Critical Factors in Ensuring Efficacy of Frequency Transposition

Part 1. Individualizing the start frequency

In a previous paper, Kuk et al. reported on the rationale and mechanism of a new linear frequency transposition scheme where the unaidable high frequency sounds above a user-defined frequency (called the start frequency) are moved downwards. The transposed sounds are heard as a lower frequency substitute mixed with the original sounds. In principle, this approach provides extra audibility for the wearers because previously inaudible information becomes audible. Indeed, this processing scheme has demonstrated its efficacy for many wearers over conventional amplification. In the first of this two-part series, we will discuss the first consideration in ensuring the full efficacy of transposition—that of the proper choice of start frequency.

A Brief Review on Transposition

Kuk et al. described the steps in the linear frequency transposition scheme used in the Widex Inteo hearing aid. As a brief review, all frequency transposition algorithms identify a frequency above which they transpose. This frequency is called the start frequency. The region of sounds that would be transposed is called the source. In general, sounds in this region will be lowered in frequency (eg, from 4000 Hz to 2000 Hz).

Sounds below the start frequency are amplified based on the individual’s degree of hearing loss at those frequencies. Transposition moves sounds from the source region to a “target” region immediately below the start frequency. The transposed sounds are mixed with the original sounds and receive amplification appropriate for the frequency. In the case of the Inteo, the clinician can also adjust the level of the source sounds by +14 dB/-16 dB in order to customize the amount of transposed sounds for the wearer.

A critical parameter that affects the efficacy of linear frequency transposition is the choice of the optimal start frequency. Such a choice is related to the rationale for frequency transposition. In principle, frequency transposition is used when traditional amplification is ineffective. There are several instances when this may be the case.

“Unreachable” High Frequencies

Limitation of the chosen hearing aid model. Typically frequency transposition is used on individuals with a severe-to-profound degree of hearing loss, especially in the high frequencies. A large amount of gain must be provided to reach audibility at the impaired frequencies. This may not be possible even in the most powerful hearing aid model.

For example, in today’s superpower hearing aids, the maximum coupler gain may be 80 dB in the low frequencies but only 60-70 dB in the high frequencies, partly because of the receiver used. Thus, even though one may meet the gain requirements in the low frequencies, the desired gain in the higher frequencies are typically not met.

Limitation from hearing aid feedback. Even though the hearing aid may provide adequate coupler gain/output, the available gain in the real world is often limited by the amount of feedback between the earmold and the ear canal of the wearer. For example, the maximum amount of available gain before feedback in an average-fit closed earmold at 4000 Hz is 45 dB. This is not sufficient to achieve audibility of the soft /s/ sounds when the individual has more than a 70 dB hearing loss at 4000 Hz.

When the hearing aid is used with a larger vent diameter, the available gain before feedback will be further compromised. In an open-tube fitting, the maximum gain before feedback at 4000 Hz decreases to 26 dB. This reflects the challenges in achieving adequate high frequency gain, and highlights the need for an effective anti-feedback system with open-fittings.

Limitation from earmold tubing.
The available high frequency output from a hearing aid is further compromised by the increasingly popular open-mold fittings. Instead of the #13 tubing which has an internal diameter of 1.9 mm, a thin tube that has less than 1 mm internal diameter is used in most open-mold fittings.

A narrow tubing diameter has two consequences as shown in Figure 1. First, it moves the tubing resonance downward—from the typical 1000 Hz region to a lower frequency around 800 Hz. Secondly, it yields a reduction in the high frequency output by as much as 5-10 dB. Thus open fittings compromise the availability of high frequency sounds from two sources: 1) The gain limitation from feedback and 2) The output reduction from a restricted tubing diameter.

Unaidable High Frequencies

Even though the technical limitations in reaching the high frequencies may be solved, there are increasing concerns to

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the benefits/efficacy of reaching/amplifying the high frequencies. Hogan and Turner systematically varied the amount of high frequency gain for a group of hearing-impaired subjects with varying degrees of high frequency hearing loss. Decreasing word identification scores were noted as the high frequency gain was increased for subjects who had thresholds poorer than 55 dB HL at 4000 Hz. Similar findings were also reported by other authors (eg, Moore).

Moore postulates that, in some severe hearing losses, all the inner hair cells may be damaged, preventing frequency-specific decoding. Acoustic stimulation at the frequency where there are no inner hair cells (ie, dead region) does not stimulate the appropriate auditory nerve fibers; rather, the nearby neurons (at a lower frequency) respond to the higher frequency stimuli. The clinical implication of the dead region is that, in order to minimize the distortion effect, these so-called dead regions should not receive additional amplification.

Despite these reasons (of unaidable and unreachable regions), an important consequence is that the information carried by the high frequency sounds will not be audible. Sounds, such as nature sounds and high frequency consonant sounds like /s/, /sh/, etc, will not be heard and may not be identified properly. To restore audibility of the missing high frequency information, one must take the missing high frequency sounds and move them to a lower frequency where the inner hair cells are more likely to be intact. This way, information conveyed by the high frequencies may be perceived as a lower frequency substitute. The addition of this information, along with the intact low-mid frequency information, should improve the audibility (and intelligibility) of sounds for the wearers of a transposition device over conventional amplification.

Choosing the Start Frequency

Because the start frequency (and the source region) represents the region where transposition occurs, it is logical to take the start frequency where the dead region begins and/or where the hearing aid is limited in gain/output. Although it is easier to identify gain/output limitation, determining a dead region is more difficult in real life. In the case of the Inteo, a two-prong strategy was used to select the optimal start-frequency. This involves making it easy for clinicians to set the parameters (through default setting) and provides additional fine-tuning when needed (through individual customization).

1. Choice of the default start frequency. Moore recommended the measurement of psychophysical tuning curves to reflect neuronal survival. Tuning curves that are much broader than expected would suggest “dead” regions. This involves extensive masking studies, often taking up to 2 hours to measure the tuning curve for one frequency.

Because of the clinical time involved in identifying these regions, Moore et al introduced a simplified version of the tuning curve test, called the Threshold Equalizing Noise (TEN) test for quick identification of potential dead regions. This test takes less than 10 minutes to determine if a frequency is “dead.” However, Summers et al reported poor correlation between the results of an earlier version of the TEN test and psychophysical tuning curves.

To further alert clinicians to the potential of a “dead” region, Moore identified several audiometric characteristics that are highly associated with a high-frequency “dead” region. These characteristics include:

- The hearing loss in the high frequencies is greater than 90 dB HL;
- The slope of the audiogram is greater than 50 dB/octave;
- Extremely poor speech recognition score in quiet and in noise, and
- Distortion of sounds such as “noise-like” perception for pure tones.

These characteristics can alert the clinicians of the presence of “dead” regions so the proper start frequency may be selected.

Incorporating these findings and those from output limitations of current hearing aids, the default start frequency on the Inteo Audibility Extender takes the first (or lowest) frequency that has a 70 dB HL threshold and an audiogram slope between 500 Hz and 4000 Hz that exceeds 10 dB/octave. Furthermore, the lowest default start frequency is limited to 1600 Hz to prevent unnecessary transposition. These default settings yielded satisfactory initial fittings in a majority of patients simply based on information from their in-situ thresholds (or sensograms).

2. Individual customization—accounting for individual differences. The use of default settings, albeit efficient, may have the same problems as using generic prescriptive formulae (eg, NAL,
of a start frequency and their likely consequences. Figure 2a shows the case where the optimal start frequency is chosen. In this case, only the “unaidable” region is transposed and added to the aidable frequencies. In principle, more unaidable sounds are now heard, and speech intelligibility may improve.

Figure 2b shows the case where the chosen start frequency is lower than optimal. In this case, more frequencies are assumed “dead” (in red) than the actual case. Having a lower start frequency has two potential effects. First, the upper range of high frequency that is to be transposed is reduced. Less unaidable sounds are transposed (larger blue area). Second, the frequency region that is previously aidable and audible (in red) will not be amplified (because it is transposed). It may be audible only as a lower frequency substitute (because of the transposition). This may decrease the audibility of the “red” frequency region and result in poorer intelligibility in the transposed state than the non-transposed state. The magnitude of the decreased performance will probably depend on how far the chosen start frequency deviates from the ideal start frequency. If the start frequency is around 1 to 2 kHz where speech importance is high (ANSI S3.5-1997), the effect of the loss of intelligibility cues in this frequency region could be significant. This may be one of the many reasons why some studies in the past on frequency transposition showed a negative result (see Braida et al. for a review).

Figure 2c shows the start frequency to be higher than optimal. In this case, the upper range of frequency where transposition occurs is extended (less blue). However, the pink region which was previously considered unaidable and should have been transposed to a lower frequency substitute is not transposed. Instead, it is amplified. Since the region is unaidable, the effect of amplification will be minimal. This may not increase speech intelligibility however, it does not reduce speech intelligibility in the transposed state. The maximum potential of transposition is simply not realized.

**Individual Customization**

The previous speculations would suggest that the optimal start frequency must be carefully chosen. Pragmatically, it is necessary to begin with a default start frequency based on the hearing loss of the wearer (as in the Inteo AE fitting). However, the fitting software should have the flexibility to allow individual customization of the default settings for the wearers who may find the default less than optimal. Thus, the Inteo fitting software allows the clinicians to select from 10 possible start frequencies and two ranges of sounds (one octave and two octaves) for transposition. As previously discussed, +14 dB/-16 dB of transposed gain is allowed so the clinicians can tailor the magnitude of the transposed sounds to the wearer’s preference.

To further assist the clinicians in the customization, we recommend a systematic approach to fine-tune the individual start frequency in order to include the wearer’s residual perceptual ability in the final selection. The steps in this approach are summarized in the flowchart in Figure 3 and described below.

1. **Ensure an optimal fit of the master program (without any transposition).** This is because the frequency characteristics of the Audibility Extender program are linked to this program. Verification of the appropriateness of this program can be done using the Frequency-Output curve and the SoundTracker of the Compass fitting software, real-ear measures, or other measures deemed appropriate by the clinicians.
2. **Give the default start frequency a chance.** Because of the nature of transposition, some wearers may find the transposed sounds to be “unnatural.” This is a natural response. It is important for the wearers to wear the default settings for 1 to 2 weeks to acclimatize to the default settings. If at the end of the two-week period the wearers are still dissatisfied with the Audibility Extender program, then follow the steps outlined below.
3. **Choose a start frequency higher than the default.** Go to the Audibility Extender (AE) listing program and start at a frequency 3 steps above the default setting. (Note: It has been determined that in cases where the default setting was suboptimal, the majority of cases required a start frequency that is 2 steps above the default.) The frequency steps that are avail-

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**Figure 2.** Three hypothetical choices for the start frequency (shown by a dark downward arrow). **A**) The optimal start frequency is chosen. The aidable region is amplified, whereas the unaidable region is transposed and becomes audible. **B**) A lower (than optimal) start frequency is chosen. Some of the aidable region (in pink) remains unaidable and should be higher than optimal. **C**) A higher (than optimal) start frequency is chosen. Some of the unaidable region (in pink) remains unaidable.

**Caveats and Consequences of Improper Start Frequencies**

A “wrong” start frequency may compromise the effect of frequency transposition. It may not improve speech understanding (although it may help in the identification of nature’s sounds) or it may lead to a poorer performance.

Figure 2 shows three possible choices...
able for the start frequency are: 630, 800, 1000, 1250, 1600, 2000, 2500, 3200, 4000, and 6000 Hz. Leave the AE gain at 0 dB and say the /s/ sound at a 30 dB HL level. If the patient repeats the /s/ sound consistently, leave the AE program at the “default + 3 steps” gain setting and record the settings. Otherwise, move to Step 4.

You might be asking, “Why /s/ at 30 dB HL?” The specific sounds that the wearers need to hear are culture specific and individual specific. For English-speaking wearers who have a high frequency hearing loss, the /s/ sound is probably the most difficult to hear because its spectrum is dominated by energy between 4000-6000 Hz, the region where these wearers have the most hearing loss. Because the /s/ sound is also an important speech marker in the English language, it is desirable that the patient hear this sound. The level of the /s/ sound is set at 30 dBHL to approximate the real-life level of this sound during conversational speech. For people who cannot hear the /s/ sound even at the lowest start frequency, the /sh/ sound may be used as the stimulus (energy from 2000-4000 Hz) instead.

4. Adjust the AE gain. Adjust the AE gain in 2 dB steps until the patient repeats the /s/ sound. Repeat several times and take the lowest AE gain setting with a consistent response. If the patient cannot hear or cannot identify the /s/ sound without distortion even at the maximum AE gain, move to Step 5.

5. Move to a lower start frequency. Reset the AE gain to “0” and lower the start frequency by one step. Repeat Step 3 and Step 4 and accept the highest start frequency setting that results in a consistent identification of /s/ (or /sh/) as the start frequency for the wearer.

There are patients who may not be able to provide a verbal response and those who cannot provide a reliable response (such as small children). The SoundTracker available on the Compass fitting software may assist in the objective evaluation of an appropriate start frequency. Figure 4 shows the SoundTracker when the hearing aid is in the Audibility Extender program (a start frequency at 4000 Hz). It displays the measured input SPL at the hearing aid microphone (indicated as the light color bars). The gain applied to each channel is represented by the darker colored bar. The estimated output at the average eardrum is represented by the height of the bar in each of the 15 channels. The in-situ thresholds (sensograms) of the wearer are also indicated. Output of the hearing aid above the sensogram would suggest audibility at the specific frequency.

The yellow-shaded region at and above 4000 Hz shows the source region for transposition. In contrast to frequencies below 4000 Hz where gain is applied (as evidenced by the dark bars), the frequency channels in the yellow shaded area (4000 Hz and higher) do not receive any amplification. This is shown by the lighter, shorter colored bars at and above 4000 Hz. Gain is applied to those sounds after they have been transposed to the lower frequencies. On Figure 4, one can see narrower dark-colored bars (blue and bluish grey) that are used to represent gain from 4000 Hz to 6000 Hz at the 2000 Hz, 2500 Hz, and 3200 Hz channels. In particular, one sees that the “blue” bar exceeds the in-situ threshold (sensogram) of the wearer at the 2000 Hz channel. This shows that the previously 4000 Hz signal, after transposition, becomes audible (blue bar above sensogram).
Frequency Transposition

gram at 2000 Hz) as a 2000 Hz signal. Using this tool, one may say /s/ to the wearer and search for the highest start frequency where the /s/ sound, after transposition, is above the sensogram (i.e., audible).

Examples of Efficacy

The following two cases represent some of the observations witnessed on the efficacy of the Audibility Extender fit using the default setting along with additional fine tuning at our research office. Many similar cases were also reported by clinicians familiar with this approach.

Case 1. Subject 1 had worn binaural Senso Diva hearing aids prior to her participation in the study. At the initial fit, she was given binaural Inteo IN-9 hearing aids with a default start frequency at 6000 Hz for the right ear and 2500 Hz for the left ear. The patient’s initial reaction was a slight “echo” in the left ear, although she could hear more sounds than her Diva hearing aids and the Inteo in the Master program. Her initial speech recognition score (as measured on the Nonsense Syllables Test or NST) was 60% for the AE program but 70% for the Inteo master program. She agreed to use the hearing aids in her daily environment and to return in 2 weeks for follow-up testing.

Upon return, Subject 1 indicated she was adjusting to the sound quality of the AE program. Her performance on the NST improved to 64%, but it was still poorer than the master program where her performance stayed at 70%. Consequently, we fine-tuned the start frequency using the “Individual” approach and determined that her preferred start frequency for the left ear was 4000 Hz.

With the new start frequency, she reported “richer” and “echo-free” sound. Her performance on the NST improved to 84% with the AE program whereas it stayed at 70% with the master program.

Case 2. Subject 2 had also worn binaural digital hearing aids for a progressive hearing loss. Binaural Widex Inteo IN-9 hearing aids with 3 mm vent, skeleton earmolds were recommended with the AE program. The start frequency was measured to be 2500 Hz after the “Individual” fine-tuning. Initially, the patient commented that the AE program was not as clear as the master program. Her initial performance on the NST was 34% with the AE program and 38% with the master program. After wearing the AE program for 4 weeks, her performance improved to 46% with the AE program. Her subjective impression of the AE program also improved dramatically. She reported hearing more sounds and listening was more effortless.

Conclusions

Linear frequency transposition increases the available cues for speech intelligibility. However, the choice of an optimal start frequency is critical to the ultimate success of this signal processing algorithm. With the customized processing and individualized counseling/training (to be described in a later paper), linear frequency transposition may further improve speech recognition of people with a high frequency hearing loss that is either unaidable or unreachable by acoustic amplification.

References


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