Abstract

Frequency lowering signal processing is an increasingly common feature in modern hearing aids. New clinical guideline documents, such as the American Academy of Audiology Clinical Practice Guideline on Pediatric Amplification (2013) stress that electroacoustic verification of frequency lowering is an important part of fitting such devices for children who use hearing aids. Verification protocols should focus on how the processors affect the audibility of speech. This article presents a specific approach to this, along with a series of three case studies that illustrate the role of speech-based verification in considering fine tuning to optimize benefit, assessment of candidacy for frequency lowering, and the use of frequency lowering for asymmetrical hearing losses.

During the past decade, the use of frequency lowering signal processing in hearing aids has received considerable attention in terms of product development, research evaluation, and clinical application. The term “frequency lowering” is used to describe a diverse category of signal processors, which have in common the ability to transfer high frequency sound to a lower frequency within the hearing aid output. Detailed descriptions of the types of signal processors that provide frequency lowering are available from Alexander (2013) and in a recent three-part series of articles online (Alexander, 2013; Mueller, Alexander, & Scollie, 2013; Scollie, 2013). At this time, there are five brands of frequency lowering hearing aids on the market: listed in order of release to market these are: Widex (AudibilityExtender® or frequency transposition), Phonak/Unitron (SoundRecover® or nonlinear frequency compression), Starkey (SpectralIQ® or spectral warping), Siemens (nonlinear frequency compression) and Bernafon (FrequencyComposition®). The suggested clinical use of frequency lowering processors is to overcome limitations in audibility of high frequency sound by presenting them to the listener at a lower frequency. This use is important when sounds are inaudible due to limits imposed by the listener’s hearing thresholds or by limitations in the high frequency hearing aid output. It is often suggested that hearing specific high frequency phonemes, such as female utterances of “s” and “f”, require that the listener have access to speech energy above 4000 Hz. Specific studies comparing the performance of children with versus without audibility above 4000 Hz reveal differences in a variety of perceptual outcome measures including rates of learning new words (Pittman, 2008; Stelmachowicz et al., 2004). Overall, studies of the effects of extended bandwidth of audible speech indicate that children benefit from hearing speech cues above 4000 Hz – in past studies that used a “full bandwidth” condition that includes energy to 9000 Hz. Clinically, our hearing aid fittings may roll off between 4000 and 9000 Hz. The exact cutoff of necessary audibility within this range (e.g., 6000 Hz, 8000 Hz) is not known at this time, and clear verification protocols for high frequency verification are not widely available. Regardless, our clinical fittings strive to provide as broad a bandwidth of audibility as possible. Improvements over the last few years, including changes in feedback control and prevention as well as microphone and receiver technologies and digital signal processing, have broadened the achievable bandwidth available in commercial hearing aids. Extended bandwidth hearing aid fitting is now more possible than ever before.

Even with improvements in technology, some fittings are still limited in audible bandwidth, to the point that access to specific phonemes (such as fricatives) remains limited. With this in mind, we may design a hearing aid
fitting that allows input of the high frequency energy into the hearing aid microphone, sends the energy to a digital signal processor that transfers it downward in the frequency domain, and amplifies the frequency-lowered sound to audible levels. Fitting this type of hearing aid requires that the audiologist perform frequency-gain shaping to optimize speech audibility (as they would with conventional processing) and also to adjust the degree of frequency lowering. This article will describe one set of procedures that may be used to evaluate candidacy for frequency lowering signal processing, and also to verify its function and adjust it for the listening needs of the individual listener.

### Recommended Protocols

A recent evidence-based Clinical Practice Guideline on Pediatric Amplification (AAA Task Force on Pediatric Amplification, 2013) provides some guidance on candidacy and fitting of frequency lowering signal processors. In terms of candidacy, this Guideline recommends that frequency lowering "...should not be prescribed until electroacoustic verification has revealed that high-frequency speech audibility cannot be restored through conventional means." In terms of verification and fine tuning, the Guideline states, "The impact of hearing aid signal processing and features such as ... frequency lowering on audibility should be verified. ... the impact of these features on audibility of speech should be evaluated." Taken together, these statements indicate clearly that verification of speech audibility is the primary consideration in deciding whether and how to fit this type of processor.

In 2009, Glista & Scollie developed a suggested clinical verification protocol, summarized in Figure 1. This general protocol has been used to fit one specific form of frequency lowering, known as nonlinear frequency compression, in several studies of efficacy and effectiveness in children. These studies have investigated outcomes in children with a wide range of hearing losses (Bohnert et al., 2011; Glista et al., 2009; Wolfe et al., 2010), sound quality effects in adults and children (Parsa et al., 2013), and the acclimatization time course and/or long term outcomes in children and adolescents (Glista, Easwar, Purcell, & Scollie, 2012; Glista, Scollie, & Sulkers, 2012; Wolfe et al., 2011).

The verification stimuli used in these studies have, however, varied to some degree. One specific hearing aid analyzer provides a filtered speech signal that supports evaluation of audibility and frequency lowering of a one-third octave band of speech (Glista & Scollie, 2009). An alternative to these third-octave bands are measures of specific fricatives (typically “s” and “sh”), measured either with live presentations by the fitter or with the use of the hearing aid analyzer.

### Fitting Steps for Frequency Lowering Hearing Aids

1. Verify the shape and gain of the fitting without frequency lowering.
   - To ensure best audible bandwidth of speech from gain & WDRC alone.
2. Verify the maximum power output (MPO)
   - To ensure that high level sounds are limited appropriately.
   - MPO measurements are not valid above cutoff frequency.
   - It may be necessary to disable frequency lowering to measure MPO at all frequencies for some hearing aids and analyzers.
3. Start with the default frequency lowering setting
   - Assess the need for frequency lowering by estimating high-frequency audibility with and without it.
   - Use a moderate level (65 dB SPL) to test this above the compression threshold.
4. Measures of frequency-specific speech bands or phonemes can help evaluate:
   - The amount of lowering that has been applied to the signal.
   - The approximate sensation level of high-frequency speech sounds.
   - The overlap between similar fricatives (S and SH). Too much overlap may lead to confusion.
   - Perform a listening check and review outcomes:
     - Consider sound quality judgments from the listener as well as the clinician.
     - Consider outcomes and feedback from user, parents, and therapists.
5. Repeat steps to fine tune as needed.

[adapted from Glista & Scollie (2009) AudiologyOnline]

Figure 1. Steps to follow in the verification and fine tuning of pediatric hearing aid fittings, taking into consideration the application and strength of a frequency lowering signal processor.
Frequency Lowering Hearing Aids: Procedures for Assessing Candidacy and Fine Tuning

Audible in the 1500 Hz region (along the sloping portion of the hearing threshold line). Additional “sh” audibility may be present between 2000 and 3000 Hz. The “s” is amplified and lowered in frequency, but is not within the auditory area for the weaker frequency lowering setting. In contrast, the stronger setting amplifies both fricatives to within the auditory area, along the sloping portion of the auditory thresholds. Some frequency separation between the two sounds is provided with this fitting, which we would expect to support differentiation of the two sounds. The impact of these two fittings was also assessed using three outcome measures: (1) a test of consonant recognition using all 21 consonants of English in a nonsense syllable format; (2) a three-alternative forced choice assessment of S-SH discrimination; and (3) an informal assessment of the child’s preference between these two settings. All three outcome measures indicated of pre-recorded fricatives presented at calibrated levels. More recent recommendations to use calibrated fricatives acknowledge that fricatives tend to be fairly broad in bandwidth compared to one-third bands of speech. For some fittings, verifying with realistic fricatives can reveal partial audibility from the lower shoulder of the fricative that acts as an important cue for the listener. Particularly for challenging fittings with steeply sloping hearing losses, this information can be important and provide a better prediction of aided outcomes. This important pattern of verification results has been illustrated in detail for specific cases from past studies (Glista, Scollie, & Sulkers, 2010; Scollie & Glista, 2011).

For these reasons, we have begun implementing verification with synthetic, calibrated fricatives. These stimuli are still under evaluation, but have the potential to make verification of frequency lowering faster and more repeatable, compared to verification with live voice stimuli. In the section below, the use of these stimuli is illustrated in several pediatric cases. These cases illustrate a range of issues we face with the use of frequency lowering signal processors, including making candidacy decisions, fine tuning, and relating verification measures to outcomes assessments.

Case 1: Tuning to Improve Benefit

In this example, we examine the hearing aid fitting provided to a young boy with a steeply sloping hearing loss. He was enrolled in a trial of frequency lowering hearing aids, in which we found that he had significant benefit from the processor. This case has been previously reported (Scollie & Glista, 2011), and is shown here with the hearing aids re-measured using calibrated synthetic “s” and “sh” stimuli, following the verification protocol in Figure 1. Although not shown here, his hearing aid response with frequency lowering disabled provided an amplified “s” that was 20 dB below his threshold at the peak of the “s”, which was consistent with his relatively poor ability to detect or recognize the “s” sound in objective testing. Therefore, the frequency lowering processor was enabled and fine-tuned by evaluating it across various strengths. In the example shown, two potential settings of his hearing aids were investigated to determine which setting should be provided. In this fine tuning process, the aids were adjusted away from default frequency lowering settings in an attempt to improve the audibility of “s” and “sh”.

Figure 2 shows verification results at both a weaker and a stronger setting. For the weaker setting, the “sh” is

Figure 2. Verification of the hearing aid fitting described for Case 1, with comparison of two strengths of frequency lowering signal processing. Outcome results for each strength are noted alongside each fitting.
improved outcomes with the stronger setting. This case, and another similar case (Glista, et al., 2010) illustrate the importance of partial fricative cues: it is possible for a child to detect and learn to recognize these fricatives based on hearing the lower shoulder of the frication band. This type of fitting provides higher objective performance on speech sound detection and recognition tests, and may be preferred by the child, compared to a fitting in which the fricatives are inaudible.

Case 2: Verification to Determine Candidacy

In our second case, we examine current candidacy for frequency lowering for a 10 year old boy with a stable flat (5 dB/octave) severe sensorineural hearing loss. He has been using frequency lowering hearing aids for several years, and was recently seen for refitting with new instruments. His old hearing aids had bandwidth limitations that restricted his access to high frequency fricatives, so his clinician provided and fine-tuned a frequency lowering processor to improve access to “s” and “sh”. He had been a regular user of these hearing aids for several years, and therefore is considered to have acclimatized to the processor. Because his new, more recently developed hearing aids have more high frequency gain and output than was available at his last fitting, verification results in steps 1-3 (Figure 1) show a different result than has been observed in previous sessions. His candidacy assessment for frequency lowering is shown in Figure 3. The “s” stimulus is 10 to 20 dB above threshold with frequency lowering turned off. The effect of enabling the frequency lowering processor certainly lowers the “s”, but is not needed to achieve audibility. The differences shown for “s” in Figure 3 would not be expected to enhance detection of “s”. His clinician was concerned about potential transition challenges in moving from frequency enabled to disabled, if the processor was turned off based on the results shown in Figure 3. After all, this child was a seasoned user of this processor, and it is possible that the processor might have benefits not revealed by this verification protocol. For example, what if the processor would allow detection of “s” in lower levels of speech than tested here (using a 65 dB SPL stimulus)? Would disabling frequency lowering then result in poorer outcomes? What if the child preferred to leave the processor on? Recalling that this child was ten years old, and able to complete outcomes assessments, his clinician completed an informal trial to determine the best settings for him.

Over the next two appointments, she completed two measures of high frequency speech sound detection: the Ling 6(HL) threshold test and the UWO Plurals test (Glista & Scollie, 2012; Scollie et al., 2012). She also provided the child with a two-program hearing aid fitting (frequency lowering enabled and disabled, all other settings held constant) and queried him about his real world preferences following a trial period of about one month. Objective tests revealed that he had good and equal performance either with frequency lowering enabled or disabled. He had no preference for either setting, nor did he notice any important differences in his ability to hear in real world environments. In the end, she decided to disable the processor. Presentation of this case generated discussion among attendees at this conference, including discussion of ideas such as use of a weaker setting, or of progressively weakening the setting across appointments to “ease” the child out of the processor. Any of these strategies, including disabling the processor, are likely reasonable in this case. Further research is certainly needed on how ongoing development of extended bandwidths impacts candidacy for frequency lowering, including how best to verify and evaluate any changes in outcome. This case illustrates the roles of verification and careful monitoring of outcomes, as suggested by the AAA (2013) Guidelines, in the management of children, particularly when new devices are being considered.
Case 3: Asymmetrical Fittings

One frequently asked question in the topic of frequency lowering is how these processors should be fitted for asymmetrical hearing losses. Should the fitting be fine-tuned for each ear? Or, like the default settings in many hearing aid software systems, should the settings developed for the better ear be carried over to the poorer ear? The second strategy was used for most of the participants in our lab’s first trial of frequency compression (Glista et al., 2009). This was done as a conservative strategy in our first attempt to evaluate outcomes from this processor: creating an experimental design that compared asymmetrical to symmetrical settings was not within the scope of that trial. Recently, researchers have begun to explore outcomes for adults who have asymmetrical hearing losses (John et al., 2013). This study revealed some interesting and positive outcomes when audibility was provided on a per-ear basis rather than using the better ear’s weaker settings for the poorer ear.

Our third case illustrates the application of the per-ear strategy on a nine year old child with significant asymmetry between ears. Consideration of this type of case is highly relevant to pediatric hearing aid fittings given the incidence of asymmetric and oddly configured hearing losses in a pediatric caseload (Pittman, 2004). In this case, the clinician had previously provided a hearing aid fitting without frequency lowering to the better left ear, and had monitored the child over a period of use. A fitting goal for the poorer right ear included addressing lack of high frequency audibility and incorporating an acoustic vent. Over time, several barriers to the addition of a vent have been crossed. At a recent appointment, the child’s ear was large enough to accommodate a vent, a vented earmold had been ordered and fitted, and the child’s behaviour was adequate to support an on-ear verification with repeated fine tuning. The clinician decided to focus the fine tuning during this appointment on the poorer ear for several reasons: (1) the fitting on the better ear was well established, successful, and did not present any major concerns; (2) the fitting context now allowed the clinician to evaluate the effects of both venting (because vented on-ear measures were now possible) and frequency lowering, so a comprehensive verification and retuning of the poorer ear seemed like the best next step. The end result of this fitting session is shown in Figure 4.

The better ear fitting has good access to high frequency fricatives, in part because of a region of better hearing in the 4 kHz area. The poorer ear has good access to the low frequencies. Detailed verification of this is not shown, but the low frequency response is the result of both vent-transmitted and aid-transmitted sound. Frequency lowering has been enabled and tuned according to Figure 1, resulting in audibility of both “s” and “sh”, while ensuring some frequency separation between these two sounds. The child’s impressions at the time of fitting were documented in chart notes as “remarked immediately on improved audibility of sounds following today’s adjustments”. Because minor tuning
was also done to the better left ear, we cannot attribute this comment only to the activation of frequency lowering. However, this fitting is highly asymmetrical in terms of hearing profile, frequency-gain response, and strength of frequency lowering, yet these differences were not barriers to perceived benefit. It is informative to observe that a per-ear fitting strategy was received as a positive improvement by this child. Further work in this area could allow us to better understand the complexities in fitting asymmetrical hearing losses.

**Summary and Implications**

Frequency lowering has become a widely available class of signal processing in hearing instruments designed for pediatric and high power hearing aid fittings. Research studies are now available that speak to the range of candidacy, effects, outcome measures, and fitting approaches for frequency lowering devices. As always, there is more to know, but consensus is emerging on acceptable, evidence-based approaches to candidacy evaluation, fine tuning, and outcome assessment for frequency lowering hearing aids. The recently issued AAA (2013) Guideline provides structured concepts for when to use it, and how to assess the impact of frequency lowering. This article presents ongoing work toward a specific protocol that would satisfy the AAA (2013) requirements. The three cases presented here illustrate typical challenges in a pediatric audiologist’s caseload, and specific assessment of frequency lowering candidacy and need for fine tuning. Electroacoustic tools are at the heart of both the Guideline and the protocol shown here: calibrated fricatives may be measured in the aided signal, and incorporated into the real ear verification protocols that are often used in pediatric hearing aid fitting.

**References**


