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Practice Guidance

Guidance on the verification of hearing devices using probe microphone measurements

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General foreword

To the best knowledge of the BSA, this Practice Guidance represents the evidence-base and consensus on good practice, given the stated methodology and scope of the document and at the time of publication.

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Contents

1.	Scope.....	5
2.	Introduction	5
3.	Background information	6
3.1	Prescriptive targets	6
3.2	Tolerance for probe microphone measurements	6
3.3	Choice of stimulus	7
3.4	Gain or Response	7
4.	Setting up the equipment	7
5.	Ambient noise and environment	8
6.	Annual calibration	8
7.	Recording the results	8
8.	Procedure for verification	8
8.1	In-situ or real ear measurements (REM)	8
8.1.1	Probe tube calibration	8
8.1.2	System calibration	9
8.1.3	Preparing the patient	10
8.1.4	Ear examination	10
8.1.5	Insertion of probe tube	11
8.1.6	Measurement of real-ear unaided response (REUR)	12
8.1.7	Measurement of real-ear occluded response (REOR)	12
8.1.8	Verification of open fitting	13
8.1.9	Recording real-ear aided response (REAR) or speech-mapping	13
8.1.10	Output sound pressure level (OSPL) or real ear saturation response	16
8.2	Coupler based measurements	17
8.2.1	RECD measurement	17
8.2.2	Aided gain measurements in coupler using RECD	19
8.2.3	OSPL or RESR in coupler	20
8.3	Verification of frequency lowering	21
9.	Aided SII and Goodness of Fit (GoF)	24
10.	References	25





1. Scope

This document is a revised version of the joint BSA/BAA document 'Guidance on the use of real ear measurement to verify the fitting of digital signal processing hearing aids' (2007).

The scope of this guidance is limited to hearing device fitting verification via probe microphone measurements. It does not address the wider hearing healthcare issues of, for example, validation of fitting via outcome measures, counselling, and family centred care. For further information on various aspects of hearing healthcare, readers are referred to the BSA guidance on Common Principles of Rehabilitation for Adults in Audiology Services (2016). It is important to remember that probe microphone measurements are a good starting point for hearing device fittings, but should not preclude further adjustment based on patient feedback and clinical judgement.

The principles laid out in this guidance are relevant to the current practices in probe microphone measurement. As both hearing device and verification technologies evolve and new evidence emerges, audiologists will be required to take contemporary developments into consideration to make the professional decisions with regards to the best verification strategy.

2. Introduction

Probe microphone measurements are used to verify frequency response and other performance characteristics of hearing devices. They ensure that hearing devices are set appropriately to provide optimal prescribed gain and output in users' ears.

There are a variety of different prescriptive fitting formulae available to audiologists in the verification software, including but not limited to: NAL-NL2 (National Acoustic Laboratory – Non-linear 2), DSL m(i/o) (Desired Sensation Level multistage input/output) and CAMEQ (Cambridge Loudness Equalisation Method). Evidence suggests that fitting to prescriptive target levels will lead to more comfortable listening, and significantly improved speech quality and intelligibility than fittings that deviate significantly from target (Byrne, 1986; Byrne and Cotton, 1988; Moore and Glasberg, 1998; Moore et al, 2001; Bentler et al, 2016). Also, for children, fitting closely to targets has been shown to ensure consistent audibility (McCreery et al, 2013; 2015), with the resulting improvement to speech audibility being an important factor in long term outcomes (Tomblin et al, 2015).

Therefore, it is important to verify if the hearing device is achieving the target level of amplification in the individual ear. Probe microphone measurements are a reliable and accurate procedure for determining how well a hearing device is matching a prescription target, and for adjusting the device in order to improve the match (Aazh & Moore, 2007). Additionally, they can be used in verifying digital features such as directionality, noise reduction and frequency lowering. (See Ontario Infant Hearing Program protocol, Child Amplification Laboratory, 2014).





This guidance recommends the use of probe microphone measurements as a starting point for the hearing device fitting process. We will lay out the technique of probe microphone measurements for children and adults in the next few sections of this document.

3. Background Information

3.1 Prescriptive targets

The choice of prescriptive targets can be broadly classified into two categories: manufacturers' proprietary targets (developed for particular hearing devices by its manufacturer) and generic targets (e.g. NAL, DSL, and CAMEQ). Research shows that the gain provided by manufacturers' version of prescriptions can differ significantly from targets such as NAL (Keidser, 2003; Hawkins and Cook, 2003; Bentler, 2004; Aarts and Caffee, 2005; Leavitt and Flexer, 2012; Sanders et al, 2015 and Munro et al, 2016). Furthermore, proprietary targets are often not available in the verification software.

This guidance recommends the use of a consistent approach to amplification provision across different manufacturers' products. It is therefore recommended that generic prescriptive targets (i.e. NAL-NL2 or DSL v5.0) should be used for hearing device fitting. It is beyond the scope of this document to describe the principles of these prescriptions but a review is available in Bentler et al (2016).

Changing existing hearing device users to a different prescription should be avoided without an appropriate clinical reason, as the speech recognition ability of these patients may be compromised by changing the acoustical characteristics of their amplification (Convery & Keidser, 2011). Further evidence is required for making such recommendations regarding younger age groups however the National Deaf Children's Society's transition guidance for young people (NDCS, 2013) recommends that the prescriptive method is not changed when young people are transferred to adult services, particularly with severe and profound losses.

Some of the advanced features in modern hearing technology, such as frequency lowering, can also be verified using probe microphone measurements. See Section 8.3 of this document for further detail on fitting frequency lowering hearing devices.

3.2 Tolerances for probe microphone measurements

Response curves ideally should fall within a tolerance of ± 5 dB to the prescription target where possible. In addition, the slope in each octave should be within ± 5 dB/octave of the target frequencies between 250Hz and 6000Hz (page 131, Bentler et al, 2016). Where the overall output shape and/or feedback from the patient precludes this, clinicians should make a professional judgement on whether to leave the prescription gain outside this tolerance limit. Any clinical reasoning should be recorded in patient notes.





3.3 Choice of stimulus

There is a wide choice of stimuli available in current probe microphone measurement equipment, and different hearing device manufacturers may recommend different signals for verifying their instruments. It is recommended that a pre-recorded, calibrated, modulated speech signal such as the International Speech Test Signal (ISTS) (BS EN 60118-15) or International Collegium of Rehabilitative Audiology (ICRA) steady noise (Dreschler et al, 2001) be used for verification.

At the time of writing, the most appropriate signal to use is ISTS as it can be used to verify the performance of a hearing device with most adaptive features enabled (as it will be used by the patient). A minimum measurement duration of 10 seconds is required in order for the Long Term Average Speech Spectrum (LTASS) measurement to result in a stable, repeatable result (Olsen, 1988; Holube et al, 2010; Page 71, Bentler et al, 2016).

The recommended stimulus is ISTS with a minimum recording time of 10 seconds.

Be aware that when digital signal processing hearing devices are tested with non-speech stimuli (including tone sweeps or composite noise (modulated speech noise/speech weighted noise), the measured gain can be substantially different from that achieved for real speech-based stimuli such as ISTS (Scollie and Seewald, 2002; Henning and Bentler, 2005).

3.4 Gain or Response

In probe microphone terminology the letter 'G' refers to Gain and 'R' to Response. Gain is derived by subtracting the input level (stimulus) from the hearing device output level for any given measurement; whereas Response refers to the overall output level for a measurement. REAR is the absolute frequency response of a hearing device as measured in the ear canal when the device is switched on. REIG is derived by subtracting the ear's natural amplification (Real Ear Unaided Gain, REUG) from the aided gain (Real Ear Aided Gain, REAG). $REIG = REAG - REUG$.

This guidance will mainly refer to Real Ear Aided Response (REAR) and this measurement is recommended for all real ear and coupler measurements made for both adults and children. Real Ear Insertion Gain (REIG) is also referred to in the sections below.

4. Setting up the equipment

Prior to using equipment, it is important to establish that the appropriate software settings are loaded. Of particular importance are the stimulus type and display parameters. The test environment should be such that the patient is not seated next to a reflective surface. Audiologists and other persons present should be sufficiently far away from the patient to ensure they themselves do not become a reflective surface, affecting the measurements (Bentler et al, 2016).





5. Ambient noise

Probe microphone measurements should be performed in a quiet room where the ambient noise does not alter the test results. 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.

6. Annual Calibration

The probe microphone measurement equipment must comply with BS EN 61669 and must have been subject to a full objective calibration within the last 12 months or sooner if there is a possibility of components having been damaged. It is recommended to follow the manufacturer's guidance regarding recalibration of components that need to be replaced due to faults or damage.

7. Recording the results

Data regarding the equipment, measurement parameters and hearing aids should be recorded in the electronic patient management system by the verification software being used. All measurement traces should be saved in the software and any noise during testing or departures from the recommended procedure should be recorded in the patient's notes.

8. Procedure for verification of hearing device settings

This section will discuss the following two categories of verification:

1. In-situ or real ear measurements
2. Coupler based measurements

8.1 In-situ or real ear measurements (REM)

This is the most direct method of verifying a hearing device fitting. It involves the measurement of hearing device output in the ear canal.

8.1.1 Probe tube calibration

Probe tube calibration is performed to remove the acoustic effects of the probe tube from the measurements. The process can detect a damaged or poorly coupled probe tube and should be performed for each patient and every time a new probe tube is used.





To perform the calibration, place the end of the probe tube so that it is close to the reference microphone aperture, without blocking either the microphone or the end of the probe tube. Unless otherwise indicated by the equipment provider, hold the headset 0.5m in front of the loudspeaker where the patient will be seated so the microphone and probe are facing the loudspeaker. Your hand should not be between the loudspeaker and the microphone.



Best practice would be to have the patient present and the probe microphone headset placed on the patient's ear. Having ensured a good position of the headset, run the calibration procedure.

8.1.2 System Calibration

Probe microphone measurement systems have a microphone near the ear to monitor the test signal. This is called the controlling, regulating or reference microphone. We will refer to it in this document as the 'reference microphone'. A system calibration (known as Modified Pressure Method of Equalisation; ANSI S3.46) is performed for each patient by placing the reference microphone near the ear (and near the microphone of the hearing device). Two methods can be used depending on the type of hearing device being fitted:

A. Modified Pressure Method with Concurrent Equalisation (MPMCE)

In MPMCE, equalisation or calibration is performed with the patient present and with the speaker sound continuously and automatically adjusting to the desired level at the patient's ear, using the reference microphone, to compensate for any movements by the patient. This is commonly used for all fittings that do not use open coupling.

B. Modified Pressure Method with Stored Equalisation (MPMSE)

Using the MPMCE method in open fitting has a risk that amplified sounds may leak out to the reference microphone, contaminating the results (for a review see Mueller et al, 2017). Therefore, an alternative





method such as MPMSE should be used for verification of open fittings. In this method, the reference microphone is used for equalisation or calibration while the patient and hearing device is in place (muted). It is then stored and used for the rest of the testing rather than being dynamically controlled during the rest of the probe microphone measurement as in the MPMCE. Any change in position of the head/torso may change the signal level at the level of ear and will require the calibration to be repeated.

This is the preferred method for probe microphone measurement with a hearing device with open coupling as the amplified sound can leak out of the ear to go back to the reference microphone if it were turned on during the measurements. This is further illustrated in section 8.1.8.

8.1.3 Preparing the patient

The clinician should explain the procedure to the patient and/or carer in appropriate terms and obtain informed consent from them.

It is recommended that speaker-to-patient distance is 80-100cm at 0° azimuth (horizontal and vertical angles) to avoid any near or far field effects (Bentler et al, 2016). The speaker should be at ear level. Modern hearing instruments increasingly include direction pattern technologies such as beam forming microphones with a frontal focus. Deviations in speaker position may therefore result in variability in the measurements. The speaker and reference microphone should be positioned approximately one metre away from the nearest reflective surface.

It is recommended that the clinics choose and position furniture appropriately (e.g. a high table and/or adjustable chair or wall mount for the speaker) so that a zero-degree vertical angle can be reached. There is limited evidence in current literature regarding the vertical angle for the loudspeaker position however, previous work has suggested that a higher loudspeaker may be better than a lower one for measurements (Killion and Revit, 1987).



8.1.4 Ear examination

Ear examination shall be in accordance with current BSA recommended procedure. Ear examination via otoscopy must always precede insertion of the probe tube, such that any outer and middle ear abnormalities may be taken account of. Probe tube placement should not take place where there is any reported pain or discharge in the outer ear. Ideally the outer ear should be clear of wax before carrying out the measurements. Appropriate hand-hygiene procedures should be followed prior to, during and after otoscopy and probe tube placement.





8.1.5 Insertion of probe tube

For infection control reasons, always use a new probe tube for each patient (and each ear, where indicated e.g. in case of possible outer ear infection on one side). The general requirement for probe placement is for the tip to be as near to the ear drum as possible without touching the surface of the drum. The tip of the probe tube should be:

1. Within 5 mm of the tympanic membrane (to measure high frequency response accurately).
2. At least 5 mm beyond the sound outlet of the hearing device (so that the point of measurement is not within the region where the sound wave is making a transition from the narrow sound-bore to the wider ear canal).



The probe tube can be positioned by using a fixed insertion depth from the inter-tragal notch. Most probe tubes have a sliding ring that can be used to mark a desired length from the open end of the tube. The average distance from the inter-tragal notch to within 5 mm from the eardrum umbo is 29 mm, and is 1.5 mm more for males and 1.5 mm less for females (Dillon, 2012).

General guidelines for probe tube insertion depths in adults are (Pumford and Sinclair, 2001):

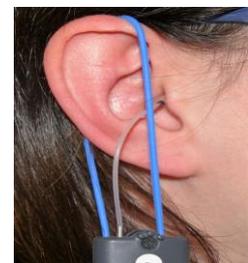
Adult females	28mm
Adult males	30mm

For children, recommended lengths are (Moodie et al, 1994):

Children above 5 years old	25mm
Children 1-5 years old	20mm
Babies under 12 months	15mm

NB: The interim guidance for babies of ages between 0 and 6 months is to extend the probe tube length to 5 mm beyond the end of the canal part of the ear mould.

The recommendation on the depth of probe tube insertion must be used in conjunction with ear examination to help position the probe tube and to adjust the insertion depth as appropriate (Scollie et al, 2002; Dillon, 2012). Care must be taken so that the probe tube is not pushed further into the ear whilst undertaking otoscopy and inserting the earpiece of the hearing device.



In general, the effect of insertion depth may be minimal at frequencies below 3 to 4 kHz (Kuk and Baekgaard 2009) if the end of the tube is beyond the medial tip of the ear mould but extending the probe tube to 10 mm beyond the tip may give results that are more accurate at higher frequencies (Caldwell et al, 2006). 28





mm probe tube insertion has been shown to reliably measure real ear response up to 8 kHz in female subjects (Vaisberg et al, 2016).

At the end of the probe microphone measurement session, the probe tube should be carefully removed and the ear checked by otoscopy. Probe tubes should be hygienically disposed of.

8.1.6 Measurement of real-ear unaided gain (REUG)

REUG, as measured in the ear canal, is the measure of the gain (natural amplification) provided by the unoccluded ear and pinna and varies significantly in terms of location and magnitude of the resonance peak of the response of the ear (Weiner and Ross, 1946).

REUR can be obtained by adding the REUG to the input signal across frequencies. REUG may be preferable as it is a gain measurement and so the measurement curve will look the same independent of the stimulus type used. This makes the curve more recognisable. Typically, the REUG is obtained to provide a reference for real-ear insertion gain (REIG). As described in Section 8.1.9, NAL-NL2 will provide REIG and REAR targets. Therefore, REUG should be performed when using the REIG NAL-NL2 prescription.

REUG measurements can also be used to ensure optimum tube placement. Optimal tube insertion depth results in a notch in the REUG curve in the upper frequency range (between 4kHz and 8kHz). The lowest point of this notch should not fall below -5dB. If it does, then tube placement may be sub-optimal and should be repeated (Dillon, 2012). Another use of REUG in conjunction with REOG is to measure the occlusion of the ear, as described in Section 8.1.8.

- **To perform REUG, with probe tube in the ear, use a 65 dB SPL ISTS or broadband (e.g. pink noise) stimulus to record a response. After the response has stabilised record it. If the shape is unexpectedly unusual or the response suggests probe tube occlusion, change the probe tube and repeat tube calibration before re-inserting and measuring again.**

8.1.7 Measurement of Real-Ear Occluded Gain (REOG)

REOG is used to measure the venting characteristics of the hearing device fitting or extent of occlusion of the ear canal by the acoustic coupler (via a mould or dome for example). In other words, it shows how 'open' the fitting is. This also confirms that the probe tube is still correctly positioned and open when the ear mould or dome is inserted in the ear.



- **To conduct REOG, insert the ear mould or dome into the ear and with the hearing device switched OFF or muted in the software, record using an identical stimulus to that used to measure the REUG.**





8.1.8 Verification of open fitting

'Open fit' is a term indicating the intention to keep the ear canal sufficiently unoccluded to let low frequency sound (usually below 1500Hz) escape from the ear, reducing the occlusion effect. This could be achieved in a variety of different ways including a custom earpiece with large or open venting or open dome.

Open fitting should not be confused with slim tube or Receiver in the Canal (RIC) fittings. It is possible to achieve low levels of occlusion using a vented ear mould. Equally, it is possible to achieve a high level of occlusion using a slim tube or RIC with a dome.

Therefore, an open fitting is where the REUG and REOG are not significantly different from each other, which means that the hearing device's coupling is acoustically transparent (open). The following guidance should be used to determine the presence of an open fitting and, therefore, influence whether MPMSE method must be used:

- a) If REUG and REOG are mirror images of each other or are otherwise significantly different above 1.5 kHz, e.g., the REOG falls near or below the input level, the fitting should be considered as occluded. In this case, the calibration for MPMSE can be taken with the hearing device microphones enabled.
- b) If the REUG and REOG are similar or the same as each other, the fitting should be considered as open. In this case, the calibration with MPMSE should be conducted with the hearing device microphones disabled. If the patient's position changes following the calibration (or equalisation) position, the calibration will have to be repeated.

8.1.9 Recording Real-Ear Aided Response (REAR)

Before undertaking this measurement, select the desired prescription target (e.g. NAL-NL2 or DSL v5.0) within the probe microphone measurement system software. Also, check that other parameters e.g. bilateral/unilateral, use of bone conduction thresholds (important in cases with conductive element in hearing), gender, experience, and date of birth are selected correctly. The number of compression channels and threshold kneepoint levels within the probe microphone measurement system software should be set to the hearing instrument manufacturer's recommendations.

Historically many UK audiologists have used NAL prescription rules for adults, with REIG measures of hearing device performance. However, REIG does not provide any indication of dynamic range or signal audibility, which is the main focus of modern hearing device fittings. REAR measured with a modulated speech-based input signal provides a better view of amplification from a given device because it will show the interactions of the input signal with the compression across multiple channels. Measuring REAR is the only way to quickly and easily see the precise inter-relationship between dynamic range of hearing and the audibility of speech before and after amplification (and maximum output). Note that some verification systems can calculate the difference between the target and measurement and may show these differences in a dedicated graph, even when REAR is used.

This guidance recommends the use of REAR for probe microphone verification for all age groups (with both NAL as well as DSL prescriptions).





NAL prescription provides REIG and REAG targets by default. Verification software can use the REAG targets to derive REAR targets for NAL prescription by adding the input stimulus. To obtain accurate REIG targets in NAL, the individual's ear canal resonance (REUG) must be taken into account. DSL prescription provides REAR targets by default. REAR gives greater visualisation of how the sounds are placed within the residual dynamic range and their relative loudness both to each other and to the patient's threshold levels and predicted or measured uncomfortable levels. Whilst valid and accurate, REIG does not allow the clinician the ability to make such judgements on the audibility of signals.

Furthermore, using a modulated input speech signal (such as ISTS) with REAR targets at different input levels plotted relative to the patient's residual range of hearing, is akin to conducting 'speech mapping' (Bentler et al, 2016). Speech-mapping is a term that has been referred in commercial and academic literature. It refers to a display of thresholds, targets (REAR) and hearing device verification measures on which the targets have been assessed for a speech signal e.g. ISTS.

If an open fitting is used, perform MPMSE calibration at this point, with the hearing device muted or switched off.

To perform the REAR measurement, switch the device on or unmute it. It should be on the everyday listening programme with all its usual features left on, other than frequency lowering feature (as discussed in Section 8.3).

- If the hearing device software provides acclimatisation/adaptation levels, set it to the highest level.
- Select a moderate (65 dB SPL) input using the chosen stimulus and record.
- Compare the measured response (REAR) to the target values. Adjust the hearing device gain in the programming software to best match the target values – a tolerance of +/-5dB is recommended at frequencies between 250Hz and 6000Hz.
- Verification at quiet (50-55 dB SPL) and loud (80 dB SPL) levels should also be carried out to provide confirmation that the appropriate compression strategy has been implemented, ensuring that audibility for the soft speech has been achieved and loud sounds are not amplified to cause any discomfort to the user. Again, adjust the hearing device gain in the programming software to best match the target values – a tolerance of +/-5dB is recommended at frequencies between 250Hz and 6000Hz.

If the recommended tolerances to target are not reached after all routine hearing device adjustments have been attempted, examine why this may be the case and consider alternative aiding strategies e.g. alternative hearing device or receiver/mould instead of slim tube fitting/frequency lowering technology. In some devices, adjusting gain for loud sounds can affect the gain for soft sound. In these cases where you may only be able to match target for one level, it may be best to match it for 65 dB input (page 127, Bentler et al, 2016).





Why REAR?

Historically, hearing aid gain in the real ear was measured in a sound field by subtracting the hearing thresholds obtained aided and unaided i.e., functional gain. With the introduction of clinical probe-tube microphone systems in the 1980s, it became possible to measure real ear gain as the difference, in dB, between the aided and unaided sound level in the ear canal i.e., real ear insertion gain (REIG). Functional gain and REIG are identical but the latter can be measured much more quickly, at a greater number of frequencies and does not involve active participation of the client. For this reason, REIG replaced functional gain as the measurement of choice.

More recently, there has been a shift towards measuring the real ear aided response (REAR) or gain (REAG) instead of REIG (and many hearing aid prescription approaches now express target values as REIG and REAR). REAR is an extremely useful approach because it enables easy visualisation of the inter-relationship between assessment data, the level of unamplified speech, and the amplification characteristics, which are typically measured in different units and at different reference points. It is to be noted that the placement of the probe-tube microphone in the ear canal is much more important if using the REAR approach because the aim is to measure the sound level close to (and normally within 5 mm of) the eardrum.

The REAR approach is one of the key building blocks of the Desired Sensation Level fitting method where the data is displayed on an 'SPL-o-gram'. Similar approaches can now be implemented for other prescription fitting procedures including the National Acoustic Laboratory procedures, where it is referred to as a 'speech-o-gram'. The REAR approach is available with all probe-microphone equipment for verification purposes, where it often is referred to as "speech-mapping."

Both REIG and REAR approaches are currently in use, although there are country-specific preferences. In the USA, for example, more than 80% of hearing aid dispensers now report using REAR as their primary method for verifying the match to the prescription target.

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Note that REIR measurement was a popular choice for measurements for a long time since the emergence of commercial verification systems because the popular prescriptive methods at the time used gain targets, and also REIR mimics functional gain - a popular verification technique before probe microphone measurements. However, since the early 2000's when the updated NAL prescription NAL-NL1 had REAR targets, verification equipment companies subsequently developed real speech stimuli to convert ear canal SPL for the NAL-NL1 LTASS to display on the fitting screen; and so REAR grew in popularity (Page 124 Bentler, 2016).





Using speech-mapping in counselling: Speech mapping can also be used for counselling purposes. For example, rather than an ISTS signal, clinician might use the live voice of patient's partner to measure the real ear response. This will show if their amplified live voice was within the accessible range of patient's target amplification levels (REAR), indicating the real-world benefit as the patient will be able to relate to the live voice easily. This approach however is not a substitute for fitting to a validated prescription.

8.1.10 Maximum Output Sound Pressure Level (MOSPL)

This has previously been referred to as Real Ear Saturation Response (RESR) but MOSPL is a more accurate term (referred as REAR 85/REAR 90 in the latest ANSI standard).

As one of the most significant effects of sensorineural hearing loss is a reduction in the dynamic range of the listener, if the maximum power output of the hearing device is set too low it will reduce the dynamic range of speech further for the listener. If set too high, it will cause discomfort. The MOSPL defines the upper limits of the dynamic range of the hearing device's amplification and subjectively corresponds to the uncomfortable loudness levels of the patient and should be performed, where possible.

The measure can be used in two ways:

- 1) to allow verification that the hearing device output for loud levels is not breaching the patient's behavioural uncomfortable loudness levels (if measured).
- 2) to verify the hearing device output when compared to the target.

To perform this measurement in situ, use a sufficiently loud level e.g. 85dB SPL. Choice of stimulus here is a swept warble tone rather than a broadband stimulus. This is because a warble tone can achieve the desired peak stimulus level (e.g. 85dB SPL) at each individual frequency whereas a broadband stimulus will not contain any stimulus level close to the desired stimulus in any frequency band. Broadband summation contributes to the overall signal averaging process. This will lead to underestimation of the real-life performance of the device.

All verification systems have in-built mechanisms to cut the signal at certain pre-set limits (i.e. ULL-10 dB) ensuring patient safety. Consult manufacturer guidance on how to adjust and set these safe limits.

For patients where, abnormal loudness discomfort is expected (based on history), consider using coupler-based verification for this step. If during the testing, the patient expresses or shows discomfort, stop the running measurement immediately, adjust the hearing device MPO and consider different options to retest; for example: perform the MOSPL measurements in the coupler to adjust the MPO before carrying out MOSPL measurements in-situ. Then consider performing OSPL at a lower level first before moving to recommended level of 85dB SPL. Note that audiologists should take appropriate care of their own hearing as well when testing the higher input levels. Consider the use of hearing protection. If real ear verification is tolerable to these patients, consider gradually increasing the signal level in steps from 65 dB SPL, rather than going straight to 85 dB SPL. Unexpected loudness discomfort may warrant uncomfortable level testing (See BSA guidance on the determination of Uncomfortable Loudness Levels (ULL)) with further hearing device adjustments made as indicated.





8.2 Coupler based measurements

In babies, younger children and patients with complex needs including those with severe and profound hearing loss or learning difficulties, it may not be practical or possible to perform probe microphone measurements. Therefore, an alternative strategy of verification using Real-Ear-to-Coupler Difference (RECD) can be employed. Coupler-based measurements reduce patients' involvement in the verification of hearing device fittings and enable verification in cases where probe tube placement causes feedback (e.g. in severe-profound loss cases). Functionally, this procedure does not replace the range of measures offered by modern real ear measurement systems however; it has a predictive accuracy and good test-retest reliability (Seewald et al, 2000; Scollie et al, 2011). Therefore, it is the recommended alternative when real ear measurements are not possible.

8.2.1 RECD measurement

RECD is the difference between the response in the real ear and the response in the coupler to the same stimulus. The broadband stimulus is measured in both the patient's ear and the coupler and the difference is calculated across the range of frequencies (in dB gain). Once the amount by which the coupler differs from the real ear is known, this can be applied to all other measurements made in the coupler (e.g. aided gain calculations), negating the need to keep the patient directly involved in further measurements. Additionally, the RECD is used to convert hearing thresholds from dB HL to dB SPL ensuing accurate thresholds estimation in infants and young children whose ear canal size and shape differ from adult calibration factors (reference equivalent threshold sound pressure level/RETSPs) used to devise the dB HL scale (Munro, 2005; Bagatto et al, 2005).

General procedure to measure RECD:

Select the coupler mode or RECD module in the verification software. Check that the appropriate prescription target (e.g. DSL v5.0) has been selected. Also, check that all parameters are selected correctly, e.g. transducer, venting, coupler tube, bilateral/unilateral, and date of birth.

1. Perform tube calibration (8.1.1) and ear examination (8.1.3)

It is to be noted that the tube calibration during coupler measurement is performed to check defects of the tube and differences between individual tube resonances and variations.

2. Measure the sound pressure output in the coupler





Couple the probe's insert earphone tube to the HA-2/2cc coupler using a length of tubing the same as used for a behind-the-ear (BTE) fitting. Closing the test box lid may be beneficial where extraneous noise is expected to affect the measurements. Record the response in the coupler. Note that input



stimulus type and level are usually pre-set by the equipment (for example, 50 dB SPL speech-weighted composite noise).

In some equipment, it is possible to use a previously measured and stored coupler response. Although this is a non-physiological measurement, measured values may vary with temperature and atmospheric pressure changes. It is therefore recommended to measure the coupler response each time. A template response from an individual coupler can be used as a reference for checking the stored coupler response during daily calibration checks.

RECD with HA1 Coupler

RECD accuracy has been shown to be influenced by coupler type (Munro 2004; Munro and Toal, 2005;), ear mould tubing length (Bagatto et al, 2005), and transducer impedance (Munro and Toal, 2005; Bagatto et al, 2005). ANSI S3.46-2013 and BS EN 61669:2016 define RECD as the difference in decibels, as a function of frequency, between the sound level produced near the tympanic membrane in an occluded ear canal by a coupled sound source having high acoustic impedance and the sound level produced in the HA-1 configuration of the 2-cc coupler by the same coupled sound source. However, it has been recognised (Scollie, 2016) that measurement of the coupler portion of the RECD with the HA1 coupler may have problems such as leakage and infection control (because putty is required) and therefore, we are currently advising the clinicians to make their own professional judgement on the use of HA1 coupler. Note that, to circumvent these issues, at least one manufacturer has produced conversion factors for performing the measurements in HA2 coupler and using HA2-HA1 conversions for the actual fitting. Ongoing developments in this area may allow us to make further recommendations in future.

Further reference: Scollie, S. 2016. New RECDs and a New ANSI Standard: Revisiting RECD Basics and Applications. <https://www.audiologyonline.com/articles/new-recds-and-ansi-standard-16380>





3. Measure the sound pressure level in the ear.

Couple the earmould to the insert earphone plastic coupling adaptor tube and insert the probe tube in the ear with the earmould (mould is preferred but a foam tip can be used if the mould is not available or suitable, or in fittings where moulds are not used). Probe tube placement guidelines in Section 8.1.5 should be followed. Some clinicians find it useful to attach the probe tube to the earmould using micropore tape or cling film. This ensures that the probe tube is not further pushed into the ear with a sudden movement of the subject.

Measure the response in the ear. The software will show a trace that is the difference between the sound pressure levels measured in steps 2 and 3, the RECD.



Where possible, RECD should be performed separately in both ears (Note: some equipment may perform binaural measurements). In some cases, it may be appropriate to use the same RECD for both ears by selecting appropriate settings in the software (Munro & Butfield, 2005). Ideally, perform tympanometry in addition to otoscopy in such cases to check the tympanometric ear canal volume and middle ear status of the ears are not significantly different.

8.2.2 Aided measurements in coupler using RECD

It is to be noted that in a test box, the most repeatable results are obtained with the forward microphone of the hearing device toward the loudspeaker at 0° azimuth. Also, the test box should be located away from sources of vibration which could affect the accuracy of the measurements.





Check that the appropriate target and its parameters are set in the verification software and select the coupler-test mode. The software will have an option of using predicted RECD, which should only be used if it has not been possible to measure the RECD. Also, where the hearing assessment has been performed via auditory brainstem response testing, a conversion from nHL (normalised hearing level) to eHL (estimated hearing level) will be needed. This should be done using appropriate conversion factors given in the BSA guidance document- Early Audiological Assessment and Management of Babies Referred from the Newborn Hearing Screening Programme. The verification software may require you to input the 'type of test', and once the eHL conversion has been applied, type of test should not be selected as 'ABR' in verification software. Otherwise, the software may apply further conversion to the thresholds.

To perform aided response measurements, switch the hearing device on or unmute it. The hearing device should be on the everyday listening programme with all its usual features left on (with the exception of frequency lowering).

Coupling of the hearing device to the coupler must be given due attention. It is important to align the test box reference microphone and hearing device microphone appropriately to avoid measurement errors (Scollie et al, 2011). The correct coupler adaptor should be selected. For a BTE hearing device to be used with an earmould, the HA2 coupler should be used. For ITE, thin-tube and RIC fittings, HA1 should be used and the device attached to the coupler using acoustic putty. Again, with HA1 coupler, clinicians should be mindful about leakage and infection control when using putty to attach the device with the coupler. Thin tubes should have their resonance damped using putty to weight the tube or secure the body of the device. Low frequency and high-level measurements may otherwise be inaccurate (Dillon, 2012).

Verify the gain at the input levels of moderate (65 dB SPL), soft (50-55 dB SPL) and loud (80dB SPL) with ISTS stimulus. If older equipment is used that only has a steady noise as input stimulus, you may have to disable noise reduction and feedback management strategies on the hearing device and set microphones to omnidirectional before making measurements.

It is important to emphasise the need to match the prescribed amplification targets in the paediatric population as quantifying the adequacy of hearing device fitting is otherwise challenging (McCreery, 2013). If precise matching of targets at all input levels is not possible, consider the necessary compromises and their implications. Young children acquiring language may benefit from a more precise matching of soft speech targets (Dillon, 2012). 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 device.

8.2.3 OSPL or RESR in coupler

Ensure output does not exceed uncomfortable loudness levels in the coupler via MOSPL with 90dB SPL warble tone sweep and adjust MPO where appropriate. Note that this is a higher level than what one would use in a measurement performed *in situ*. This is an important measure to consider owing to the potential resultant high sound pressure levels likely to be generated in smaller ears.





8.3 Verification of frequency-lowering

The goal of probe microphone measurements is to sufficiently meet the target amplification at the given frequencies. Just as conventional amplification, it is reasonable to assume that the best outcomes with amplification involving frequency-lowering (FL) will also be achieved when the real ear aided output after the FL meets prescriptive targets. This is particularly important where subjective feedback on the amplification cannot be obtained reliably e.g. in younger children. Also, children with hearing loss need better speech quality than adults when identifying speech in noise due to their relative lack of linguistic expertise (Nitttrouer and Boothroyd, 1990; Fallon et al, 2002; Hall et al, 2002). FL seem to provide some improvement in an individual's speech intelligibility (Simpson et al, 2018)

A detailed discussion on FL techniques in contemporary hearing devices is outside a scope of this document but interested readers are referred to Alexander (2013) and Muller et al (2016). However, regardless of the FL technique used, the aim is to ensure that the lowered signal is audible and useful to the user i.e. it should not negatively impact speech understanding. To avoid unnecessary distortion created by strong settings of FL, it is pertinent that audibility is maximised across the widest range of frequencies possible whilst using the weakest possible setting of FL. A high frequency signal that is lowered will be amplified using the same rules (of compression and gain) as the low frequency region it falls within. Therefore, the first step in fitting FL is to ensure gain has been matched to target as well as possible at every frequency with FL disabled.

Probe microphone measurements can be used to assess which parts of speech are inaudible with conventional amplification and therefore suggest candidacy for frequency lowering. REAR measures can be used to identify the maximum audible output frequency (MAOF); that is the point where the peak levels of the aided response intersect with the hearing thresholds (just above 4 kHz on both REAR screen shown in figure in this section below. It is to be remembered that amplified speech has peaks that are 10-12 dB above average levels, meaning that those peaks can sometime still be audible even if the target cannot be matched (Scollie, 2013).

Once the decision to try FL has been made, validation needs to occur to ensure the best parameters of FL are selected i.e. settings which maximise audibility while minimising distortion and provide a measurable benefit to the user. There is currently no gold standard approach for the selection and validation of FL. Rather clinicians should use a range of measures to ensure aided audibility has been improved with FL enabled and that benefit has been obtained (Alexander, 2016). Researchers at the University of Western Ontario (UWO) have developed calibrated recordings of /s/ and /j/ which can be useful when selecting FL settings. Optimum settings of FL should move /s/ into a region of audibility while simultaneously maintaining a spectral distinction with /j/ (Scollie et al, 2016). These signals are present in most commercially available verification equipment and can be used for determining the optimum strength of FL. The steps below provide guidance on selection and validation of FL parameters reflecting current knowledge and evidence-base.

1. Deactivate FL and perform routine verification of hearing device by performing REAR (or coupler aided response measurement using measured RECD) with a 65 dB SPL ISTS input signal. Identify MAOF and decide if FL is required i.e. if high-frequencies are inaudible and/or below the prescription target then FL may be appropriate.





2. Apply frequency lowering for the frequencies at or just above the identified maximum audible output frequency or MAOF where it is impossible to match the target at the recommended tolerance range of + or – 5 dB with the best hearing device selected for the hearing loss.

The online fitting calculator developed by the Purdue EAR lab may also be a useful starting point in selecting the optimum setting of FL i.e. settings that will provide audibility of the widest possible bandwidth (<http://web.ics.purdue.edu/~alexan14/fittingassistants.html>). The value of MAOF is used in the calculator to predict optimum FL parameters although it is not intended to substitute for what the clinician observes with an actual electroacoustic measurements.

Where possible, use self-report measures and behavioural test to evaluate benefit from FL and ensure no detriment for the user i.e. an age-appropriate speech test combined with a validated self-report questionnaire (AAA, 2013).

Furthermore, there have been rapid technological advances in this area over the past few years and it is likely the evidence-base around FL will continue to evolve. Clinicians using FL hearing devices are encouraged to review the peer-reviewed published evidence regularly in order to establish best-practice techniques when fitting this feature to adults and children.

Below is the process to use specifically developed calibrated fricatives /s/ and /j/ stimuli to test the efficacy of frequency lowering. (Adapted from UWO PedAMP)

1) Aided REAR's without frequency lowering.

Begin by verifying and fine-tuning the hearing device to optimise the fitting without frequency lowering. Fine tune the hearing device to ensure that the aided speech spectra meet prescriptive targets and provide a broad bandwidth of audibility.

2) Determine candidacy for frequency-lowering.

Frequency-lowering may be required if the high frequencies are not within audibility range.

- a. With frequency lowering OFF and noise reduction OFF, measure the aided response at 65 dB SPL with calibrated /s/. Determine if the response falls within the audible range (MAOF). If the response does not fall within the audible range, the candidacy criterion for frequency-lowering has been met. Note that for some listeners with milder degrees of hearing loss, it may be possible to measure an /s/ within the audible range without enabling frequency lowering due to improved high-frequency bandwidth in latest hearing devices.
- b. Consider measuring the calibrated /s/ at 55 dB SPL. This signal may not be audible for soft speech. Decisions regarding activation of frequency lowering in this case are at the discretion of the audiologist and should consider caregiver reports.



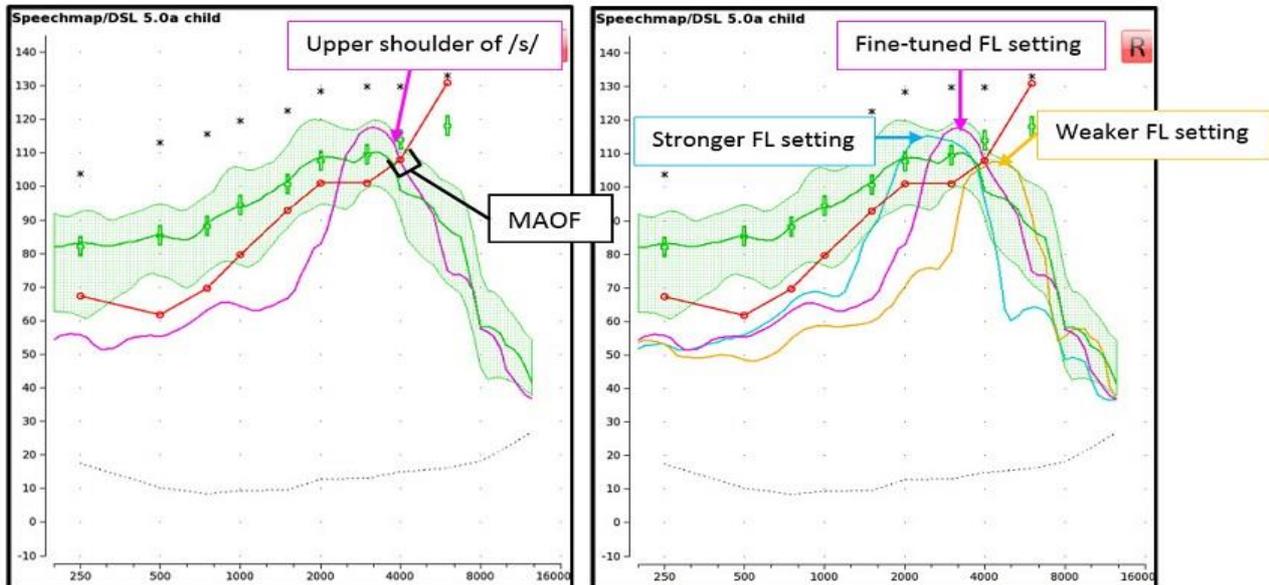


Figure: Both screen captures display the aided LTASS measured using a presentation level of 65 dB SPL (green). The LEFT screen capture displays the /s/ (pink) after fine-tuning the frequency lowering setting. The /s/ has been made audible and the upper shoulder falls within the MAOF range. The RIGHT screen capture depicts a setting that was considered too strong (blue /s/), the fine-tuned setting (pink /s/) and a setting that was considered too weak (yellow /s/). Figure courtesy Glista, Hawkins and Scollie, 2016 <https://www.audiologyonline.com/articles/update-on-modified-verification-approaches-16932> Reprinted with permission.

3) Enable frequency lowering and adjust to optimise.

The goal here is to use the least amount of frequency-lowering needed to obtain audibility of /s/. Start by enabling the default frequency-lowering setting in the hearing instrument. Measure the aided response for /s/ presented at 65 dB SPL to determine if most of the signal is in audible range (i.e. the upper shoulder is within the MAOF range of the LTASS). Fine-tune the strength of the frequency-lowering setting until the /s/ is audible and falls within the MAOF range using the weakest possible setting. For some listeners with greater severity of hearing loss, it may not be possible to achieve full audibility of /s/, even with the maximum frequency-lowering setting.

Optional: Also measure the aided /j/ to make a descriptive measure of the frequency separation between /s/ and /j/. This measure may help with counselling or troubleshooting difficulty with discrimination between /s/ and /j/. Because the fine-tuning steps above have already determined the weakest possible setting of the frequency-lowering processor, the frequency separation between /s/ and /j/ is likely already maximized. Note that listening checks are also useful for these purposes and should be completed after frequency-lowering is verified and should be done at the user's frequency-lowering setting.





9. Aided SII and Goodness of Fit (GoF)

One of the most important outcomes of hearing device fitting is aided audibility, which can be quantified using aided Speech Intelligibility Index (SII; ANSI S3.5–1997). SII is a numerical estimate of audibility (value between 0 and 1, where 0 means no audibility and 1 means complete audibility, whereas, some equipment may represent it in percentage, meaning a value of 0.5 would be expressed as 50%). It represents the proportion of speech that is available to the listener via the hearing device. This has traditionally been calculated using behavioural measures, but modern verification equipment can electro-acoustically calculate the SII for the fitting response.

Aided SII has been used to predict speech recognition in adults with relative accuracy. (Amlani et al, 2002). The use of aided SII in the paediatric population is more pertinent where choice of outcome measures could be limited due to developmental factors. Unlike adults, the SII may vary in children as a function of age (McCreery and Stelmachowicz, 2011).

In fact, the latest version of UWO PedAMP (see references) tracks the SII of the fitting for soft and average inputs instead of targets as the ‘clinical process outcome measure’ of fitting. Researchers at Western University have developed a worksheet with normative SII values from a study of 161 paediatric fittings (Moodie et al, 2011), which allows the clinician to determine whether the aided SII value calculated by the verification software for the 50 and 65dB SPL insertion gain/response levels, is appropriate for the patient's degree of hearing loss. The worksheet is available on the DSL website http://www.dslio.com/wp-content/uploads/2014/03/D_Aided_SII_Normative_Values_Form_v1_r1.pdf and could be used as an important tool for measuring the quality (or clinical outcome) of hearing device fitting as ‘increasing the audibility of speech has a direct positive effect on auditory skill development and speech-recognition abilities and also may enhance these skills by improving language abilities in children who are hard of hearing’ (McCreery, 2015). Consider when using SII, that the use of frequency lowering techniques affect the relationship between input and output frequencies measured.

Another clinical outcome measure is Goodness of Fit (GoF) as described by Hostler (2004) and is available on the MCHAS website. GoF is based on the closeness of fit to target, deviation in shape, and overall gain. It has been shown to correlate highly with the subjective judgements of experienced clinicians (Hostler et al, 2004). GoF is a concept which has been used in research studies (Munro, 2015; Chin et al, 2015).





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