Over recent years, evidence has been mounting that modern hearing aids may not provide enough audibility of the high frequency energy in speech for children while they are developing speech and language. Specifically, studies have shown both that children’s ability to understand and use high frequency speech sounds are affected (Stelmachowicz, Pittman, Hoover, Lewis and Moeller 2004) and that the ability to produce high frequency speech sounds is significantly delayed compared to other sounds that are lower in frequency (Moeller et al. 2007a, 2007b). These unwanted outcomes occur despite early and high quality intervention programs. The question then, is why do they occur? Scientific data clearly show that certain sounds of speech, such as the phonemes /s/ and /ʃ/ have significant energy well above 4000 Hz, with peak energies in the range of 4500 to above 8000 Hz (Boothroyd and Medwetsky 1992; Pittman, Stelmachowicz, Lewis and Hoover 2003) depending on the age and gender of the talker. Specifically, the speech sounds produced by women and children are likely to occupy the higher frequency portion of this range. It has been speculated that this frequency range, which is well beyond the electroacoustic passband of today’s hearing aids, is likely to be important for speech and language acquisition (Stelmachowicz et al. 2004). Infants and young children typically spend the bulk of their time with either adult women or other children and are therefore routinely exposed to the higher-frequency versions of high frequency phonemes during the critical infant, toddler, and preschool years of speech and language acquisition. Two realities collide in our attempts to deliver these high frequency stimuli to the children whom we serve: (1) hearing loss is often greatest in the highest frequencies (Pittman and Stelmachowicz 2003); and (2) hearing aid gain is least in the highest frequencies, which can also be understood as frequencies above the passband of the device. Therefore, we likely cannot provide enough audibility above about 4000 Hz to support consistent acquisition of the high frequency speech sounds by the majority of children who have permanent hearing losses.

These problems explain, in part, both recent and not-so-recent interest in signal processing strategies that provide frequency lowering. Early attempts at frequency lowering have been reported in the literature for decades, some with significant reported benefits (Johansson 1961). In recent years, commercially available hearing aids have made a variety of frequency lowering strategies an option for clinical use. These include time-varying whole-band frequency transposition (e.g., the AVR Sonovation Transonic), time-varying frequency transposition of a passband centered on a high frequency peak (e.g., the Widex Inteo), time-varying proportional frequency compression (e.g., the AVR Sonovation Nano) and high-frequency nonlinear frequency compression (e.g., the Phonak Naida). All of these technologies provide frequency lowering. They differ from one another along four dimensions:

(1) whether the frequency lowering processing is always on or is time-varying;

(2) whether the frequency lowering is achieved by shifting frequencies down (i.e., transposition) versus narrowing the output bandwidth (i.e., compression);
(3) whether the shift is linear (i.e., proportional) or non-linear in the frequency domain; and
(4) whether the lowering is done for all frequencies or is restricted to the high frequencies.

At the time of this writing, no studies exist that compare these various strategies to one another. However, some evidence exists to support the use of some forms of frequency lowering, either with some hearing loss profiles or with certain populations. Studies with early frequency lowering products that used time-varying transposition found that speech recognition enhancements were possible, and evaluated their effectiveness with children and adults who had hearing losses (MacArdle et al. 2001; McDermott and Knight 2001; McDermott, Voula, Dean and Ching 1999; Miller-Hansen, Nelson, Widen and Simon 2003; Parent, Chmiel and Jerger 1997). Of these, one study on a large sample of children and young adults with hearing loss found that the Dynamic Speech Recoding algorithm improved the detection of speech sounds and improved speech recognition: children with severe hearing losses showed the largest improvements. Some studies reporting benefits also report concerns with either sound quality, consistency of benefit, and/or mechanical robustness of some products used (Gifford, Dorman, Spahr and McKarns 2007; Miller-Hansen et al. 2003). Recent studies have also examined the effects of an alternative time-varying high frequency transposition device, as implemented in the Widex Inteo, finding that a subset of adult participants receive subjective benefits (Kuk et al. 2006).

Our laboratory has recently worked with a prototype hearing aid that uses high frequency nonlinear frequency compression (NFC). This signal processor was developed at the University of Melbourne, and an early version of it has been evaluated on adults with moderate to severe (Simpson, Hersbach and McDermott 2005) and steeply sloping hearing losses (Simpson, Hersbach and McDermott 2006). Results revealed that some, but not all, adults derived significant objective benefit from this processor for understanding high frequency speech sounds, with greater benefits in the adults with moderate to severe losses than in the adults with steeply sloping losses. Unresolved questions with this scheme at our study’s inception included the lack of a systematic fitting and verification method, undetermined limits of candidacy and unknown outcomes in the pediatric population. The sections below will describe the current status of our work to increase our knowledge base in some of these areas.

Developing a Fitting Rationale for Frequency Lowering

Our goal in conducting a clinical field trial of the NFC processor was to determine if it would help us to overcome the bandwidth-related limitations in pediatric hearing aid fitting described above. Clearly, this required a clinical field trial. However, because the candidacy limits and fitting method for the technology had not yet been determined, several up-front decisions had to be made. First, we decided to recruit both children and adults in order to see whether adult-child differences would emerge with this technology in ways similar to those already demonstrated for adult-child differences due to bandwidth (for a review, see Stelmachowicz et al. 2004). Second, we decided to recruit participants with a wide range of hearing losses, rather than restricting our sample to children with severe or precipitous hearing losses. This was done because the effects of bandwidth had been clearly demonstrated even for children with moderate hearing losses, and the candidacy limits of the NFC processor were unknown. Third, we constructed a set of fitting goals for frequency lowering, so that we could develop a fitting method for use in our clinical field trial.

The fitting goals specified that an individualized NFC fitting should:
(1) provide more audibility for high frequencies than is available with a non-NFC fitting;
(2) not cause confusion of the phonemes /f/ and /s/;
(3) preserve normal formant relationships as much as possible; and
(4) maintain high sound quality, as perceived by the wearer.

These goals formed the basis for three recent studies. First, they formed the basis of the individualized fittings that we provided to both adults and to children in our clinical trial (Glista, Scollie, Bagatto, Seewald and Johnson submitted). Second, they were evaluated in a blinded study of consistency among the fitters in our clinical field trial with a series of custom-developed electroacoustic indices corresponding to each fitting goal (Scollie et al. submitted). A third study conducted a systematic evaluation of the effects of NFC settings on sound quality ratings by adults and children (Parsa et al. submitted). These studies used prototype hearing aids that were based on the Savia 311 or 411 hearing aid, with modifications to allow the use of NFC processing via custom programming software.

The following case study provides a brief illustration of how we applied these fitting goals in our studies. This
case study was developed using NFC processing as implemented in the Phonak Naida UP hearing aid, which is called “SoundRecover”. Figure 1 shows an electroacoustic verification of a hearing aid fitting that uses conventional multichannel amplitude compression, but does not use the NFC SoundRecover processor. This fitting has been done without SoundRecover, so that we can observe what speech audibility would be available without any form of frequency lowering. This type of fitting is representative of a well-fitted, conventional level of technology by today’s standards.

Figure 1 uses the DSL Method’s SPLogram format (Seewald, Moodie, Scollie and Bagatto 2005), which includes the listener’s thresholds, converted to the dB SPL scale, predictions of the listener’s upper limits of comfort and targets from the DSL v5.0 algorithm for conversational speech at an input level of 65 dB SPL (Scollie et al. 2005). Together, these three variables describe the listener’s auditory area (the range between the thresholds and the upper limit of comfort), and the target level within that range intended for aided speech.

The DSL SPLogram is then overlaid with the electroacoustic verification of the hearing aid. In this test case, a simulated real ear measurement approach has been taken in which the measured real ear to coupler difference (RECD) is used together with other variables to predict the Real Ear Aided Responses (REAR) for both tones at 90 dB SPL (to evaluate high-level output) and speech at 65 dB SPL (to evaluate mid-level speech output). The 90 dB tone sweep should be matched to the “+” targets and limited to the “∗” targets, while the latter should have the center line of the crossed area matched to the “∗” targets. In the test case shown, the hearing aid is able to provide a good match to the speech targets up to and including 4000 Hz. Also, the hearing aid maintains at least 10 dB SL for the aided peaks of speech to about 5000 Hz. Above this frequency, the audibility is limited, and this is likely attributable to the passband limits of the hearing instrument, and therefore is not resolvable via fine tuning.

The consequences of the limited high frequency audibility in this fitting are more clearly illustrated by the display shown in figure 2. In these measures, a female talker has presented a sustained live voice utterance of the phoneme /s/, and the aided spectrum of this isolated phoneme has been measured. The process was also repeated for the phoneme /œ/. The audibility of each of these two high frequency phonemes can be approximately assessed from these measurements; bearing in mind that live voice presentation is not calibrated and therefore does not ensure consistency of level. Care was taken during these measures to use a moderate conversational production level. Assuming that appropriate production levels were used, these measures indicate that while the frication noise of the /œ/ phoneme is audible, the frication noise of the /s/ phoneme is not. In fact, the /s/ frication noise is difficult to discern on this plot, as no clear spectral peak is present. This is likely because the peak associated with /s/ is located in a higher frequency region, such as 6000 to 9000 Hz (Pittman et al. 2003), and is being rolled off by the shape of the hearing aid’s response (Stelmachowicz, Pittman, Hoover and Lewis...
Therefore, improvement of /s/ audibility is certainly a fitting goal if frequency lowering processing is used.

It is important, when using this fitting method, to remember that audibility of frication noise is not the only possible cue for the recognition of /s/ and /ʃ/, nor is it the only cue for the discrimination between /s/ and /ʃ/. It is well understood that speech contains multiple redundant cues. For /s/ and /ʃ/, some of these cues include the transitions of vowel formants into and out of the voiceless region in time during which /s/ and /ʃ/ are being produced. These formant transition cues are typically derived from the second formant and higher, and therefore occupy the mid to high frequency range of 2500 Hz through 5000 Hz (Stevens 1998). However, research has also shown that children with hearing loss make use of the frication energy itself when recognizing the /s/ and /ʃ/ phonemes (Pittman and Stelmachowicz 2000). This has important implications for the use of frequency lowering technology such as NFC/SoundRecover. Provision of audible frication cues is likely a practice that can help to support the recognition of certain high frequency speech sounds for children with hearing impairment. However, there are many hearing losses that may in fact limit audibility of even lower-frequency formant transition cues in addition to the spectral cues of frication. For these users, if the application of NFC can restore or improve audibility of mid-frequency formant transition energy, speech recognition may be better supported. The savvy clinician is therefore reminded of the importance of incorporating knowledge of speech acoustics and speech perception when incrementing audibility through the use of frequency-lowering processing strategies such as SoundRecover.

Figure 3 illustrates the changes made to the /s/ and /ʃ/ phonemes when the NFC processor was activated at pediatric default settings of 2900 Hz and 4:1. These settings indicate that the band from 2900 Hz to the response limit of the hearing aid will be compressed into one-quarter of its original width. This processing lowers the /ʃ/ frication noise in frequency (compare figures 2 and 3), but does not change its audibility because it was audible without NFC. The processing also lowers the frequency of the /s/ frication noise, which now has a clear and audible peak that was not present without NFC (again, compare figures 2 and 3). Because the /s/ sound receives more frequency lowering, figure 3 shows some frequency overlap between the two sounds. In extreme settings, this can cause the listener some difficulty in discriminating between the two sounds. In this case, a listening check indicated that the two sounds remained clearly distinguishable to the fitter, even though they do sound somewhat altered by the use of the SoundRecover processor. The electroacoustic measurements indicate that complete overlap of the two spectra has been successfully avoided. Putting these observations together, the fitter can suspect that both sounds may now be audible and discriminable from one another (i.e., that the fitting goals have been met). Further follow-up on this with the end user is recommended to ensure that /s/ and /ʃ/ can be heard and discriminated. Electroacoustically, complete overlap of the frication spectra of these two phonemes is likely not advisable, especially if the two phonemes are indistinguishable to the fitter (i.e., if speech takes on a lisping characteristic). A second combination of verification and a listening check was also made to assess the overall audibility (figure 4) and sound quality provided for running speech when SoundRecover was activated. Both listening checks and electroacoustic measures indicate that the fitting goals of audibility with high sound quality have been met.

Some Thoughts on Verification and Fitting

The case example of a fitting using nonlinear frequency compression shown in the previous section illus-
trates a few important points about measurement of high frequency gain or output, and measurement of maximum output. Both of these warrant special consideration with this, and perhaps with other, frequency lowering technologies. First, a paradox emerges when measuring a hearing instrument with active NFC: it looks as though the hearing aid has less high frequency gain/output, compared to measures made without NFC (figure 4, with NFC versus figure 1, without NFC). This paradox occurs because the speech energy that is present in the higher frequencies (those greater than 2900 Hz in this case) has been shifted to a lower frequency prior to output from the hearing aid. Therefore, the apparent “cut” that is shown in the 4000 Hz region, for example, is not in fact a cut at all. Rather, the energy has been shifted downwards in frequency and now likely exists within the passband of the device. This is not directly portrayed by the verification screen itself, but instead must be conceptually overlaid by the clinician when interpreting the measurement. It was this paradox that led us to routine measurements of isolated phonemes as illustrated in figures 2 and 3, in an effort to index more directly the frequency-lowering properties of an individual’s fitting.

A similar phenomenon occurs during evaluation of maximum output. Typically, this is done using high-level sweeps of narrowband stimuli, as shown by the test labelled “MPO” in figure 4. Above the cut-off frequency of 2900 Hz, the maximum output of the device apparently drops precipitously, even below the known aided levels of speech. This type of configuration does not normally occur in devices without frequency lowering processors. Again, we must consider the role of the NFC processor when interpreting the measurements. In this case, the energy that goes in to the hearing aid at 4000 Hz is coming out of the hearing aid at a much lower frequency. The hearing aid analyzer is only measuring energy in the 4000 Hz region, and therefore does not register the actual level of output for the test signal. Particularly for narrowband tests such as pure tone sweeps or tests of maximum output using narrowband test signals, these effects are very strong, and do not give valid information above the cut-off frequency of the test signal. Some clinicians are rightly concerned about this: preferred practice protocol documents recommend routine evaluation of the maximum output of hearing aids. This can be accomplished by measuring the MPO with the NFC processor temporarily disabled. The observed maximum output in this condition has not, in our experience, ever been exceeded by frequency-lowered signals once the NFC processor was re-enabled. Essentially, this is analogous to setting the hearing instrument to have appropriate outputs in the conventional (no NFC) condition prior to enabling the NFC processor. In summary, it seems that an acceptable maximum output setting without NFC also provides acceptable output limiting when NFC is activated.

**Early Clinical Findings**

The previous sections have attempted to explain our thoughts on how the NFC strategy can be applied to meet specific goals for pediatric hearing aid fitting. We
used this general strategy when evaluating clinical outcomes using a prototype NFC hearing aid in a sample of adults and children with high frequency hearing loss. An early analysis of our findings is shown below, for a subset (n = 13) of the children and adults we tested. All of these listeners had better ear, high frequency pure tone averages (average of 2000, 3000, 4000 Hz) in excess of 70 dB HL. The seven children ranged in age from 6 to 17 years, with a mean age of 11 years at the beginning of the study. The six adults ranged in age from 50 through 81, with a mean age of 68 years. All participants were fitted using targets and protocols from the DSL v5 method (Bagatto et al. 2005; Scollie et al. 2005), and verified using the Audioscan Verifit as shown in the figures above. Outcomes for all participants were evaluated using a test battery that evaluated speech sound recognition, sound quality, speech production, and real world performance, on a larger sample of patients. The results of this larger trial have been submitted for publication, and are currently in review (Glista et al. submitted; Parsa et al. submitted; Scollie et al. submitted). Case study evaluations from this work have also been reported (Bagatto, Scollie, Glista, Parsa and Seewald 2008).

Our outcome measure test battery included two tests of high frequency speech sound recognition. The first used ten high frequency consonants (tʃ, d, f, tʃ, k, s, f, t, ð, z), spoken by two female talkers within the nonsense syllable context /CiL/. These were selected from a larger test of consonant recognition (Cheesman and Jamieson 1996). In this task, listeners selected the consonant they heard from ten choices listed on a computer screen. The second used the singular and plural forms of 15 words (ant, balloon, book, butterfly, crab, crayon, cup, dog, fly, flower, frog, pig, skunk, sock and shoe), selected to evaluate word-final plural recognition as was done in previous studies of high frequency bandwidth in adults and children who use hearing aids (Stelmachowicz et al. 2002). In this task, listeners selected the word they heard from two choices (singular, plural) shown on a computer screen. For both tasks, the test level used was individually determined, aiming for a performance level of about 70% in the no-NFC condition. The lowest test level used was 50 dB SPL, and this level was increased if performance was very poor. Both tasks were completed while wearing bilateral hearing instruments that had been fitted using the procedures described above and worn for at least two weeks. Testing was completed both with and without the NFC processor.

Results from these two tasks are shown in figure 5. The data from both adults and children indicate that five of seven children and four of seven adults had significant improvement on at least one of the two tests when the NFC processor was activated. Four of seven children showed significant improvement on both tests. Both children and adults who benefited from NFC tended to have greater degrees of hearing loss. In no case was speech recognition made worse by the use of the NFC processor. These data provide early evidence that the NFC processor, combined with the gains associated with DSL v5 and the NFC fitting approach illustrated in figures 1 through 4, was able to provide additional cues for speech sound recognition for at least some listeners. It may be that greater degrees of hearing loss indicate greater candidacy for the NFC processing. Significant benefits for these listeners were seen, with average improvements for plural recognition in the range of 30%. These results are very encouraging, and may also be associated with improvements in speech production. Our longitudinal project to evaluate speech production changes is currently ongoing, but early re-
Some Thoughts on Fine Tuning

Although we have described our general fitting approach in this chapter, the use of NFC signal processing in our studies also required individualized fine tuning, in order to optimize the audibility of the frequency-lowered band. If sounds are lowered too much, speech may take on a lisping quality that may be noticeable and objectionable to the wearer. Other indications of excessive frequency lowering include excessive loudness or unpleasant sound quality for high-frequency sounds, whether they are speech sounds or environmental sounds. If sounds are not lowered enough, the end user may not derive any additional benefit over and above what the hearing aid provides without NFC processing. Unacceptable NFC settings were typically resolvable with small changes at the time of follow-up, with the greatest effect usually seen when the cross-over frequency was adjusted. Cross-over frequency adjustments in the range of a few hundred Hertz are generally small changes, while adjustments in the range of one thousand Hertz or more are generally large changes.

When NFC is used, whether it is too much, too little, or just right, it may result in very high output levels delivered to the ear without feedback. These high output levels may be audible to conversational partners with normal hearing, particularly when talking at close proximity and in a quiet room. This occurs because the amplified sound leaks out of the earmolds as usual, but does not result in an oscillation cycle, since the input and output frequencies are not the same. Therefore, the conversational partner may be able to hear some of their own speech, lowered in frequency. One’s own speech, once frequency-lowered, may be more noticeable than it would be otherwise, and may be most noticeable when fricatives or affricates are produced. This effect is not necessarily a problem, but rather a new side effect associated with NFC processing that has not been noticed with previous technologies. In some cases, more occluding earmolds and/or thicker earmold tubing may reduce or alleviate the effect.

As with any new technology, it may take some time and patience to become familiar with how best to fine tune. This may be similar to the issues we faced in becoming accustomed to tuning wide dynamic range compression for the best effect when it was first considered a “new” technology.

What Don’t We Know?

Well, probably a lot! These are early days for most forms of frequency lowering hearing aids, and NFC is certainly not an exception. We feel that we’ve learned a lot from our studies with it, but also that more is left to be learned. For example, some but not all of our participants had asymmetrical hearing losses. We chose to fit based on the needs of the better ear, and provided both ears with that setting. Some would argue that more audibility (via a stronger NFC setting) could have been provided to the poorer ear. However, the alternative position is that asymmetry in the frequency domain may prevent binaural integration of sound. We chose to err on the side of caution, and gave a symmetrical NFC setting, with the NFC cut-off frequency and compression ratio determined only by the fit to the better ear. We don’t know at this time if the fitting would be improved or degraded by taking a more ear-specific strategy. This is certainly a question for further research, and likely depends on the degree of loss in both ears and the degree of symmetry between them.

Other unresolved issues include whether NFC processing should be fitted on infants, and how to evaluate whether it provides them benefit, as well as whether NFC processing is important to consider in evaluation of cochlear implant candidacy. For both infants and cochlear implant candidates, individual trials with NFC may be warranted, especially when accompanied by a high quality hearing aid fitting protocol and multidisciplinary monitoring of progress and performance with amplification. Also, should NFC be used for music listening or for understanding speech in noise? If so, would the optimal settings differ from those used for understanding speech in quiet? One might certainly speculate that different amounts of frequency lowering might be appropriate for these varying listening situations, but hard data on these issues are not yet available.

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