

The preferred prescription target for children is DSL i/o. However, if children are fitted to NAL-NL1, REAR must be selected as opposed to REIG. This is because REIG targets are based on average adult ear canal resonance and are therefore inappropriate for use with children who often have ear canal resonances at higher frequencies than are typical for adults. Failure to apply the appropriate target could result in under-amplification in the mid frequencies. Another important reason for choosing REAR is because it allows visualisation of all relevant variables, e.g. if the decision is to "under amplify" relative to targets, then it is the only way to check that speech remains audible.

It is necessary to check whether the implementation of the prescription rule takes account of either binaural summation or conductive elements. An appropriate correction factor may need to be applied to targets for bilateral fittings (e.g. -3 dB) and for conductive elements (e.g. 25-75% of air-bone gap).

3.4 Choice of stimulus type

Until running speech (with time-averaging) is available widely, a modulated speech-shaped noise is recommended for both REIG and REAR procedures, for the following reasons:

- Broad band stimuli are less susceptible to the artefactual measurements related to hearing aid processing (e.g. the "blooming effect" which can be noted in the low frequencies when using a swept pure tone)
- Speech-shaped noise is a more realistic stimulus than tonal signals.
- Speech-shaped noise may be selected within the prescription software, thus ensuring compatibility of signals between prescribed gain and measured gain.
- Modulation of the speech-shaped noise enables the hearing aid to be set up as used by the patient without risk of the noise suppression circuits being activated, although audiologists need to check this with manufacturers' protocols for each individual type of hearing aid.
- At the time of writing, it is available on REM equipment in common clinical use in the UK
- Experience has shown that modulated speech-shaped noise is more user friendly for training purposes than e.g. International Collegiate of Rehabilitative Audiology (ICRA) processed babble or real speech. If the response is not time-averaged then it may be more difficult for inexperienced audiologists to relate the measured response to the prescription targets. When audiologists are confident with using REM with modulated speech-shaped noise, then using ICRA processed babble or live speech may be more appropriate.

In order to document that targets have been met accurately, it is preferable to use a time-averaged response for these modulated stimuli, if available.

For conducting real-ear saturation response (RESR) verification, where high intensity levels are employed, it is advisable to use a swept warble tone rather than a speech-shaped noise. This is because a warble tone will be less loud, and will be capable of achieving the desired stimulus level (e.g. 90 dB SPL) accurately at each frequency through the REM loudspeaker.

A broad band stimulus will probably have no single frequency near 90 dB SPL, and this may lead to underestimates of the real life performance of the aid. A warble tone can also be varied in centre frequency to allow fine tuning of the hearing aid in areas of discomfort.

Some hearing aid manufacturers use a broadband noise to set the maximum output (normally those with 10+ channels) therefore it is more appropriate to use a modulated speech-shaped noise to measure RESR for these aids. If in doubt, test with both a swept warble tone and speech-shaped noise signal and use the measurement which will ensure that the hearing aid is set most conservatively.

4. Setting up the equipment

Prior to using equipment, it is important to establish that the appropriate software defaults are loaded. Of particular importance are the stimulus type and display parameters. Hardware configuration should also be checked, in particular when measuring RECDs, check the positioning of coupler and reference microphones. If REM equipment is used for both paediatric and adult clinics it may be prudent to set up different files in which default settings appropriate for each clinic are included.

4.1 Ambient noise and environment

It is not necessary to perform REM in a sound-attenuating booth. However, a quiet room is preferable, in which the ambient noise should not alter the test results by more than 1 dB at any frequency. The test signal should be at least 10 dB above the noise floor in all frequency bands. The sound field environment should allow the test signal level to be controlled to within 3 dB of the desired test signal level (ISO 12124: 2001).

The loudspeaker should be positioned so that it is not at the back of a table, and there are not large, flat reflecting surfaces near the patient. If it is possible, the loudspeaker, and the reference microphone when positioned on the patient, should both be 1 m away from the nearest reflective surface. Having the loudspeaker facing the centre of the room is often the best way to set up the room. It is acceptable to site the loudspeaker on a wall as long as it is 1 m from the corner.

4.2 Calibration

The REM equipment must comply with BS EN 61669 (2001) and must have been subject to a full objective calibration within the last 12 months. If the equipment is portable, and used in a variety of different locations, it is advisable for this calibration to be carried out at 3-6monthly intervals, or more frequently if there is a possibility of the microphone being dropped.

4.3 Recording the results

The following data (stored electronically within NOAH if appropriate) should be included in the record or readily available:

- Patient ID, tester, test ear, date of test
- Details of equipment, including serial number and version number of software, and date of last calibration.
- Type of REM, e.g. aided response, insertion gain.
- Test signal, type and level, type of sound field, measurement method and method of equalisation used.
- Azimuth angle of sound incidence, elevation angle of sound incidence and distance from loudspeaker
- Type of hearing aid and its settings
- Type of coupling to the ear, including details of venting
- Ambient conditions

It is recommended that all traces are saved (i.e. initial settings, best match to REM and patient preference) at all intensity levels used, but it is not necessary to save traces that may have been recorded during the process of adjustment.

5. Procedure for verification in adults

Check that the appropriate prescription target (e.g. NAL-NL1) has been selected within the REM software. Also check that the parameters within the software are selected correctly, e.g. multi-channel limiting, number of channels of compression, compression threshold, bilateral/unilateral, date of birth, vent size.⁴ The reference position should be head surface, and orientation set at 45° or 0°.

5.1 Tube calibration

This must be done each time a new probe tube is used. That is, it must be done for each patient, and if the probe tube is changed halfway through testing a patient, the probe calibration must be repeated.

Place the probe tube so that it is close to the reference microphone aperture, without blocking either of the microphones. Hold the headset 0.5 m front of the loudspeaker so the microphone and probe are facing the loudspeaker. Your hand should not be between the loudspeaker and the microphone. Having ensured good position of the headset, run the calibration procedure.

5.2 Check calibration

Holding the tube and microphone in the same position, record as if an open ear response were being measured using a 65 dB SPL broad band (e.g. pink noise) stimulus. Check that there is a flat response (as defined by the supplier of the equipment). If not, repeat the calibration. Below 250 Hz this may not be achievable - within 5 dB is acceptable.

NB See also section 4.2 on calibration.

5.3 Prepare patient

The patient should be seated so that the ear under test is:

- (a) at 45° or 0°⁵ azimuth to the loudspeaker, (there should be a policy on this within a department, and all patients should be seated at the same angle) and
- (b) at a distance of 0.5 m from the loudspeaker, and level with the centre of the loudspeaker itself, rather than its cabinet (not higher or lower).

It is helpful to attach a piece of string to the loudspeaker, to enable easy positioning of the patient, and also to have markers on the wall for the patient to look at. There is useful evidence-based guidance on aspects of patient placement (Stone and Moore, 2004). They tentatively suggest that 0° is preferable to 45° because this led to less variability with position in the REUR.

The patient should be instructed to sit as still as possible during recording, in particular to maintain the same head position. They should also be informed that they may interrupt the test at any time in the case of discomfort.

⁴ The number of adult patients with open ear fittings is currently increasing with more sophisticated feedback management systems. It is essential for verifying these fittings that all software is set appropriately, and that REM equipment is applying a substitution-like method (Lantz et al, 2007) and see glossary. It may also be appropriate for patients with mild-moderate hearing impairments to accept poorer matches to target at frequencies below 1000 Hz in order to provide the benefits of non-occluding earmoulds.

⁵ 0° azimuth is achieved when the patient's nose is directly facing the loudspeaker.

5.4 Otoscopy

Otoscopy must always precede REM. Proceed with caution in any of the following circumstances: perforation, grommet, mastoid cavity, discharge or glue ear, wax filling more than one-third of the cross-sectional area of the canal. As discussed in section 3.2 above, it may be advisable in these circumstances to consider fitting to real-ear aided response (REAR), rather than insertion gain (REIG). See section 6.4.2 for details on REAR measurement.

5.5 Insertion of probe tube

Always use a new probe tube for each patient. It is recommended to use the thinner (e.g. 1.1 mm) probe tube since this will be less uncomfortable for the patient if you touch the canal wall or tympanic membrane.

Accurate placement of the probe tube is important. ISO 12124 (2001) describes four methods for inserting the probe tube in order to achieve the general requirement that the sound inlet of the microphone is within 6 mm of the tympanic membrane, and at least 5 mm (wherever possible) beyond the sound outlet of the hearing aid.

This document recommends a combination of two of the methods described in ISO 12124 (2001). Visual positioning, using a marker 27 mm from the end of the probe tube, is used initially, with an acoustic positioning check later at 6000 Hz, as described in section 5.6.

Set marker 27 mm (this length may be varied to accommodate shorter or longer ear canal lengths) from the end of the probe tube, check that the probe tube will extend 5 mm beyond the sound outlet of the hearing aid. If so, insert probe tube down the ear until the marker is at the tragus. If not, the 27 mm may be extended, but with caution, particularly in small ears. It is helpful to attach a short (15 cm) ruler to the top of the REM equipment so that measuring 27 mm is very quick.

Use an otoscope to check that the probe-tube is lying along the bottom of the canal.

5.6 Measure real-ear unaided response (REUR)

With the probe tube in place down the ear, use a 65 dB SPL broad band (e.g. pink noise) stimulus. As this measurement is used to derive gain, the precise spectrum of the broad band stimulus is not critical.

After the response has stabilised, check that it does not look very peaky, or that the absolute gain at 6000 Hz is not below -5 dB. If it is, reposition probe or move patient slightly. Record the response.

Carefully insert the earmould and hearing aid into the ear, being careful not to dislodge the probe tube. With the hearing aid in place, the marker should still be at the tragus.

5.7 Measure real-ear occluded response (REOR)

With the hearing aid switched OFF (muted in the software), record using a 65 dB SPL broad band (e.g. pink noise) stimulus.

A reduction of the peak around 2000 -3000 Hz (the natural resonance of the ear canal) is expected. Check that the gain has not reduced very much at the low frequencies. If so, reposition the hearing aid, and check the probe tube for wax/moisture.

The REOR may also be used to check for any vent associated resonance (e.g. around 500 Hz) which may alert the audiologist to consider earmould modifications.

5.8 Derivation of real-ear insertion gain (REIG)

Switch the aid on (unmute it in the software) without moving it. It should be on the everyday listening programme with all its usual features⁶ left on, the correct vent size having been selected. Leave on feedback cancellation where appropriate to avoid feedback.

Select an input of 65 dB SPL modulated speech-shaped noise stimulus and record. (If you choose to use a steady noise for any reason, e.g. your REM equipment does not have a suitable modulated speech-shaped noise stimulus, disable any gain reducing noise reduction strategies on the hearing aid before making measurements.)

Remember to consider use of real-ear aided response (REAR) rather than real-ear insertion gain in cases where the middle ear is abnormal, or the real ear unaided gain is atypical

5.9 Modify the programming in the aid

Compare the measured REAR or REIG to the target values. If necessary, adjust the programming software to bring the measured values close to the target values for the stimulus type and level being used. It is more efficient to adjust the programming while viewing the REIG or REAR in real time. If the programming software provides acclimatisation / adaptation levels that reduce the gain for first time users, it is advisable to set the aid to the highest acclimatisation / adaptation level for verification to generic targets.

Advice from hearing aid suppliers should be sought regarding the most appropriate modifications to make in particular individual circumstances.

Verification using 65 dB SPL will ensure audibility for the average speech intensity level. Verification at different input levels (e.g. 50, 65 and 80 dB SPL) is useful for the audiologist to provide visual confirmation that the appropriate processing strategy has been implemented by the hearing aid fitting software.

When using 80 dB SPL, proceed with caution, and only if you are an experienced audiologist, (or an audiologist under supervision, as deemed appropriate by Head of Department). For some patients, consider increasing the intensity in steps from 65 dB SPL, rather than going straight up to 80 dB SPL, to check that no discomfort is experienced. It may be necessary to adjust gain for soft sounds differently from gain for loud sounds to get close to target at all input levels. Consider adjusting the maximum power output (MPO) if indicated by any report of loudness discomfort, or to achieve target for 80 dB SPL input. In some rooms, it may be necessary to record at 55 or 60 dB SPL rather than 50 dB SPL, see section 4.1 on ambient noise.

If, after adjustment, the patient finds the sound of the hearing aid too loud, use clinical judgement and reduce the acclimatisation/ adaptation level of the aid. Ensure that these changes maintain the frequency shaping that you have set during REM. (If changing the acclimatisation/ adaptation level does not preserve the frequency shaping, then use the gain controls to achieve acceptable loudness levels for the patient.)

5.10 Check output does not exceed uncomfortable loudness levels

This is an essential part of every hearing aid fitting and it is especially important if the gain has been increased to meet the target at 65 dB SPL. It is an area where there has been much debate amongst “experts,” but there is consensus that it is preferable to adjust the MPO in a

⁶ Directional microphones should be set to omni-directional, unless specific measurements of directionality are being made.

controlled way in the clinic, rather than leaving the patient open to the possibility of discomfort in real life situations. It may be achieved in one of the following two ways:

- Measure real-ear saturation response (RESR). **Proceed only with caution, and only if you are an experienced audiologist**, (or an audiologist under supervision, as deemed appropriate by Head of Department). A 90 dB SPL signal can be used to ensure that the patient's uncomfortable loudness level (ULL) is not being exceeded.⁷ It may be appropriate to work up in steps to a signal of 90 dB SPL for some patients. RESR should be performed using REAR rather than REIG. In general, a warble tone is preferable to a noise for reasons as stated in section 3.4 on stimulus type. It may be preferable to test discrete frequencies (e.g. at frequencies where the REAR peaks) prior to, or instead of, using a sweep across all frequencies.

The patient should be warned that the signal is loud, and (where appropriate) that the tone will sweep up through the frequencies, taking longer than the modulated speech-shaped noise. **Always use clinical judgement and caution as appropriate, particularly in patients with tinnitus or hyperacusis.** If the patient expresses or shows discomfort, stop immediately, adjust the MPO and re-test.

- Use a coupler-derived approach, for example by measuring the patient's RECD (see appropriate section in paediatric protocol) to measure RESR. Another option would be to make coupler measurements first and adjust the MPO if required, before carrying out RESR measurements in-situ as described above.

Additionally, use environmental sounds to check that output does not exceed uncomfortable loudness levels, e.g. use of a spoon in a cup near the ear, banging scissors on a desk, sending the patient to walk along a busy road, etc

It is the responsibility of the audiologist to consider the Noise Risk Criteria set by the Physical Agents Directive and balance this for each individual patient against the clinical benefits obtained from measurements. Noise exposure from other audiometric testing (e.g. masking in pure tone audiometry, determination of uncomfortable loudness levels, acoustic reflex testing) should also be considered. (See Physical Agents Noise Directive, 2003/10/EC).

It is advisable for audiologists to position themselves away from the loudspeaker to avoid excessive noise exposure.

At the end of the REM session, the probe tube should be carefully removed and the ear checked by otoscopy.

6. Procedure for verification in children

For children the use of real-ear aided response (REAR) is recommended. The REAR can either be measured or estimated by a coupler-derived approach.

For the measurement of hearing thresholds in children, the selection of transducer type is particularly important, as it will dictate which correction factor is used to convert thresholds in dB HL to dB SPL at the tympanic membrane. Whenever possible insert earphones coupled to custom earmoulds should be used to measure hearing thresholds and RECDs measured to ensure accurate conversions. An RECD should also be measured if coupler-derived as

⁷ Some equipment has an automatic cut-off to prevent sound pressure levels exceeding a user-specified value.

opposed to in-situ measurements are employed. It is important to ensure that any options for hearing aid type, signal processing strategy and compression threshold are set appropriately.

6.1 Tube calibration (same as adult protocol)

This must be done each time a new probe tube is used. That is, it must be done for each patient, and if the probe tube is changed halfway through testing a patient, the probe calibration must be repeated.

Place the probe tube so that it is close to the reference microphone aperture, without blocking either of the microphones. Hold the headset 0.5 m front of the loudspeaker so the microphone and probe are facing the loudspeaker. Your hand should not be between the loudspeaker and the microphone. Having ensured good position of the headset, run the calibration procedure.

6.2 Check calibration (same as adult protocol)

Holding the tube and microphone in the same position, record as if an open ear response were being measured using a 65 dB SPL broad band (e.g. pink noise) stimulus. Check that there is a flat response (as defined by the supplier of the equipment). If not, repeat the calibration. Below 250 Hz this may not be achievable - within 5 dB is acceptable.

6.3 Otoscopy

Otoscopy must always precede REM. Proceed with caution in any of the following circumstances: perforation, grommet, mastoid cavity, discharge or glue ear, wax filling more than one-third of the cross-sectional area of the canal.

6.4 Decide on coupler-derived (RECD) or in-situ REAR approach

At this juncture, the audiologist will need to make a decision as to whether to follow a coupler-derived approach (section 6.4.1) which will include the measurement of an RECD, or an in-situ REAR measurement (section 6.4.2). This decision will depend on a number of factors including how co-operative the child is. A coupler-derived approach using a measured RECD has been shown to be reliable and accurate (Munro and Hatton, 2000), and offers the advantages of only requiring one measurement, and more effective use of clinical resources.

If a coupler-derived approach is adopted but the RECD has not been measured, (i.e. steps 6.4.1.1. and 6.4.1.2. are not carried out) the audiologist should verify that an appropriate predicted RECD transform is employed and particular attention should be paid to the correct calculation of the child's age by the software.

6.4.1. Measurement of the real-ear to coupler difference (RECD)

6.4.1.1. Coupler measurement

Wherever possible, the coupler step should be measured first (this does not require the presence of the patient and can be performed in advance to maximise use of clinical time).

Ensure the reference microphone and measurement microphones are connected to the correct ports, and that the REM system is in coupler mode. Carefully couple the insert earphone transducer to the coupler, using a length of tubing the same as used for a BTE fitting. Close the test box lid.

Record the microphone response in the coupler (the stimulus type and level are usually pre-set by the equipment). On some equipment it is possible to use a stored coupler response. This is a non-physiological measurement, and should not change over time. Changes may indicate problems with the coupler and/or coupling or the need for the coupler microphone or test box to be recalibrated. It is suggested that a laminated template is produced of the expected response, so that the audiologist can easily identify such changes.

6.4.1.2. Real-ear measurement

The next step is to perform the real-ear measurement, which will require careful placement of the probe tube in the child's ear.

Always use a new probe tube for each patient. It is recommended to use the thinner (e.g. 1.1 mm) probe tube since this will be less uncomfortable for the child if you touch the canal wall or tympanic membrane.

Accurate placement of the probe tube is especially important. ISO 12124 (2001) describes four methods for inserting the probe tube which are adult specific (see adult protocol). Modifications for paediatric populations are as follows:

The black marker on the probe tube should be set according to the following guidelines:

0-6 months	11 mm
6-12 months	15 mm
1-5 years	20 mm
5+ years	25 mm

Following otoscopy the probe tube is inserted down the ear until the marker is at the tragus. It is helpful to attach a short (15 cm) ruler to the top of the REM equipment so that measuring the marker distance is very quick. Use an otoscope to check that the probe-tube is lying along the bottom of the canal. It is ideal to ensure the end of the probe tube is at least 5 mm beyond the end of the earmould tip to avoid standing wave effects. In infants this may not be possible due to short canal lengths.

Carefully insert the earmould (attached to the insert earphone transducer) into the ear, ensuring that the probe tube is not dislodged. Measure the second part of the RECD.

Alternative probe tube insertion for measuring RECDs in infants less than 6 months of age involves inserting the probe tube and tip at the same time (Bagatto et al, 2006). The probe tube can be coupled to the earmould, or an otoacoustic emission (OAE) tip using cling film and a distance of 11 mm from the marker to the end of the tube.

RECDs should be measured bilaterally but if this is not possible the RECD recorded from one ear should be used on the untested ear (Munro and Butfield, 2005), assuming similar middle ear function based on the findings of otoscopy and tympanometry. It is considered good practice to save these RECD measurements in an explicit NOAH session prior to proceeding to further verification to minimise the risk of possible data loss.

6.4.1.3 Coupler-derived REAR measurement

Carefully couple the hearing aid to the coupler, using a length of tubing the same as used for a BTE fitting.

Check that the appropriate target has been set in the REM software and that you are in the correct measurement (coupler-test) mode. Ensure that you have selected either measured RECD or predicted RECD, according to which measurement you are using.

Switch the hearing aid on (or unmute it in the software). It should be on the everyday listening programme with all its usual features left on, highest acclimatisation level and the correct vent size having been selected.

Select an input of 65 dB SPL modulated speech-shaped noise stimulus and record the REAR. (If you choose to use a steady noise for any reason, e.g. your REM equipment does not have a suitable modulated speech-shaped noise stimulus, disable any gain reducing noise reduction

strategies on the hearing aid (select in-situ/coupler test in hearing aid software) before making measurements.)

Compare with the 65 dB SPL target making a note of any frequencies where the response deviates substantially from the target. Increase the input level to 80 dB SPL and then decrease it to 50 dB SPL noting any discrepancies from target.

Linear hearing aid (peak-clipping or output compression limitation)

Follow the procedure above but test at 65 dB SPL input level only (additionally at 80 dB SPL for output compression limitation). Make sure the appropriate parameters are selected in the REM software.

6.4.2. In-situ REAR approach

6.4.2.1. General

In theory, as the REAR is an absolute measure, it is not necessary to measure a REUR. However, if the child is co-operative it may be worthwhile performing this measurement as it is an additional check of good probe tube placement and to inform the audiologist of any significant deviations in ear canal acoustics.

The child should be seated so that the ear under test is at 45° or 0° azimuth to the loudspeaker. However, young children conditioned to Visual Reinforcement Audiometry will turn their head in response to loudspeaker signal. With this group of children it is more appropriate to have them positioned at 0° azimuth and have an interesting picture on the wall or other distracter for the child. They should be seated 0.5 m from the loudspeaker, and level with the centre of the loudspeaker itself, rather than its cabinet (not higher or lower).

Once again, careful probe tube positioning is required for in-situ REAR measurements, and the same guidance as for RECDs should be followed (see section above).

6.4.2.2. REUR measurement (optional)

With the probe tube in place down the ear, use a 65 dB SPL broad band stimulus. After the response has stabilised, check that it does not look very peaky, or that the absolute gain at 6000 Hz is not below -5 dB. If it is, reposition probe or move patient slightly. Record the response.

6.4.2.3. REAR measurement

Carefully insert the earmould and hearing aid into the ear, being careful not to dislodge the probe tube. With the hearing aid in place, the marker should still be at the tragus.

Non-linear hearing aid

Check that the appropriate target has been set in the REM software and that you are in the correct measurement (e.g. real-ear/probe) mode

Switch the hearing aid on (or unmute it in the software). It should be on the everyday listening programme with all its usual features left on, highest acclimatisation level and the correct vent size having been selected.

Select an input of 65 dB SPL modulated speech-shaped noise stimulus and record. (If you choose to use a steady noise for any reason, e.g. your REM equipment does not have a suitable modulated speech-shaped noise stimulus, disable any gain reducing noise reduction strategies on the hearing aid (select in-situ/coupler test in hearing aid software) before making measurements.)

Compare with the 65 dB SPL target making a note of any frequencies where the response deviates substantially from the target. Increase the input level to 80 dB SPL and then 50 dB

SPL noting any discrepancies from target. **When using 80 dB SPL, proceed with caution, and only if you are an experienced audiologist,** (or an audiologist under supervision, as deemed appropriate by Head of Department). For some patients, consider increasing the intensity in steps from 65 dB SPL, rather than going straight up to 80 dB SPL, to check that no discomfort is experienced.

Linear hearing aid (peak-clipping or output compression limitation)

Follow the procedure above but test at 65 dB SPL input level only (additionally at 80 dB SPL for output compression limitation). Make sure the appropriate parameters are selected in the REM software.

6.5. Modify the programming in the aid

Depending on the selected approach, this will be performed either on the coupler or in-situ. Ensure that if a coupler -derived approach has been employed that the REM system is in coupler mode (use probe/real-ear mode if an in-situ approach).

It may be appropriate to incorporate any measured RECD data into the hearing aid software to improve the accuracy of the initial 'auto-fit'. If this is the case the audiologist should be clear how this information is being utilised by the hearing aid software.

Make the necessary adjustments in the hearing aid software to best match targets at all input levels. This usually requires separate adjustments for soft input levels (50-65 dB SPL) and loud input levels (80 dB SPL). If possible make adjustments to the aid while the relevant signal level in the REM system is running so that effects of any modifications are immediately recorded. For some combinations of software and hardware this may not be possible and staff are advised to test this out in their own department: seek advice from hearing aid suppliers.

If precise matching of targets at **all** input levels is not possible, consider the implications. Young children acquiring language may benefit from more precise matching of soft speech targets (Dillon 2001). It may also be argued that matching the very loud target is important to avoid exceeding the uncomfortable loudness level, and to verify the wide dynamic range compression strategy of the hearing aid.

If the hearing aid is under target for soft input levels (50 dB SPL) it is likely that the hearing aid is functioning in a linear fashion and therefore the volume control should be activated. Compromises in matching all three targets may have to be made. The target may not be met for soft levels of a speech shaped noise because of low level expansion, especially at high frequencies.

6.6. Check output does not exceed uncomfortable loudness levels

This is an essential part of every hearing aid fitting and it is especially important if the gain has been increased to meet the target at 65 dB SPL. It is an area where there has been much debate amongst "experts," but there is consensus that it is preferable to adjust the MPO in a controlled way in the clinic, rather than leaving the patient open to the possibility of discomfort in real life situations.

Measure real-ear saturation response (RESR). **Proceed only with caution with in-situ measurements, and only if you are an experienced audiologist,** (or an audiologist under supervision, as deemed appropriate by Head of Department). High level verification can be performed either in-situ or by utilisation of a coupler-derived approach, for example by measuring the child's RECD (see above). It should be performed using REAR rather than REIG.

A 90 dB SPL warble tone can be used to ensure that the child's (predicted) uncomfortable loudness level (ULL) is not being exceeded and that the patient is happy at high intensity levels. In general, a warble tone is preferable to a noise for reasons as stated in section 3.4 on stimulus type. It may be preferable to test discrete frequencies (e.g. at frequencies where the REAR peaks) prior to, or instead of, using a sweep across all frequencies.

The audiologist should be aware of any potential limitations of using predicted ULLs.

It is advisable to verify the hearing aid response at this high intensity level in a coupler initially to avoid any discomfort (note:- this will necessitate the measurement of the RECD- see section 5).

If an in-situ REAR has been performed then carefully remove the hearing aid from the earmould and couple using a length of tubing the same as used for a BTE fitting.

Select coupler mode in the REM software.

Adjust the maximum output of the hearing aid if ULLs are exceeded or 90 dB SPL targets are not matched. ULLs should never be exceeded, whenever possible shape the maximum power output (MPO) using the appropriate electroacoustic parameters.

If an isolated peak is present in the hearing aid response which exceeds target or ULL, consider the use of a greater degree of damping. Always use clinical judgement if RESR is to be measured in-situ and warn the child that the signal is going to be loud, and stop immediately if the child shows discomfort.⁸

It is the responsibility of the audiologist to consider the Noise Risk Criteria set by the Physical Agents Directive and balance this for each individual child against the clinical benefits obtained from measurements. Noise exposure from other audiometric testing (e.g. visual reinforcement audiometry, acoustic reflex testing) should also be considered. (See Physical Agents Noise Directive, 2003/10/EC).

It is advisable for audiologists to position themselves away from the loudspeaker to avoid excessive noise exposure.

7. Notes on other types of patients

Patients with a conductive element to their hearing loss.

Be aware that real-ear measurement on ears with conductive hearing loss needs careful interpretation because it is difficult to know whether the intensity level that is recorded is the same as that being transmitted into the middle ear (e.g. Cleaver, 1998). However, in an ear with a stable conductive hearing loss, REM will be useful as a baseline measure at least.

It is generally accepted that patients who have a conductive element to their hearing loss need more gain than those with pure sensorineural losses.

If the patient has a significant conductive loss, (use >15dB air-bone gap averaged over 500, 1000 and 2000 Hz as a guideline), then a percentage of the conductive element (between 25-75%) may be added to the target to increase overall gain. Audiologists need to be clear whether any additional gain is added to the targets generated within the hearing aid fitting

⁸ Some equipment has an automatic cut-off to prevent sound pressure levels exceeding a user-specified value.

software, (most manufacturers will slightly modify generic prescriptions), and ensure that verification with REM also takes this into account.

However, listen especially carefully to the patient's comments on the loudness of the sound, and apply extra caution in cases of fluctuating air conduction hearing levels especially in children.

Patients who have a **purely** conductive hearing loss may prefer a linear fitting strategy. Further research is needed in this area especially for children, however this population can generally tolerate higher gain and maximum output than children with SNHL (Stelmachowicz, personal communication).

Note that NAL-NL1 will take account of bone conduction thresholds, but is important that the appropriate parameters are selected in the NAL-NL1 setup screen.

DSL [i/o] 4.1 does not take account of bone conduction thresholds but DSL m[i/o] 5.0 does (see Poster by Bagatto et al, Sound Foundation, Chicago, 2004)

Patients with severe hearing losses.

The guidance is broadly the same for patients with severe losses as with mild to moderate losses. However, the emphasis is more on audibility and comfort rather than strict adherence to targets.

Patients with a profound hearing loss

It is generally accepted that hearing aid amplification for adults with an acquired profound sensorineural hearing loss often improve a patient's lip-reading skills. High compression ratios (>3:1) should be avoided and the patient may benefit from a linear (peak-clipping or output compression limitation) strategy. However, there are examples of the benefit of wide dynamic range compression (WDRC) for children and young adults with severe to profound hearing impairment (Marriage et al, 2005). Again the emphasis is more on audibility and comfort rather than strict adherence to targets.

8. Glossary

There is a certain amount of confusion surrounding terminology in real-ear measurement work. For the purposes of this document, the terms “insertion gain” and “aided response” have been used throughout. Insertion gain refers to the difference (gain) in decibels between an aided and an unaided measurement, whereas aided response refers to the dB SPL (output) that is measured in the ear canal when the hearing aid is in-situ and switched on. The position in the ear canal at which real-ear measurements are made is referred to as the “measurement point.”

It is noted that equipment in common use at the time of writing use varying terms, and that within NAL-NL1, REAR is referred to as REAG. The definitions below represent ISO12124 (2001). Care needs to be taken to ensure correct interpretation of the terminology!

Real-ear unaided gain (REUG)

The difference in dB, between the SPL at the measurement point and the test signal level, as a function of frequency, with an un-occluded ear canal.

Real-ear unaided response (REUR)

SPL as a function of frequency at the measurement point for a specified test signal level with an un-occluded ear canal.

Real-ear occluded response (REOR)

SPL as a function of frequency at the measurement point for a specified test signal level with the hearing aid in place and turned off.

Real-ear aided gain (REAG)

Difference in dB as a function of frequency between the SPL at the measurement point and test signal level with the hearing aid in-situ and turned on.

Real-ear aided response (REAR)

SPL at the measurement point as a function of frequency for a specified test signal level with a hearing aid in-situ and turned on.

Real-ear insertion gain (REIG)

The difference in dB as a function of frequency, between the real-ear aided response and the real-ear unaided response or between the real-ear aided gain and the real-ear unaided gain.

$REIG = REAR - REUR$ or $REIG = REAG - REUG$

Real-ear saturation response (RESR)

Measurement of the sound pressure level at the measurement point with the hearing aid in-situ and turned on and with sufficient stimulus level to drive the hearing aid into its maximum output (normally 90 dB SPL pure tone).

Substitution method

A method of measurement using stored (rather than concurrent) equalisation where the SPL at the reference microphone is calibrated in a separate measurement with the hearing aid inactive. The reference microphone does not then influence the test signal from the loudspeaker.

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