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Modern Applications of Multi-Channel Non-Linear Amplification

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Introduction:
As the tenth anniversary of the first commercially available digital hearing aid passes (September, 2005), we reflect and appreciate the tremendous advances in hearing aid sciences.

Recently, due to significant advances in parallel processing and artificial intelligence, environmentally adaptive directional and noise reduction schemes have received appropriate and significant attention.

However, it is important to remember that modern adaptive directional and adaptive noise reduction features are criterion based; the input signal must have certain characteristics for these systems to activate.In contrast, compression is a "24/7" function in hearing aids - all signals pass through the compression system. Multi-channel, non-linear (MCNL) amplification is widely considered to be the primary treatment for sensorineural hearing loss (SNHL).

Linear vs. Non-linear Amplification
For decades, hearing aids used only linear amplification: the gain applied remained the same no matter what the level of the input signal. When the output (the simple sum of the input level and the gain) reached the physical limit of the hearing aid, the peaks of the signal were simply clipped off.

Why Compression?

As technology improved. output limiting compression was used to more elegantly limit the signal. The hearing aid continued to employ linear amplification throughout most of the operating range. However, as the output signal approached the device maximum, the signal was compressed using very high compression ratios, at times approaching infinite compression (no significant change in output as the input level increased).

During the 1980s, our understanding of SNHL improved and implications for non-linear amplification became clear (Stach, 1998). Two important characteristics of SNHL emerged:

1- SNHL is typically associated with reduced dynamic range, with uncomfortable loudness levels not changing from normal until the hearing loss exceeds approximately 50 dB.

2- Loudness Growth Functions of ears with SNHL are quite different from ears with normal hearing. Due to the reduced range from threshold to discomfort, the perceived change in loudness as the signal increases is greater in the impaired ear.

SNHL

Linear amplification simply could not easily match the broad range of input signals to the reduced dynamic range. Wide Dynamic Range Compression (WDRC) became an obvious solution to the amplification needs for patients with SNHL. Across a broad range of inputs, the amount of gain could be varied in order to compensate for the reduced dynamic range and the variations in loudness growth functions.

Why Multi-Channel Compression?

WDRC was developed to manage and deliver amplification within a given reduced dynamic range. Nearly all hearing aids designed to treat SNHL employ WDRC processing. WDRC processing packages the broad world of sound into the restricted dynamic range of the patient.

Importantly, compression cannot inherently improve ***intelligibility*** of the speech signal. In fact, poorly applied compression may very well detract from intrinsic recognition of the signal. However, compression can improve ***audibility***.

Under typical fitting rules, linear amplification provides gain so that moderate level input signals are amplified within the middle range of the patient's dynamic range. MCNL processing provides greater gain, and audibility, for softer speech inputs. Of course, greater audibility is possible with linear amplification, however, user intervention would be required. Therefore, MCNL compression provides ***automatic*** audibility for soft speech inputs.

MCNL

MCNL processing provides greater user acceptance in louder environments (Haskel et al., 2002; Noffsinger et al., 2002). With gain for soft to moderate input levels set to provide maximal audibility, the full range compression effect reduces gain for louder sounds, thereby avoiding loudness and annoyance issues while providing a "cleaner" sound.

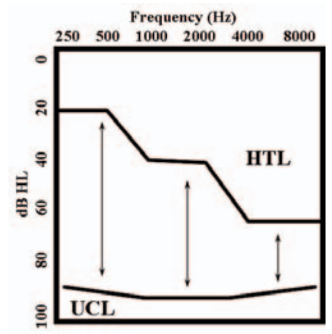

Figure 1: The thresholds (HTLs) and uncomfortable loudness levels (UCLs) of a typical patient with a moderate, sloping hearing loss. Notice how the size of the dynamic range varies across frequency.

As noted above, nearly all newly developed hearing aid products use ***multi***-channel, non-linear processing. There are two reasons why multiple channels are employed. First, the majority of SNHLs have a sloping configuration, while typical uncomfortable loudness level curves are usually flatter (Figure 1). Therefore, gain and compression need to vary across frequency.

(blue curve, Figure 3). The goal is to drop the gain for very soft sounds such as the ambience of quiet rooms. Although normal hearing individuals hear these sounds all the time, individuals with hearing loss may have missed these sounds for many years and may find the re-introduction of these sounds to be distracting or annoying. Additionally, low level internal sounds inherent in hearing aid microphones might be amplified by the hearing aid circuit, expansion minimizes the audibility of these same internal sounds.

More Complex Approaches:

In the last several years, more complex input output functions have been introduced to the market (e.g., Flynn, 2004). Given the processing power of digital platforms, designers now have the freedom to create more intricate response patterns, often based on a specific conceptual model (e.g., Buus & Florentine, 2001).

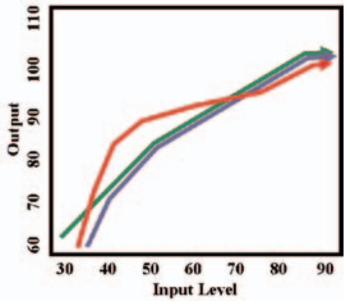

Figure 3: The input/output functions showing traditional WDRC (green), WDRC with expansion (blue) and modern curvilinear compression (red).

Input/Output

Recently, the market has seen a drop in the level of the primary kneepoint and more use of curvilinear responses, as indicated by the red curve in Figure 3. These more complex input/output functions allow a more targeted approach for the use of compression.

For example, in Oticon's Syncro, significant gain and compression is used for the soft to moderate speech levels but less gain and less compression is applied for speech inputs in the moderate to loud range. The assumption behind this strategy is that at softer levels, speech is more likely to occur at favorable signal-to-noise ratios (S/Ns) and thus can handle compression without a major concern of loss of intelligibility. At higher input levels, it is assumed that the S/N will be poorer, and therefore, compression is applied more judiciously.

Looking Forward:

Of course, there will be continued advancements in areas such as noise reduction and directionality. However, we also expect significant improvements in the way hearing aids provide non-linear amplification.

The basic need for non-linear processing is well recognized. However, our understanding of the finer details of how a broad range of complex, time varying, input signals are mapped onto the remaining, disrupted hearing of the patient continues to evolve.

Audibility can now be assured.

What lies ahead is the further exploration and definition of optimal ways to enhance intelligibility and acceptability via careful non-linear signal processing.

Channels

more channels to set the response of the hearing aid? Typically, we are given little guidance regarding setting channels which don't correspond to specific test regions of the audiogram. Nonetheless, filter slopes are worthy of consideration here. If a given circuit has fairly broad filter slopes at their channel boundaries, multiple channels might be needed to create separation between the required response at one audiometric frequency and the next. However, remarkably steep filter slopes are available, too, and as they approach 200 dB per octave, transition channels are not needed to create the audiometric precision called for by the fitting rationale.

Another issue regarding the appropriate number of channels is the bandwidth of the processed signals. If the typical input has bandwidths on the order of one third octave or less, an amplifying device that separates out such narrow-band signals would likely be desirable. However, the typical input signal to a hearing aid is speech, and speech sounds are not typically narrowband (Figure 2).

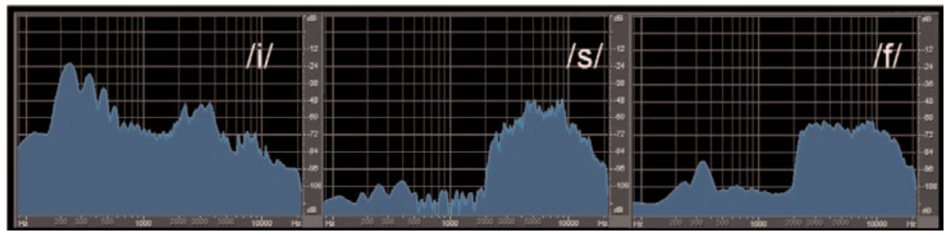

Figure 2: The spectra of the phonemes /i/, /s/ and /f/.

Expansion

Input/Output Function:
When MCNL amplification gained prominence during the 1990s, most devices were created with a simple, three-part Input/Output function (green curve, Figure 3). These devices provided linear amplification up to a primary kneepoint (referenced to the input signal) usually determined around 40 to 50 dB SPL. From that kneepoint to the point of maximum output, "linear compression" was used, meaning the same compression ratio was operational from the kneepoint to the point of maximum output. Above the point of maximum output (also called "the second kneepoint" usually defined between 80 and 100 dB SPL) nearly infinite compression (output limiting compression) was operational.

Expansion:
One parameter used in nearly all advanced technology hearing aids isexpansion. Expansion is the opposite of compression. In expansion, as input levelincreases, gain increases. Expansion is usually used for signals below 35 dB SPL

Secondly, speech amplitude varies dramatically across time. Vowels have strong low and mid-frequency energy whereas unvoiced consonants have a weaker, mid and high-frequency profile. Depending on the timing characteristics of the compression system, a vowel may drive the gain of the device down, due to the higher input intensity. Given a single- channel system, these actions can affect the audibility of softer, high frequency consonants. Multiple channel systems allow the amplitude of one phoneme from unduly affecting the processing of others.

Therefore, the role of MCNL amplification is to take a broad range of sounds from the acoustic environment and automatically place them within the "working space" of the listener. When selected and adjusted properly, MCNL amplification goes a long way towards seamlessly integrating the world of sound into the remaining hearing capacity of the user.

Fitting Rationale:

Primary Parameters
Fitting rationales prescribe gain, frequency, compression and other electro-acoustic characteristics. Patients may notice differences between rationales depending on their type and degree of hearing loss, and the acoustic var ables of the listening environment. In the days of linear technology, Berger, POGO, NAL-RP, DSL and other rationales prevailed. With the advent of WDRC technology, non-linear fitting rationales were developed to maximally apply these technologies. Non-linear formulae provide gain prescriptions for various input levels (or, conversely, compression ratio). Independent formulae such as DSL i/o, NAL-NL1, IHAFF & Fig6 (Dillon, 2001) were developed to be used with multi- channel, WDRC instruments. Additionally, several manufacturers of advanced technology products developed rationales specific to their products.

Essentially, all non-linear fitting rationales provide access to a broad range of sounds in everyday listening environments. However, different rationales represent different solutions to this problem.

Rationales

For example, DSL I/O (Cornelisse, Seewald & Jamieson, 1995) maximizes audibility across the entire bandwidth by restoring access to the full normal dynamic range. In contrast, NAL NL1 (Dillon, 1999) maximizes speech intelligibility across a large range of inputs while maintaining normal loudness perception and emphasizing mid and high frequencies -- where the greatest proportion of speech information falls. Under some circumstances, different philosophies will lead to different levels of prescribed gain and compression.

Secondary Parameters:
With non-linear hearing aids, the prescription of gain, frequency response and compression ratio is not sufficient to describe the entire array of processing and performance characteristics. Secondary parameters such as; number of channels, crossover frequencies, attack time, release time, knee-points and other parameters need to be prescribed.

For some patients, secondary parameters impact objective and subjective performance (Neuman et al., 1998). Some manufacturers prefer slower attack and release times whereas others recommend a faster approach. For some patients, the decisions on how the secondary parameters are set may "make" or "break" the fitting.

Release Times

Attack and Release Times:
At Oticon, we believe most patients are better served using a slow acting approach to amplification. Slower release times help preserve the linear nature of speech on a moment to moment basis, while applying appropriate gain changes to longer term variation in the overall input level. Although fast acting, syllabic compression changes the phoneme-to-phoneme amplitude, most patients have sufficient dynamic range to handle the natural 30 dB variation from phoneme to phoneme, as long as overall gain changes account for the overall input level. Nonetheless, the ability to use a faster acting approach varies from patient to patient. Therefore, we offer a range of adjustment options in ou non-linear products. Direct changes on timing parameters can be made by changing rationale choice (i.e., Adapto) or changing device "Identity" (i.e., Syncro, Tego, Sumo DM).

Fitting Rationale Choices:
Some manufacturers provide only one, proprietary approach to fitting their products and they provide a good description as to what their fitting rationale is. For example, in Syncro, the core fitting rationale is based on the Voice Aligned Compression fitting rationale (Flynn, 2004). Nonetheless, significant flexibility to maximally address individual needs is available via "Identities" (Schum, 2005).

In some cases, manufacturers provide more than one fitting rationale. For example, in Tego, we offer NAL-NL1 and DSL i/o. Although either fitting rationale is designed to maximize audibility through a combination of gain and compression selections, with concomitant decisions on attack and release times and other parameters, a single hearing aid can be altered to sound significantly different.

Fitting Rationales

Choosing a Fitting Rationale: 3 Points to Consider

1. What is the core philosophy of the fitting rationale? Whether choosing an independent or an imbedded rationale, the audiologist needs to have a good understanding of the basic goals of the fitting rationale and must decide if that rationale is consistent with the fitting goals for the individual patient.

2. Is the implementation understandable and easy to use? Whether independent or imbedded, the implementation must be sensible and practical. Manufacturer's proprietary software should not feel like a black box where the clinician has no idea how audiometric and demographic data impacts the prescribed fitting. If the software is independent, the prescribed fitting parameters need to match the technical controls in the chosen hearing aids. NAL-NL1 is a good example of an independent software package that matches the range of technical settings available in many advanced technology hearing aids.

3. Independent or Proprietary? The advantage of independent fitting options is they can be applied to many available MCNL devices. However, one important limitation of independent rationales is they often do not specify settings for parameters such as; crossover frequency, attack time, release times and compression kneepoint. As advanced technology becomes increasingly complex, clinicians using independent rationales may find little or no guidance for unusual situations, presentations, observations or complaints.

In contrast, manufacturer's imbedded prescriptions generally prescribe all technical settings and options for their products. In most cases, manufacturers provide clear explanations as to why certain settings and parameters are recommended. Additionally, manufacturers of advanced technology products update their fitting rationales and prescriptions through new software releases based on field experience, feedback and the accuracy and usefulness of their fitting rationales.

Number of Channels
The number of channels in available MCNL products range from 2 to 64. If there are too few channels, the audiologist will not have enough flexibility to match the audiometric characteristics of the patient. However, if there is an excessive number of channels, processing resources may be wasted. There are two issues to be addressed regarding the "right number of channels."

First, are there enough channels to match the audiometric precision of the audiogram? In other words, if we only measure thresholds at 250, 500, 1000, 2000, 4000 and 8000 Hz (6 points of a continuum) why would we need 16, 24 or

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