

# Signal Processing for Severe-to-Profound Hearing Loss

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## Introduction

Wide dynamic range compression has become the mostly used signal processing strategy for mild to moderate hearing losses although there is still some discussion going on regarding the details of such compression systems. Furthermore, sophisticated signal processing strategies such as automatic program selection, adaptive digital directional microphones and sophisticated noise canceling schemes have been developed and applied in modern digital hearing instruments. Digital technology offers a great deal of flexibility for easily designing and implementing new signal processing algorithms.

The most common strategy applied with individuals who have severe-to-profound hearing loss has been to provide them with as much power as possible. However, so far few attempts have been undertaken to apply more sophisticated signal processing strategies with this segment of the hearing-impaired population. In this paper we will review existing knowledge on basic psychoacoustic mechanisms, speech perception as well as different approaches to optimally amplify and process sounds for the group of severely to profoundly hearing impaired subjects.

## Physiology, Psychoacoustic and Speech Perception in Profoundly Hearing Impaired Subjects

### Physiology

The understanding of the exact mechanisms of stimulus excitation within a profoundly-impaired

cochlea is limited at this time. Hinojosa and Marion (1983) have analyzed temporal bones of patients with severe hearing impairment to deafness (16 subjects and 22 subjects respectively) by counting hair cells and supporting cells as well as ganglion cells. These cell counts were then correlated with the cause of deafness. The authors found viral or bacterial infections, trauma to the head, ototoxicity and congenital deafness as the main causes of profound sensorineural hearing impairment. Based on the impairment patterns observed in the Organ of Corti the authors identified 5 different groups: Group 1 showed a complete degeneration of the Organ of Corti and peripheral axons, the ganglion cell counts were 0 to 22.000; Group 2 showed complete degeneration of the Organ of Corti and severe to profound degeneration of peripheral axons, the ganglion cell counts were 8000 to 23.000; Group 3 had sites of remaining inner hair cells which correlated well with sites of remaining peripheral axons, ganglion cell counts were 16.000 to 25.000; Group 4 also had sites of remaining inner hair cells which correlated weakly with sites of remaining peripheral axons, the ganglion cell counts were 6.000 to 13.000; Group 5 (only one case) showed complete degeneration of inner hair cells but almost normal peripheral axon population.

Thus, we know something about the pathophysiology of profound hearing impairment but we are lacking the understanding of “pathofunctionality” of the profoundly impaired Cochlea. Specifically, we believe that knowledge of the process of neural stimulus excitation would be particularly helpful also for designing and selecting signal processing algorithms for profoundly hearing-impaired subjects (Harrison, Shirane, Fukushima and Mount 1991).

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## Psychoacoustics

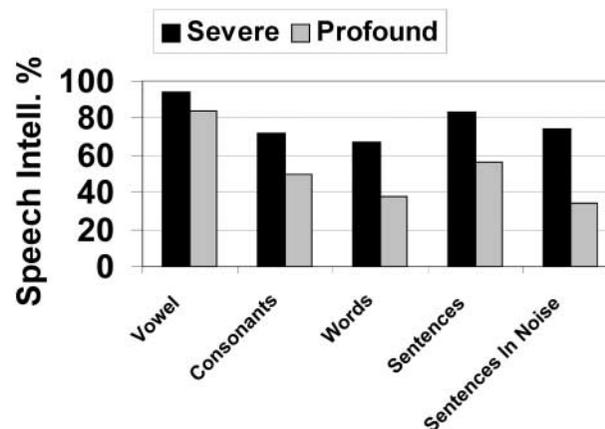
Very little information also exists on the basic psychoacoustic capabilities of profoundly hearing-impaired individuals (Faulkner, Fourcin and Moore 1990; Faulkner, Ball, Rosen, Moore and Fourcin 1992; van Son, Bosman, Lamore and Smoorenburg 1993). Faulkner et al. (1992) reported results of three basic psychoacoustic experiments in a group of 13 profoundly hearing-impaired adults with average hearing losses  $> 95$  dB HL and residual hearing in the frequency range from 100 Hz to 500 Hz only. Their subjects form an extreme case as they probably would receive a cochlear implant today. The experiments performed by Faulkner and colleagues studied aspects of spectral analysis as well as of temporal analysis by the profoundly impaired auditory system that included: (1) measuring the ability to distinguish the frequency of two low frequency tones (“frequency difference limen”) using a two alternative forced choice procedure (2AFC); (2) determining a simplified, two-point, psychoacoustic tuning curve using a 80-Hz wide noise masker centered at 125 or 250 Hz and a probe tone at 250 or 125 Hz respectively. In each subject the threshold of the tone in each of the two masking conditions was determined. The “masking level difference” (MLD) was determined by averaging the threshold of both measurements; and (3) measuring a small temporal gap in a wide band noise masker for determining the temporal acuity the detection threshold.

The results showed a strongly degraded performance of the profoundly hearing impaired auditory system compared to the performance of the normal auditory system. As with other hearing-impaired subjects, between-subject variability was large. For example, for the frequency difference limens, the achieved frequency resolution varied between 4 to 41% percent (trained normal hearing subjects: 1.5–2%). The psychoacoustic tuning curves for the subjects with hearing loss, measured as the MLD, yielded results between 0 dB (no frequency selectivity at all!) to 14 dB. A normal hearing subject achieved an MLD of 39 dB in the same task. In the gap detection experiments the resulting thresholds were between 20–26 ms for seven subjects and around 40 ms for two subjects. A normal hearing subject would achieve a threshold of about 8 ms. Overall, the capability of the profoundly impaired auditory system is strongly degraded regarding several different aspects of spectral and temporal acuity.

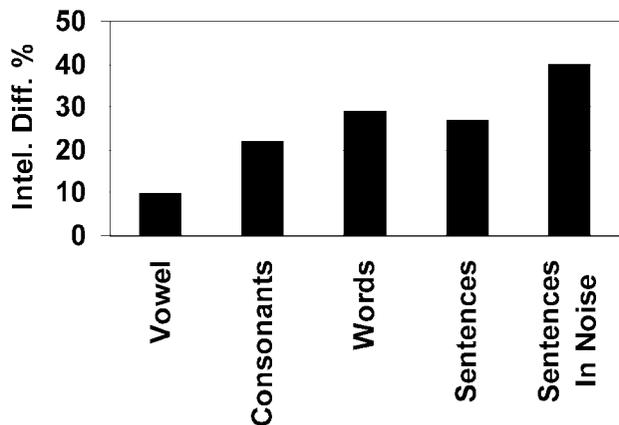
## Speech Perception

Flynn and coworkers 1998 (Flynn, Dowell and Clark 1998) reported the findings of a study on aided speech intelligibility in two groups of adults. One group of subjects ( $n = 18$ ) had average hearing losses in the range of 60–80 dB HL (i.e., severe) and the second group ( $n = 16$ ) had average hearing losses in the range of 80–100 dB HL (i.e., profound). Several different procedures for measuring speech intelligibility were applied. The authors used a vowel recognition test, consonant recognition test, monosyllabic word identification (CNC) and sentences (CUNY) in quiet and in noise. The presentation level was always “normal speech” (i.e. 65 dB SPL) with a 10 dB signal to noise ratio for the sentence in noise condition. All subjects were experienced hearing instrument users and wore their own hearing instruments in the speech intelligibility testing. The results of this study are shown in figure 1. It can be seen that performance for both groups of subjects was found to be quite good ( $>80\%$ ) for the vowel perception condition and somewhat poorer for consonant perception and perception of words.

When using sentences in quiet, both groups of subjects appear to have benefited from the use of lexical and context information and thus showed an increase in performance over the score achieved with single words. Note that the difference in performance between the severe and the profound groups is not constant over the different test conditions. Rather it was found that between-group performance



**Figure 1.** Results of the different speech intelligibility tests reported by Flynn et al. (1998). The black columns show the results of the severe group, gray columns show the results of the profound group. Adapted from Flynn et al. (1998).



**Figure 2.** This graph shows the difference between the speech intelligibility results of the severe group and the profound group shown in figure 1. Adapted from Flynn et al. (1998).

differences increased with increasing complexity of the task. The results shown in figure 2 illustrate this finding. This might be caused by the strongly degraded psychoacoustic capabilities of the profoundly hearing impaired subjects which hinders them from being able to do a detailed, highly resolved analysis of complex sounds and especially mixtures of different sounds.

A similar finding has been reported in normally hearing subjects when listening to speech sounds that have been highly degraded spectrally. In quiet, normally hearing subjects recognize vowels, consonants, words and sentences remarkably well when listening to speech that has been processed through a only a few (i.e., 3–20) temporally modulated noise bands. Performance drops dramatically, however, when noise is added at speech-to-noise ratios between  $-12$  and  $+24$  dB (Shannon, Zeng, Kamath, Wygonski and Ekelid 1995; Dorman, Loizou and Fitzke 1998; Fu, Shannon and Wang, 1998; Loizou, Dorman and Tu 1999; Lorenzi, Berthommier, Apoux and Bacri 1999; Friesen, Shannon, Baskent and Wang 2001).

### Signal Processing for Amplification: WDRC versus Linear

A limited number of studies have been reported that have analyzed which amplification strategy is best suited for the needs of individuals with severe to profound hearing loss. In the following section, we will review four studies on this topic that were conducted with adults and one study that had been conducted with children.

In the studies reviewed, we found a slight preference for WDRC processing which tends to decrease as amount of hearing loss increases. When linear processing is preferred, it is preferred in combination with compression output limiting over peak clipping.

In the first study on the use of compression systems for profoundly hearing-impaired subjects, Boothroyd and coworkers (Boothroyd, Springer, Smith and Schulman 1988; Boothroyd 1990) investigated a WDRC and compression limiting strategy in nine subjects with prelingually acquired profound hearing loss. They conducted a 3-alternative forced choice (3AFC) test of speech pattern contrast perception to analyze the perception of phonologically contrastive dimensions. Three frequency average threshold of the subjects test ears ranged from 80 to 107 dB HL with a mean of 97 dB. The stimuli were processed with a master hearing aid in two different ways: (1) linear amplification with broad band limiting compression (fast attack and slow release time) at high input levels versus compression limiting; and (2) fast syllabic compression (release time 20 ms) of the signal in two frequency bands. Only one out of nine subjects performed better with the fast compression than without. For all other subjects there was a small but significant reduction of performance when compression was introduced. The authors argue that the degraded performance with fast acting compression is mainly due to the distortions of time-intensity cues introduced by amplitude compression. The primary conclusion from this study is that syllabic compression, in addition to an otherwise optimized signal, is unnecessary, or even detrimental, for most profoundly deaf subjects, but could be beneficial for some.

Barker and colleagues (Barker, Dillon and Newall 2001), analyzed different amplification schemes in 16 trained subject with profound hearing loss. They compared fast acting single-channel WDRC with linear amplification plus compression limiting and compression limiting with peak clipping which had been programmed in the different memories of their hearing instruments. For their 16 subjects (mean four-frequency hearing loss: 87 dB HTL), only 8 (group I) could be fitted with two fast acting WDRC systems differing in the compression threshold: a low compression threshold (45–57 dB SPL) with a high compression threshold (65–73 dB SPL). In a second phase, these subjects compared their preferred compression setting with a linear amplification scheme with compression limiting. Another five subjects (group II) were comparing high compression

threshold WDRC with a linear amplification plus compression limiting setting. The remaining three subjects (group III) compared compressing limiting with peak clipping. This separation of subjects into three groups had to be done due to loudness insufficiencies in the other settings. The subjects were given a questionnaire that they had to fill in during a trial period of several weeks. No experiments were conducted in the laboratory. In the first phase of experiments, six out of the eight subjects in group I preferred the low compression threshold and two subjects preferred the high compression thresholds. In the second phase, when comparing preferred WDRC with compression limiting, seven out of eight subjects preferred WDRC over compression limiting. In group II, four out of five subjects preferred WDRC with a high compression threshold over linear amplification plus compression limiting. In group III, two subjects preferred compression limiting over peak clipping and one subject was not satisfied at all due to loudness insufficiency and distortions. The difference between the three groups lies in the average audiograms of the subjects. Group I had about 10–20 dB less hearing loss in the low and mid-frequency range than the subjects in either group II or III. Thus, in summary, the results of this study suggest that the profoundly hearing-impaired subjects tended to prefer WDRC processing over linear amplification although this preference was found to shift toward linear processing with increasing hearing loss. This latter aspect might also be the explanation of the difference between the results of the study of Boothroyd and coworkers (1988) who showed a preference for linear signal processing and Barker et al. results as the subjects in the Boothroyd et al. study had a more profound hearing loss.

A third study, also comparing linear processing with WDRC processing, found similar results (Ringdahl, Edberg, Thelin and Magnusson 2000). Twenty-five subjects with severe-to-profound hearing loss participated. All subjects were experienced hearing instrument users. Two different signal processing schemes (three channel WDRC system and a linear amplification) were compared in a cross-over design: 12 subjects were tested with linear amplification in a first phase and were then switched to WDRC processing in the second phase, while 13 subjects were tested using WDRC first followed by a phase using linear amplification. The two systems were compared using a variety of different measures including: (1) speech intelligibility in quiet and in a background of different

noises; and (2) subjective evaluation using paired comparison measures with speech in quiet and in different background noises or music serving as stimuli. Results showed a benefit of WDRC processing over linear processing in all speech intelligibility tests conducted. For the subjective measures, the results were less clear and depended on the situations considered in the evaluation. For speech in quiet, speech in a loud background noise and music stimuli subjects preferred WDRC to linear amplification while for speech in a moderately loud background noise subjects preferred linear amplification over WDRC processing. At the end of this study 17 of the 25 subjects selected the WDRC processing over the linear processing based on their subjective experience during the field trial. Unfortunately, no correlation between subjective preference of signal processing strategy and degree hearing loss was reported in the study.

A fourth study might help understand the preference for WDRC over linear processing found in the above-mentioned studies. Souza and Bishop (1999) analyzed the effect of audibility on speech intelligibility when using WDRC processing or linear amplification. Both amplification strategies were applied in such a way that audibility had been equated at high input levels. In their study vowel-consonant-vowel (VCV) syllables and sentences were off-line processed and then presented to two groups of hearing-impaired subjects: 10 moderately and 11 severely hearing impaired subjects. The VCV stimuli were processed using a two-channel (split frequency 1.5 kHz, 2:1 compression in the low frequency channel and 5:1 in the high-frequency channel) fast acting WDRC system while the sentences were processed using a single channel fast acting compression system with 2:1 compression. Compression thresholds were set to 45 dB. Speech intelligibility was measured at 55, 70, 85 dB SPL and 70, 85 dB SLP for the VCV stimuli and sentences respectively. The results of the speech intelligibility measures used in this study showed a significant benefit in speech intelligibility for the WDRC system over the linear amplification.

Marriage and Moore (2001) recently reported the results of a study in which a comparison was made between linear and compressive amplification systems in a group of children with severe (4 children) and profound (4 children) hearing losses. In this study they tested speech intelligibility in quiet at different input levels using both amplification strategies. They reported a significant benefit for the severe group and a small but consistent benefit for the profound

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group when using the compressive signal processing strategy.

Overall, the little existing data suggest a slight preference for WDRC processing over linear processing for the group of severe to profound hearing losses but this preference seems to be decreasing for increasing severity of hearing losses. Note that all participants of the studies reported had been experienced hearing instrument users prior to these field studies. Ideally, hearing instruments designed for profoundly hearing-impaired subjects should offer different signal processing strategies from which a fitter can select the preferred strategy of the individual.

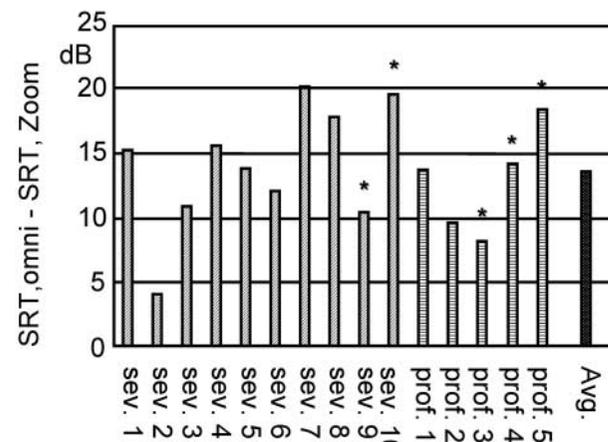
### Signal Processing for Intelligibility in Noise

The results of a study reported by Flynn et al. (1998) has shown, that speech perception in noise is much worse in profoundly hearing-impaired subjects relative to the performance obtained by severely hearing impaired subjects and that the difference in performance between the two groups is much larger for the speech in noise perception than it is for speech perception in quiet listening conditions. Thus, when discussing signal processing strategies for profoundly hearing impaired subjects, methods for improving speech-to-noise ratio could be extremely helpful especially in this group (Kühnel, Margolf-Hackl and Kiessling 2001).

Kühnel et al. (2001) investigated the potential benefit of hearing instruments with multi-microphone technology in laboratory and in field tests for users with severe-to-profound hearing loss. Twenty-one experienced hearing aid users were fitted with high-power multi-microphone hearing instruments (Phonak PowerZoom P4 AZ). The following measures were used: (1) an adaptive speech test (Speech Reception Threshold (SRT) for HSM sentence test) in quiet and in noise with their own instrument and the test instrument in the omnidirectional (basic program) and directional mode (party noise profound + Zoom algorithm); (2) paired comparisons of loudness, sound quality, and speech intelligibility for both the omni and zoom program; and (3) questionnaires on satisfaction and self-assessment of communication in different listening conditions. This questionnaire was filled in by the subjects themselves as well as by their partners.

Only 10 subjects achieved 50% correct (SRT) on

the sentence test in noise (speech presented at 0° azimuth/ noise presented at 180° azimuth) with both their own instrument and the test instrument in the omnidirectional mode. However, 15 subjects succeeded in the SRT measurement in the directional mode at a noise level of 60 dB SPL. The average SRT improvement of the directional over the omnidirectional mode was 13.7 dB. The individual results of the speech intelligibility tests in noise are shown in figure 3. Overall, the test instrument was rated very positively by the subjects.



**Figure 3.** SRT improvement, in dB, for those subjects who were able to perform the speech test in noise (HSM-Test). Subjects marked with \* could perform the test only in zoom position. In these cases the SRT for the Omni condition was supposed to be +18 dB SNR, which was the worst score observed in this study.

The results of the partner's questionnaire were almost identical with those of the subject's questionnaires. In summary, both in the laboratory and in the field trial the test instrument was shown to be significantly superior the subject's own aids. Particularly in noisy situations the zoom program was ranked significantly higher than the omnidirectional program and the subject's own hearing aids.

The results of this study suggest that listeners with severe-to-profound hearing loss can benefit significantly from multi-microphone technology when it is appropriately designed for this group in multi-program hearing instruments. The benefits are both improvement of speech intelligibility and sound quality in noisy situations. In addition, experiences with the test instrument were rated positively by the subjects. Both in the laboratory and in the field trial the

test instrument was shown to be significantly superior to the subject's own instruments. Particularly in noisy situations the zoom program was ranked significantly higher than the omni-directional program and the subject's own hearing instruments.

### **Other Approaches: Frequency Transposition and Feature Extraction**

The study by Faulkner et al. (1992) reported earlier showed that the psychoacoustic performance of the profoundly hearing-impaired population is strongly degraded compared to that of normally hearing subjects. In other words, the information processing capacities of the auditory channel is substantially reduced in individuals with profound hearing loss. For this reason, several approaches have been discussed in the literature for reducing the amount of information in a speech signal by extracting and amplifying the relevant information only.

One approach that has been followed is to transpose or compress high-frequency information into the residual *spectral* range ("frequency compression" / "frequency transposition"). Only few studies report results on using this approach in profoundly hearing-impaired subjects (Parent, Chmiel and Jerger 1998; Davis 2001; MacArdle et al. 2001). MacArdle and colleagues reported an extensive longitudinal study with children at the age of 2.5 to 15.6 years. Most of the 36 children participating in the study were borderline cochlear implant candidates and had used a frequency transposition device for 20 months (11 children) or 48 months (25 children). The frequency transposition device was evaluated using speech perception measures and measures of the intelligibility of children's speech. Of the 36 children in this study, four children were found to significantly benefit from using the frequency transposition device. Davis (2001) and Parent et al. (1998) also report two case studies with two subjects each that also showed benefit from using frequency transposition.

Another approach was used in a study reported by Faulkner et al. (1992) and Rosen, Walliker, Fourcin and Ball (1987). They applied a laboratory compound speech pattern aid that encoded voice fundamental frequency, amplitude envelope and the presence of voiceless excitation or voice fundamental frequency alone. Of the 11 subjects participating in

the study, 5 showed benefit from using this experimental device. These subjects had hearing loss of 110 dB HL or more (four frequency average). At the present time, these subjects would be good candidates for cochlear implantation. A similar approach with a similar finding as that of Faulkner et al. was reported by van Son (1993).

Overall, the studies discussed above have shown that some individual subjects might benefit from other signal processing approaches rather than solely applying amplification. However, at present, no other signal processing strategy exists of which a large percentage of profoundly hearing-impaired subjects have been shown to benefit.

## **Discussion and Conclusions**

In this chapter, we tried to review and summarize the existing literature about psychoacoustics and signal processing strategies for profoundly hearing-impaired individuals. At the present time there are very few published studies on this topic. Thus, our knowledge of the basic psychoacoustic and physiological mechanisms of profound hearing impairment is very limited. Of the few studies that have been reported, the results have shown much poorer performance on basic psychoacoustic measures as well as in speech perception tests for profoundly hearing-impaired individuals. In particular, speech perception in difficult (e.g., noisy) environments appears to be strongly affected in individuals with profound hearing loss.

The literature we have summarized related to the optimal amplification strategy for profoundly hearing-impaired subjects suggest that, for designing hearing instruments for this target group, we may need to offer a choice of different signal processing strategies such as compressive processing as well as linear processing within the same instrument. An unsolved issue is a predictor of the individual preference for the amplification strategy. Based on the audiogram there seems to be a trend for preference of linear processing for more profound hearing losses. However, this statement is based on a very limited set of experimental data. Although four studies reviewed within this chapter have shown a slight preference for compressive over linear amplification schemes it is premature to draw final conclusions from these few studies. Unfortunately, the results of these studies cannot be easily compared or pooled as they have

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used different compression systems (different number of channels, different time constants etc.). The number of subjects does not allow a thorough statistical analysis of the data in order to prove the significance of the preferences as well as to deduce a clear predictor of the preference such as the audiogram. There is clearly a need for conducting an extensive study on this issue seeking for a predictor of preference between linear and compressive signal processing strategies in the severely to profoundly hearing-impaired target group.

One signal processing approach that appears to offer potential for improving the performance of profoundly hearing-impaired subjects in noisy environments is multi-microphone switchable directional microphones. The study summarized here has shown a significant improvement in signal to noise ratio for achieving 50% speech intelligibility of 13 dB when compared to performance with an omni-directional microphone system.

Several other approaches of signal processing for profoundly hearing-impaired subjects were reviewed. Again, however, very limited research exists on such alternative strategies. The studies summarized here, followed two lines of reasoning. First, it has been suggested that performance might be improved by reducing the amount of information presented to the ear through extraction of special features of a stimulus such as pitch. The other strategy that has been proposed is to apply spectral transposition in order to shift the available information contained at higher frequencies into the low-frequency range where usable auditory capacity is present. However, for both approaches no significant improvement of performance has been demonstrated. Only a small number of subjects participating in these studies showed a benefit when using either of the approaches when compared to traditional "power-amplification".

Overall, in our view, currently the best strategy for signal processing for the profoundly hearing-impaired individuals appears to be to offer systems that provide the fitter with some flexibility for selecting the amplification preferred strategy. Furthermore, given the large performance drop for speech intelligibility in noisy conditions, it appears to be of special importance to offer an effective means (e.g., multi-microphone technology) for improving speech intelligibility in noisy conditions for this target group.

Finally, our knowledge about the basic psychoacoustic and physiological mechanisms, as well as about optimal signal processing and fitting strategies

for the profoundly hearing-impaired persons, is built on a very limited number of published studies. Therefore, to move ahead in matching the advanced signal processing capabilities of modern hearing instruments to the characteristics and need of individuals with severe and profound hearing loss, more studies that address these fundamental issues will be required.

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