EFFICACY OF NON-LINEAR FREQUENCY COMPRESSION IN INDIVIDUALS WITH AND WITHOUT COCHLEAR DEAD REGIONS

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A Dissertation Submitted in Part Fulfillment for the Degree of
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ALL INDIA INSTITUTE OF SPEECH AND HEARING
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May 2009

Certificate

This is to certify that this dissertation entitled **"Efficacy of Non-Linear Frequency Compression in individuals with and without cochlear dead regions"** is a bonafide work in part fulfillment for the degree of Master of Science (Audiology) of the student Registration No. 07AUD018. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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May, 2009

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This is to certify that this dissertation entitled **"Efficacy of Non-Linear Frequency Compression in individuals with and without cochlear dead regions"** has been prepared under my guidance and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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Declaration

This Dissertation entitled **"Efficacy of Non-Linear Frequency Compression in individuals with and without cochlear dead regions"** is the result of my own study under the guidance of Dr. P.Manjula, Reader in Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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“Kayena vacha manasendriyairva
Buddhyatmana va prakrite swabhavath
Karoomi yadyad sakalam parasmai
Narayanayeti samarpayami”

Whatever I do with my mind, body, speech or with other senses
of my body,
or with my intellect or with my innate natural tendencies
I offer everything to Lord Narayana.

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“Mukam karooti vachalam
Pangum langhayate girim
Yat krupa tamaham vande
Paramanandam Madhavam”

Bhagavad Gita

“I pay obeisances to that supremely blissful Madhava (who has Lakshmi
as his consort), whose compassion makes a dumb person speak and makes a
lame person to climb the mountain”

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Chapter 1

INTRODUCTION

Among the adults and elderly, high-frequency sensorineural hearing loss is one of the most common configurations and types of hearing loss seen in the audiology clinic. Pittman and Stelmachowicz (2003) reported that the most prevalent audiometric configuration among adults with hearing loss is the sloping type which is around 50%. Usually, the client with this configuration of hearing loss presents with complaints of difficulty in understanding or recognizing conversational speech, particularly if the speaker is talking softly or in the presence of background noise. A hearing aid is the preferred form of ‘‘management’’ for a sensorineural hearing loss because this type of loss is not remediable with medication or surgery.

American Speech-Language- Hearing association (1998) asserts that amplification should provide audibility and comfort for soft and average input levels, and tolerance for high input levels. The primary goal of current hearing aid fitting strategies is to make the speech signal audible in those regions where the sensitivity is reduced, and in the case of high-frequency hearing loss this means providing high-frequency amplification.

During the selection of a hearing instrument, several relevant issues should be considered. First, the listeners are exposed to a wide range of input levels. Providing audibility of a wide range of input levels from a broad frequency spectrum is a goal of any hearing aid fitting. In typical communicative situations, the overall level of speech a listener is exposed to may vary over a 30 dB range (Pearsons, Bennet, & Fiddel, 1977) while the individual's acoustic elements within speech may vary as much as 40 dB (Levitt, 1982). Traditionally, the greater the hearing loss, the more is the gain needed at that frequency. For listeners with high-frequency sensorineural hearing loss, this goal can be challenging to meet with amplitude compression technology for several reasons. Firstly, this technology is limited in its ability to provide the appropriate amount of gain for high-frequency sounds that are soft. If suitable gain is achieved in the high-frequency region, acoustic feedback may result when the aid is worn by the listener. Thus, application of a feedback management strategy and/or gain reduction is a common solution. Additionally, the output bandwidth of conventional hearing aids is not broad enough to make high-frequency sounds consistently audible for listeners with hearing loss (Stelmachowicz, Pittman, Hoover, & Lewis; 2001). These factors limit the audibility of important high-frequency sounds, especially for individuals with a sloping and/or severe to profound hearing losses.

It is important to point out that providing audibility of high-frequency information to listeners with severe to profound hearing impairment remains a controversial topic (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998; Plyler & Fleck, 2006; Turner & Henry, 2002). Large variability in aided listening performance is thought to be due to both the level of high-frequency audibility the listener is receiving as well as the listener's ability to extract useful information from the audible signals.

There have been equivocal findings in the area of high frequency amplification for sloping hearing loss. Some studies suggest that listeners who are provided with audibility at frequencies where hearing levels are severe and/or sloping will not show speech recognition benefit (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998). This is thought to be due to a limited ability to use the amplified signal in that frequency region. On the other hand, other studies have reported that significant improvements in speech understanding, especially in noisy environments, occur when listeners with sloping sensorineural hearing loss are provided with high-frequency information (Plyler & Fleck, 2006; Turner & Henry, 2002). Further, listeners with suspected dead regions in the high-frequencies perform similar to normals on speech recognition tasks when broadband amplification is used in a quiet listening environment (Mackersie, Crocker, & Davis, 2004), while listeners without dead regions are better able to make use of high-frequency cues (Moore, 2004). Thus, the different outcomes may be due to factors such as the inner hair cell (IHC) loss which can be referred to as dead regions, congenital versus acquired hearing loss, and wide band versus frequency lowering technology. The results of these studies have important implications for clinical practice. If amplifying speech to audible levels in the high frequencies does not improve speech recognition, then attempts to provide gain may not be necessary or desirable in certain cases.

Various signal processing strategies have emerged to allow high-frequency information to be moved to a lower-frequency region so it can be more easily accessed by the listener. The first attempts were done well before non-linear and digital technology was applied to hearing aids. Methods such as slow-playback, time-compressed slow-playback, frequency modification with amplitude modulation, vocoding, zero-crossing rate division, frequency shifting, and frequency transposition were all major approaches (Braida, Durlach, Lippman, Hicks, Rabinowitz, & Reed,1978).

Frequency transposition and frequency compression technology are the two main types of frequency-lowering technology available even today. Frequency transposition shifts each frequency component in the sound by a constant factor. Frequency shifting is a technical term specifically relating to lower the signal by a fixed frequency value. A possible advantage of this form of transposition is that ratios among the frequency components of the signal are not changed by the processing. This may be beneficial for speech perception because frequency ratios convey important information. On the other hand, a possible disadvantage is that overall pitch of the speech signal is also lowered. Another problem with shifting is that it does not reduce the bandwidth. It only shifts the signal down. This creates very strong distortions when the shifting frequency is greater than the signal frequency.

Frequency compression is of two types, linear compression and non-linear frequency compression. The frequency compression technology compresses the output bandwidth of the signal by a specified ratio. Also frequency compression reduces both the frequency and the bandwidth by a preset compression ratio / factor (for instance, anywhere from 1.5 to 5.0 in steps of 0.25). Because the spectrum is “squeezed” with frequency compression, operating in real-time requires a complex algorithm that maintains the critical information. This action takes place extremely rapidly, in the order of two to four milliseconds. When the next sound comes along, usually a vowel in the normal syllabic sequence, the aid reverts to its normal amplification pattern. The voiced sounds are simply passed through and processed as determined during the initial programming. When the next voiceless sound is detected, the frequency compression circuit is again activated. For these users, both the hearing levels at specific frequencies and the slope of the audiogram across frequencies are taken into account. For calculation of the cut-off frequency, relatively high frequencies are selected, if the hearing impairment is mild or the audiogram is flat. Lower cut-off frequencies are selected for more severe levels of impairment or for audiograms with relatively steep slopes. The frequency compression ratio is then derived from the cut-off frequency. The compression ratio effectively determines the strength of the frequency compression processing above the cut-off frequency (Ross, 2000).

Some listeners have obtained speech perception benefits when listening to proportional frequency compression (Turner & Hurtig, 1999). This method of frequency compression preserved the ratios between the frequencies of the components of natural speech, as well as the temporal envelope of the unprocessed speech stimuli. Both frequency-compressed speech and the control condition of unprocessed speech were presented with high-pass amplification. An advantage of this method is that frequency ratios are preserved. In other words, the relationship between the frequencies of different formant peaks in speech remains constant. These ratios may be particularly important cues for the recognition of vowels in speech (Neary, 1989).

Simpson, Hersbach, and McDermott (2005) evaluated the performance of an experimental frequency compression hearing device using tests of speech understanding in experienced hearing aid users with moderate-to-severe sensorineural hearing loss and sloping audiograms. Of the 17 participants, eight showed a significant improvement in score, eight participants did not show any change in the score whereas, one participant showed a significant decrease in score.

A similar study was done by the same investigators Simpson, Hersbach, and McDermott (2006) who examined speech perception in seven individuals with steeply sloping hearing loss. No significant differences in group mean scores were found between the frequency-compression device and a conventional hearing instrument for understanding speech in quiet. Testing in noise showed improvements for the frequency-compression scheme for only one of the five participants tested. In fact, subjective comparisons between conventional hearing aids and the frequency compression scheme using the Abbreviated Profile of Hearing Aid Benefit-APHAB revealed that the majority of listeners preferred conventional amplification (Cox & Alexander, 1995). So the studies on frequency lowering technologies have led to equivocal results which indicate the need for more research in the field.

NEED FOR THE STUDY

1. The major benefits of a non-linear frequency compression is that a pre-selected range of high frequencies is compressed based on the listener’s hearing loss, no special frequency analysis of incoming signals is required and the frequency compressed output signals do not overlap with lower frequencies.
2. There is dearth of information regarding the benefits of the non-linear compression in hearing aids among individuals with hearing impairment.

AIMS OF THE STUDY

- To study the effect of non-linear frequency compression (NLFC) in hearing aids on the speech identification performance of individuals having sloping sensorineural hearing loss
    1. With cochlear dead region and
    2. Without cochlear dead region.
- To study the effect of non-linear frequency compression (NLFC) on the perceived quality of speech in individuals having sloping sensorineural hearing loss
    3. With cochlear dead region and
    4. Without cochlear dead region.

Chapter 2

REVIEW OF LITERATURE

Hearing occurs when a sound wave reaches the internal structures of the ear which converts the sound wave vibrations and transduction helps in the movement of air molecules into the electrical signals in the brain. This process is made possible by external structures which detect these movements and convert them into neural energy and by circuits within the nervous system which convert these signals into what we perceive as sound. The inner hair cells are the transducers of the cochlea, responsible for converting the vibration patterns on the basilar membrane into action potentials in the auditory nerve (Yates, 1995). Most hearing loss results from damage to the cochlea. Cochlear hearing loss may arise from many different causes (Moore, 2004; Schuknecht & Gacek, 1993), but is often associated with damage to hair cells in the cochlea (Borg, Canlon, & Engström,., 1995; Engström, Flock & Borg, 1983; Schuknecht & Gacek, 1993). The hair cells in the cochlea may break or become bent and nerve cells might degenerate. When the nerve cells or the hairs are damaged or missing, the electrical signals are not transmitted as efficiently and thus results in a sensory neural hearing loss.

The present study aimed at evaluating the efficacy of frequency compression on speech perception in individuals having sloping hearing loss. In this connection, the review of literature being collected is being given under the following headings.

2.1 Importance of high frequency information in speech understanding

2.2 Effect of cochlear hearing loss on speech perception

2.3 Support against high frequency amplification in sensorineural hearing loss

2.4 Support for high frequency amplification in sensorineural hearing loss
2.5 High frequency amplification in cochlear dead regions
2.6 Management for high frequency sensorineural hearing loss
2.7 Technologies to improve speech understanding in high frequency sensorineural hearing loss
    2.7.1 Frequency Transposition
    2.7.2 Frequency Compression: Linear and non-linear

2.1. Importance of High Frequency Information in Speech Understanding

Literature differs on the importance of frequencies above 2000 Hz for understanding speech. In studying noise induced hearing loss, research has shown that thresholds at 3000 Hz and above are not significantly related to the hearing and understanding of everyday speech (Glorig, Ward & Nixon, 1961; Quiggle, Glorig, Delk, & Summerfield, 1957). On the other hand, other researchers (Harris, Haines, & Myer, 1960; Kryter, Williams, & Green, 1962; Mullins & Bangs, 1957) have found that information in the frequencies above 2000 Hz to be significant for understanding speech in the presence of noise. Pascoe (1975) suggested that the critical range of frequencies which have a significant effect on word recognition, particularly in noise, are those between 2500 and 6300 Hz.

Sher and Owens (1974) reviewed the evidence that acoustic cues above 2 kHz are necessary for discriminating isolated words containing certain high frequency phonemes. It is also observed that cues above 2 kHz are necessary to extract meaning even from rather highly contextual sentences when the redundant nature of acoustic, grammatical, lexical, linguistic, and prosodic content of such sentences is reduced by distortion. It is also noted that greater the distortion the higher the frequencies required for maximum understanding.

2.2. Effect of Cochlear Hearing Loss on Speech Perception

Individuals with sensorineural hearing loss (SNHL), particularly the elderly, tend to have the greatest amount of hearing loss in the higher speech frequencies (above 2000 Hz), which generally corresponds to more extensive pathophysiological changes in the corresponding region of the inner ear (Liberman & Dodds, 1984; Willott, 1991).

The relative effects of cochlear damage on the perception of various speech features are well established. It has been shown that, in individuals with sensory neural hearing loss, suprasegmental features are perceived better than segmental features, vowels better than consonants, vowel height better than vowel position (front and back), word initial consonants better than word final consonants, and consonant voicing and continuance better than consonant place (Erber, 1972; Martony, Risberg, Spens, & Angelfors, 1972; Bilger & Wang, 1976; Hack & Erber, 1982).

Adult listeners with normal hearing seem to make more use of spectral cues for place of articulation information (Harris, 1958; Hedrick & Ohde, 1993; Heinz & Stevens, 1961; Hughes & Halle, 1956; Nittrouer, 1992; Nittrouer & Miller, l997; Nittrouer, 2002; Zeng & Turner, 1990) and temporal information for the voicing distinction (Raphael, 1972; Cole & Cooper, 1975; Soli, 1982). Listeners with hearing impairment may have difficulty integrating amplitude and spectral cues, and may generally place less weight on formant transitions than listeners with normal hearing (Hedrick, 1997; Hedrick & Younger, 2003; Zeng & Turner, 1990).

Speech recognition deficits resulting from high frequency hearing loss may not be limited to the loss of high frequency speech information. The evidence shows that damage to basal region of the cochlea may be accompanied by physiological and behavioral changes such as reduced contributions from the tails of high frequency auditory nerve fibers (Kiang & Moxon, 1974); reduced phase locking and synchronization to low frequencies (Jorris, Smith, & Yin, 1994); disproportionate loss of activity from low spontaneous rate afferent fibers (Schmiedt, Mills, & Boettcher, 1996) and efferent fibers (Liberman, Dodds & Pierce, 1990); reduced intensity discrimination (Florentine, 1983); and reduced temporal resolution, as measured by recovery from forward masking (Jesteadt, Bacon, & Lehman, 1982), modulation detection (Bacon & Viemeister, 1985), gap and decrement detection (Buus & Florentine, 1985; Moore, Peters, & Glasberg, 1993), and speech recognition in amplitude modulated maskers (Bacon, Opie, & Montoya, 1998; Eisenberg, Dirks, & Bell, 1995).

2.3. Support against High Frequency Amplification in Sensory Neural Hearing Loss

There are a number of studies that make different claims about the effect of high frequency amplification. Byrne (1986) reported that listeners with sloping high frequency hearing loss judged the amplification providing the most extended high frequency emphasis to be the poorest in intelligibility. Most of the hearing instruments used in the study failed to amplify beyond 3 kHz.

Hogan and Turner (1998) evaluated the effects of hearing loss configuration and severity as well as the frequency bandwidth that maximized speech recognition scores. Speech recognition was tested at various band pass settings for five listeners with normal hearing and nine individuals with varying degrees of high frequency hearing loss. The test stimuli were presented through a Sennheiser HD 25-SP earphone with a supra-aural cushion. Results for the listeners with normal hearing demonstrated an increase in speech recognition scores as audibility increased. Results for the listeners with mild high frequency loss were similar to the listeners with normal hearing, whereas, results for listeners with moderate high frequency loss were poorer than those obtained from either the listeners with normal hearing or listeners with mild hearing impairment.

Generally, the results indicated that benefits of amplification were diminished once the degree of loss exceeded 55 dB HL. Benefits of amplification were significantly more decreased when the degree of loss exceeded 55 dB HL and the hearing loss fell in regions beyond 4 kHz as compared to when the hearing loss fell in regions below 4 kHz.

Likewise, Turner, and Cummings (1999) evaluated the benefit of providing audible speech information to listeners with a high frequency hearing loss. Speech recognition was tested over a wide range of presentation levels for ten listeners with various degrees and configurations of sensorineural hearing loss. The test stimuli were presented through Sennheiser HD 25-SP headphones. They reported that for listeners with a sloping loss, amplifying frequencies beyond 3 kHz resulted in little to no improvement in speech recognition scores when hearing loss exceeded 55 dB HL. For flat configurations, however, amplifying frequencies beyond 3 kHz resulted in an increase in speech recognition when hearing loss exceeded 55 dB HL. These results suggest that benefit obtained from amplifying beyond 3 kHz depends on the configuration of loss. The implications of these results are that in most cases providing audible speech to lower frequency regions will be beneficial. For higher-frequency regions in hearing impaired listeners, amplification may not always be beneficial.

Sullivan, Allsman, Nielsen, and Mobley (1992) speculated the increase in speech recognition for listeners with flat configurations was contributed to greater gain in the high and mid-frequencies rather than simply amplification beyond 3 kHz. Without amplification, listeners with sloping losses were already receiving the maximum mid-frequency speech cues plus some high frequency speech cues. With amplification, listeners received only additional high frequency speech cues which resulted in little to no improvement in speech recognition scores. Without amplification, listeners with flat configurations received some mid frequency and high frequency speech cues. With amplification, listeners with flat configurations received additional mid frequency and high frequency speech cues which resulted in a significant improvement in speech recognition scores. Stated differently, with amplification, listeners with sloping losses were receiving high frequency speech cues, whereas, listeners with flat losses were receiving speech cues in the high frequencies as well as the low to mid frequencies. Therefore, Sullivan, Allsman, Nielsen, and Mobley (1992) concluded that studies suggesting speech recognition scores improved due to high frequency amplification are questionable.

In a follow- up study, Turner and Brus (2001) evaluated the effects of providing audible speech information to the low and mid-frequency regions for listeners with various degrees of sensorineural hearing loss ranging from mild to severe degree of hearing loss. Non-sense syllable recognition was tested on five listeners with normal hearing and 13 listeners with hearing impairment with a range of hearing loss in the low and mid-frequency regions. The test stimuli were presented through Sennheiser HD 25-SP circumaural headphones. They reported that for frequencies below 2800 Hz, amplification provided positive benefit for recognition scores regardless of degree of loss.

Amos and Humes (2007) conducted a study to find out the contribution of audible high-frequency information to speech understanding performance in listeners with varying degrees of high-frequency sensorineural hearing loss. 36 listeners with hearing impairment and 24 listeners with normal hearing were tested in quiet (+20 dB speech-to-noise ratio [SNR]) and noise (+5 dB SNR) and under three band-pass conditions (narrow = 200–1600 Hz; mid = 200–3200 Hz; broad = 200–6400 Hz) both without and with spectral shaping of the stimuli. Results for spectrally shaped speech showed that the group of listeners with hearing impairment showed no change in performance between the mid-band and broad-band conditions while the group of listeners with normal hearing demonstrated improved speech understanding attributable to the higher frequencies for the broad-band condition in both the unshaped and shaped conditions.

Taken together, results of these studies suggest that restoring audibility of high-frequency information to persons with severe high-frequency SNHL provides limited benefit to speech understanding. Based on these limited benefits, one recommendation may be to provide minimal or no amplification in some high-frequency regions when severe or greater hearing loss is present. In summary, research suggests that the benefit of providing high frequency amplification depends on degree of loss and type of configuration. Results indicate that benefit of amplification beyond 4 kHz diminishes once the hearing loss has exceeded 55 dB HL for listeners with a sloping configuration but not for listeners with flat configuration.

2.4. Support for High Frequency Amplification in Sensory Neural Hearing Loss

There are some studies that provide support for high frequency amplification. Sullivan, Allsman, Nielsen, and Mobley (1992) evaluated the effects of various cut-off frequencies on objective and subjective performance of listeners with steeply sloping, high frequency hearing loss. Non-sense syllable recognition and subjective ratings of speech intelligibility and speech quality were obtained from 17 males with bilateral symmetrical high frequency sensorineural hearing loss. The test stimuli were presented through a headphone transducer. Sullivan, Allsman, Nielsen, and Mobley (1992) found that syllable recognition increased when additional high frequency information beyond 2 kHz was available; however, the additional amplification was reported to be detrimental to sound quality. Stated differently, performance improved but at the expense of sound quality.

Vickers, Moore, and Baer (2001) evaluated the effect of high frequency amplification on speech perception for hearing impaired listeners with and without dead cochlear regions in the high frequencies. Speech performance was measured using non-sense syllables that were low-pass filtered at various cutoff frequencies for ten listeners.

The test stimuli were presented through HD580 earphones. Seven listeners had dead regions in the high frequencies and three listeners were without dead regions in the high frequencies. Results suggested that listeners without dead cochlear regions were able to make use of high frequency information towards speech intelligibility; however, continued increases in amplification resulted in decreased performance. Vickers, Moore, and Baer (2001) stated that determining where dead regions occur can be used as an alternative to articulation index calculations when determining amplification needs. It should be noted that the clients with dead regions had more high frequency hearing loss than those without dead regions. Therefore, the improved performance by clients without dead regions may have been attributed to the degree of hearing loss rather than the absence of cochlear dead regions (Rankovic, 2002).

Schwartz, Surr, Montgomer, Prosek, and Walden (1979) examined the effect of an experimental high-pass hearing instrument versus a conventional high frequency emphasis hearing instrument on word recognition and consonant discrimination in both quiet and noise conditions. Ten male listeners with bilaterally symmetrical high frequency sensorineural hearing loss past 1 kHz were tested in quiet and in noise under three conditions: unaided, conventional high frequency emphasis hearing instrument (own aid) and wearing the experimental high-pass instrument. Results suggested similar benefit for both hearing instruments in the quiet conditions. However, in the noise conditions, results indicated a greater increase in recognition scores with the experimental high pass instrument. The experimental high-pass instrument's frequency response amplified up to 5200 Hz, whereas, most of the conventional high emphasis hearing instruments amplified up to 3000-4000 Hz. The listeners reported that the high-pass hearing instrument was superior, quieter and improved clarity of speech. Results judging quality and superiority should be interpreted with caution mainly because testing was conducted under ideal laboratory conditions using the listener's old hearing instruments versus the new hearing instruments. Also, many dispensers are hesitant to rely on results obtained from speech scores in a simulated environment or ratings of sound quality unless listeners have a period of time to adjust to the new aided signals (Berger, 1992).

Hornsby and Ricketts (2003, 2004) compared the speech understanding of persons with flat hearing loss and sloping high frequency hearing loss with that of listeners with normal hearing to examine the contribution of speech information in various frequency regions. Speech understanding in noise was assessed using multiple low-pass and high-pass filter cut-offs frequencies for all groups of listeners. Results indicated that listeners with flat sensory neural hearing loss (SNHL) showed improvements comparable to those for listeners with normal hearing, as high frequency information was made available (Hornsby & Ricketts, 2003). Further, although listeners with sloping sensory neural hearing loss (SNHL) made less use of high-frequency information than with listeners with flat hearing loss, results suggested that high frequency speech information (>3 kHz) did improve speech understanding for listeners with sloping sensory neural hearing loss.

Similarly, Turner, and Henry (2002) reported that listeners with sloping SNHL were able to use amplified high-frequency speech information to improve speech understanding when listening in a background of noise regardless of the degree of hearing loss. Taken together, results of these studies suggest that restoring audibility of high-frequency information to persons with severe high-frequency SNHL may provide significant benefit to speech understanding.

Pyler and Fleck (2006) did a study to determine if amplifying beyond 2 kHz affected the objective and subjective performance of hearing instrument users with varying degrees of mild-to-severe high-frequency sensorineural hearing loss. Two trials were done in which the hearing aid is programmed to maximum high-frequency audibility during one trial period and minimum high-frequency audibility during the other trial period and objective evaluations were conducted in quiet using the Connected Speech Test (CST) and in noise using the CST and the Hearing in Noise Test. Subjective performance was evaluated by administering the Abbreviated Profile of Hearing Aid Benefit and a questionnaire. Results indicated that high-frequency amplification significantly improved objective performance in noise and subjective preference in quiet for listeners with varying degrees of mild-to-severe high frequency hearing loss. Results also suggested that high-frequency amplification may affect subjective preference in noise and overall for listeners with varying degrees of mild-to-severe high-frequency hearing loss when feedback is eliminated.

Horwitz, Ahlstrom, and Dubno (2008) designed a study to determine the extent to which high-frequency amplification helped or hindered speech recognition as a function of hearing loss, gain-frequency response, and background noise. The results showed that the mean speech recognition generally increased significantly with additional high-frequency speech bands. The one exception was that recognition of speech processed by the non-individualized response for the listeners with hearing impairment did not improve significantly with the addition of the highest frequency band. Significantly larger increases in scores with increasing bandwidth were observed for speech in noise than quiet.

Beamer, Grant, and Walden (2000) examined the effect of high-frequency amplification on subjective benefit in listeners with normal hearing through 2 kHz. The Profile of Hearing Aid Benefit (PHAB) was administered in the unaided and aided conditions on listeners using BTE or in-the-ear hearing instruments, with linear processing and peak clipping for output limiting (Cox & Gilmore, 1990; Cox & Rivera, 1992). Results indicated that listeners with normal hearing through 2 kHz reported significant subjective benefit for speech communication from high-frequency amplification.

In summary, research has demonstrated that providing an extended frequency response is beneficial to the listener, especially in noisy conditions, regardless of degree of loss or type of configuration. However, providing the extended frequency may be detrimental to sound quality. Furthermore, research suggests that listeners without dead cochlear regions are able to make use of high frequency information. It should be noted that the amount of benefit may be dependent on the degree of loss rather than the absence of cochlear dead regions.

Contradictory outcomes regarding the benefit of high frequency amplification may relate to

- The degree of high-frequency hearing loss
- Whether conclusions were drawn from individual or mean results

- Differences across studies in gain-frequency responses which varied from gain with no frequency shaping to ‘one size-fits-all’ approaches to individualized, but at times unrealistic, gain-frequency responses
- The extent to which increases in cut-off frequency or level led to increases in audible high-frequency speech, which was not clear in some studies; and
- Whether lower frequency speech cues were largely available (as when listening in quiet) or largely unavailable (as when listening in noise).

2.5. High Frequency Amplification in Cochlear Dead Regions

Investigators have reported that speech recognition remained constant or deteriorated as amplification was added in the higher frequencies (Amos & Humes, 2007; Baer, Moore, & Kluk, 2002; Ching, Dillon, & Byrne, 1998; Hogan & Turner, 1998; Turner & Cummings, 1999; Vickers, Moore, & Baer, 2001). These results led some to suggest that benefit of higher frequency speech audibility is related to the magnitude of high frequency hearing loss and /or the presence of cochlear “dead regions.”

A dead region is a complete loss of inner hair cell and/or neural function over the basal region of the cochlea. Dead region can be defined as a region in the cochlea where the IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected (when it is sufficiently intense) by off-place or off-frequency listening (Moore, 2004). The ability to make use of amplified speech information in various frequency regions may depend on the presence or absence of extensive inner hair cell damage known as cochlear dead regions (Baer, Moore, & Kluk, 2002; Moore, Huss, Vickers, Glasberg, & Alcantara, 2000; Vickers, Moore, & Baer, 2001).

Recent research suggests that high frequency amplification may be beneficial for persons with high frequency dead regions. Mackersie, Tracy, and Davis (2004) compared speech perception benefit in threshold matched ears with and without suspected cochlear dead regions.

Results suggested that when absolute thresholds were matched, listeners with and without suspected cochlear dead regions benefited equally from high-frequency amplification when listening in quiet or in low levels of noise. However, listeners with suspected cochlear dead regions benefited less from high-frequency amplification than listeners without suspected cochlear dead regions when listening in high levels of noise.

Vickers, Moore, and Baer (2001) evaluated the effects of high-frequency amplification on consonant recognition in listeners with and without high-frequency dead regions. Suspected dead regions were identified using psychophysical tuning curves as well as the threshold equalizing noise test (Moore, Huss, Vickers, Glasberg, & Alcantara; 2000). Speech stimuli spectrally shaped using the Cambridge fitting formula (Moore & Glasberg, 1998) were low-pass filtered at various cut-off frequencies to produce differing amounts of high-frequency amplification. Vickers, Moore, and Baer (2001) found that high frequency amplification produced limited speech understanding improvement in quiet for listeners with high-frequency dead regions; however, listeners without dead regions demonstrated consistent gains in speech understanding as high frequency amplification was increased.

Gordo and Iorio (2007) examined speech recognition in individuals with sensory neural hearing impairment with and without cochlear dead regions at high frequencies. Clients undertook word recognition score and speech reception threshold tests, with and without background noise. The speech tests were done with and without hearing aids in two situations: program 1 - broadband amplification (bandwidth 8000 Hz); and program 2 - amplification up to 2560 Hz, without high frequency gain. Results showed that performance improved for broad band amplification for subjects with no dead regions in the cochlea and performance improved when restricted band amplification for subjects with dead regions in the cochlea.

Furthermore, Baer, Moore, and Kluk (2002) observed similar results for persons with and without dead regions when listening to non-sense syllables in the presence of background noise. These results suggested that listeners with cochlear dead regions benefit less from high-frequency amplification than listeners without cochlear dead regions. Preminger, Carpenter, and Ziegler (2005) in their study concluded that listeners with dead regions perceived poorer subjective hearing aid performance in listening environments with reverberation or background noise as compared to those without dead regions.

For a dead region, it may be necessary for spectral information corresponding to that region (and temporal information normally carried by those fibers) to be encoded by nerve fibers that typically respond to other frequencies. Given that these fibers may already be responding to other speech information and may be best able to encode information only within a region near their characteristic frequencies, processing of speech information within a dead region may be of limited benefit (Baer, Moore, &

Kluk., 2002; Vickers, Moore & Baer., 2001). Such an explanation is consistent with reduced benefit of amplification over a frequency range where there is moderate-to-severe hearing loss, although differences in audibility between individuals with and without dead regions may also account for some differences in benefit of aided high frequency speech (Mackersie, Crocker, & Davis, 2004; Rankovic, 2002).

Most of the investigators (Vickers, Moore, & Baer, 2001; Baer, Moore, & Kluk, 2002; Gordo & Iorio, 2007) concluded that subjects with no dead regions in the cochlea benefited from high-frequency information while subjects with dead regions in the cochlea benefited from reduced gain at high frequencies.

2.6. Management for High Frequency Sensory Neural Hearing Loss

The management for individuals with sloping high frequency hearing loss is a challenging task. The conventional solution for individuals with a sloping audiometric pattern is a hearing aid with a frequency-gain response that improves audibility of high-frequency speech cues. However, even within a given frequency band, speech levels vary by at least 30 dB (Fletcher, 1953; Skinner, 1988). This range is considerably increased by the variety of sound levels in different listening situations. For listeners with sloping loss, this variation in speech levels, coupled with a reduced high-frequency dynamic range, may limit the ability to restore audibility without discomfort or distortion from higher level speech.

Multichannel compression amplification offers an attractive option for improving speech audibility in listeners with sloping loss. When speech varies over a range of input levels, the compression can improve recognition by placing greater amounts of the speech signal in the range between threshold and discomfort (Moore & Glasberg, 1986; Souza & Turner, 1998). Use of more than one compression channel allows the audiologist to maximize audibility by accommodating variations in threshold and dynamic range across frequency. However, maximizing audibility in the regions of greater loss can deteriorate the performance in individuals with a sloping hearing loss (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Hogan & Turner, 1998).

2.7. Technologies to improve speech understanding in High Frequency sensory neural hearing loss

The fact that most of the individuals with hearing loss have poorer thresholds at the high frequencies when compared to low frequencies had led the researchers to develop processing schemes for hearing aids that attempt to present information extracted from the high frequencies of speech signals at low frequencies. The main objective is to make use of the better thresholds at lower frequencies to improve the audibility of high frequency information-bearing components of speech. 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 (Kuk, Keenan, Peeters, Korhonen, Hau, & Andersen, 2007). It is also possible that frequency lowering can improve the ability of some listeners to perceive details of spectral shape, perhaps resulting in better speech intelligibility. This benefit may be obtained if the broadening of auditory filters, which usually accompanies sensory neural hearing loss, is not as extensive at low frequencies as at high frequencies.

The two main types of frequency-lowering technology available commercially are

- 2.7.1. Frequency transposition
- 2.7.2. Frequency compression technology

2.7.1. Frequency Transposition

Frequency Transposition in hearing aids shift the incoming high frequency sounds into the low frequency residual hearing range by a fixed amount, as shown in Figure 2.1. By providing a representation of the high frequency sounds which would otherwise be inaudible, it is anticipated that improvements may occur in speech perception and intelligibility in individuals with high frequency sensory neural hearing loss as it provided additional cues for the discrimination of speech. When the right candidates are chosen and when specific guidelines are followed, frequency transposition provides a viable solution for adults and children with an unaidable hearing loss in the high frequencies (Kuk, Keenan, Peeters, Korhonen, & Auriemmo, 2008).

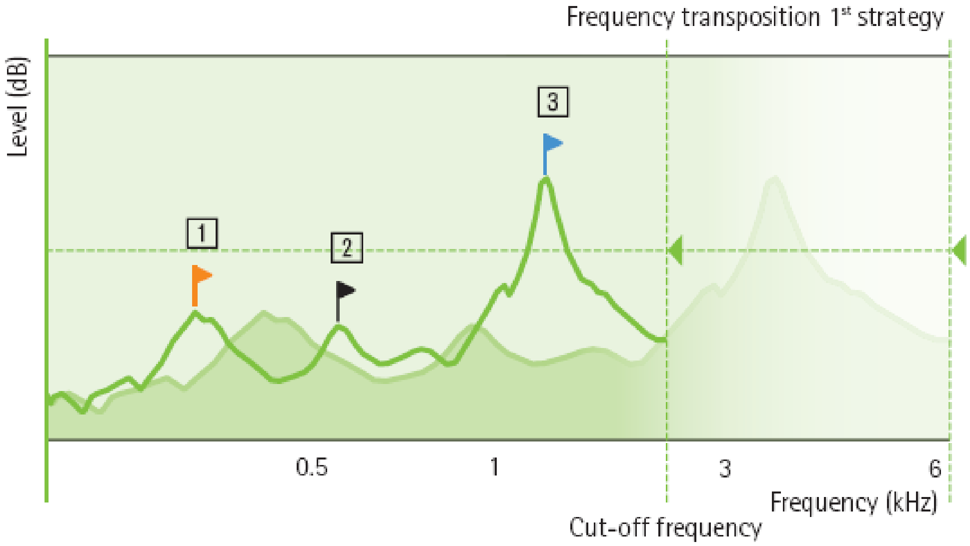


Fig. 2.1: Frequency transposition scheme where all frequencies are shifted down. 1, 2 and 3 represent the formant frequencies of speech (McDermott & Glista, 2008).

The first strategy for frequency shifting is a technical term specifically relating to lower the signal by a fixed frequency value. The problem with shifting is that is does not reduce the bandwidth. It only shifts the signal down. The advantage of this approach is that it preserves the temporal structure of the original signals, although it could result in masking the original sounds and cause initial confusion (Kuk, Keenan, Auriemmo, & Korhonen, 2009). For example, if the unaidable region is above 4000 Hz and the transposition targeted is one octave, 4000 Hz will be moved to 2000 Hz and 8000 Hz will be moved to 4000 Hz. However, the original 4000 Hz will remain at 4000 Hz, and 2000 Hz and 1000 Hz (and so forth) will remain at their original frequencies where they will be mixed with the transposed sounds above 4000 Hz. This is the second strategy for frequency transposition.

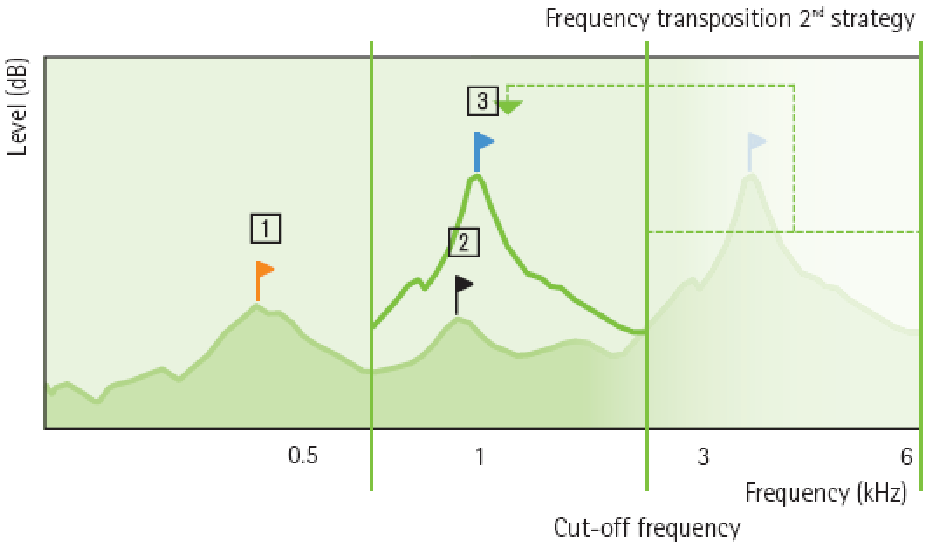


Fig. 2.2: Formant transposition scheme where shifting results in overlapping of the 3rd formant over an area of audible hearing, producing artifacts. 1, 2 and 3 represent the formant frequencies of speech (McDermott & Glista, 2008).

Parent, Chmiel, and Jerger (1997) evaluated four experienced hearing aid users using a frequency transposition hearing system. Following a trial period, the Abbreviated Profile of Hearing Aid Performance (APHAB) and a variety of speech audiometric measures were used to compare the frequency transposition fitting with each subject's conventional hearing aids. Two of the four subjects demonstrated statistically significant benefit with the frequency transposition device indicating the efficacy of frequency transposition in improving speech understanding and quality of life in some individuals with severe-to-profound hearing loss.

Raj (2007) investigated the efficacy of frequency transposition in individuals with cochlear dead regions. 10 individuals (15 ears) with moderate to severe high frequency sloping hearing loss with dead regions were tested. The speech identification scores were measured using high frequency word and sentence lists for three different conditions - unaided, aided without transposition and aided with transposition. The results showed that the performance with FT was better and this difference was significant.

Ribeiro and Migueis (2008) evaluated the frequency transposition scheme on eight clients presenting a significant high frequency hearing loss. Results showed evident improvement on the level of perception of sounds of the environment and consonant recognition. The improvement was significant as well on the tonal sensitivity as on the threshold of vocal intelligibility with a conservation of the percentage of speech discrimination for monosyllabic words.

Mc Dermott, Dorkos, Dean, and Ching (1999) compared the performance of five adults with sensorineural hearing impairment using frequency-transposing hearing aid and their own conventional aids. Four participants obtained significantly higher scores with the frequency transposition hearing aid than with their own aids on at least one of the tests. There was only limited evidence for two of the participants that the frequency-lowering function was effective at improving speech perception.

Mc Dermott and Knight (2001) compared the performance of three listeners with hearing impairment using a BTE transposition hearing aid and their conventional hearing aid. Recognition of monosyllabic words and medial consonants did not differ significantly between the two types of aids. This suggests that the transposition hearing aid was not effective at providing these subjects with increased high-frequency speech information.

Mc Dermott and Dean (2000) researched the effect of frequency transposition on the speech perception in individuals with steeply sloping hearing loss. Six adults with a very steeply sloping high-frequency hearing loss listened to monosyllabic words in several conditions. In the first condition, results were similar to those of listeners with normal hearing listening to the same material through low-pass filters having comparable cut-off frequencies at a signal-to-noise ratio of 6 dB. In the remaining two conditions, both listened to speech in quiet with and without frequency transposition, no significant differences were found between the two conditions in these subjects' recognition of words. The participants of their study reported poorer speech quality with the transposed speech which the authors attributed to the extensive transposition which was applied. The authors also pointed out to the importance of training which can improve the subjective benefit from the transposition hearing aids.

2.7.2. Non-Linear Frequency Compression

The non-linear frequency compression technology compresses the output bandwidth of the signal by a specified ratio. Also the non-linear frequency Compression reduces both the frequency and the bandwidth by a preset ratio / factor (anywhere from 1.5 to 5.0 in steps of 0.25).

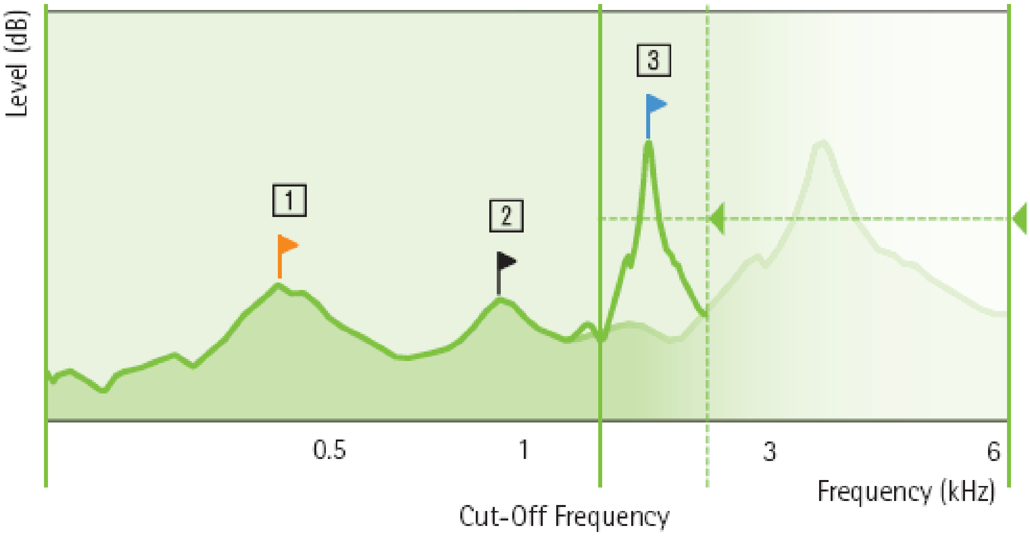


Fig. 2.3: Non-Linear Frequency Compression scheme in which the compression of the 3rd formant into an adjacent area that has lesser cochlear damage without interfering with the audibility of lower frequency sounds. 1, 2 and 3 represent the formant frequencies of speech (McDermott & Glista, 2008).

Because the spectrum is "squeezed" with Frequency Compression, operating in real-time requires a complex algorithm that maintains the critical information. This action takes place extremely rapidly, in the order of two to four milliseconds. When the next sound comes along, usually a vowel in the normal syllabic sequence, the aid reverts to its normal amplification pattern. The voiced sounds are simply passed through and processed as determined during the initial programming. When the next voiceless sound is detected, the frequency compression circuit is again activated (Ross, 2000). For these users, both the hearing levels at specific frequencies and the slope of the audiogram across frequencies are taken into account.

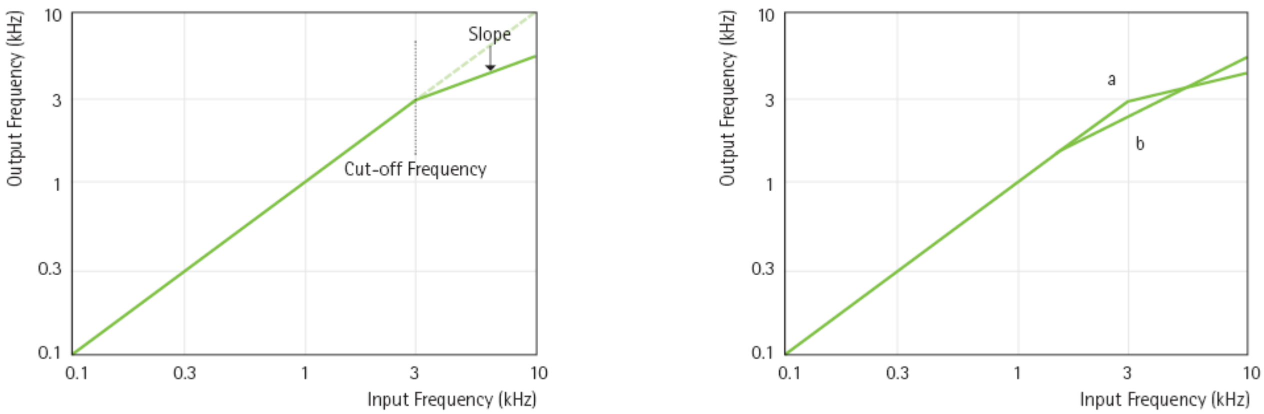


Fig. 2.4: The graphical representation of the cut-off frequency selected according to the hearing loss and the effect of different cut-off frequencies (McDermott & Glista, 2008).

For calculation of the cut-off frequency, relatively high frequencies are selected, if the hearing impairment is mild or the audiogram is flat. Lower cut-off frequencies are selected for more severe levels of impairment or for audiograms with relatively steep slopes. That is higher the degree and steepness of the hearing loss, lesser the cut-off frequency and more is the degree of frequency compression that is applied.

The initial frequency compression cut-off frequency and compression ratio values are found out by selecting the better ear thresholds per audiometric frequency and calculating the high frequency pure-tone average (HF-PTA) using 2 to 4 kHz. The final HF-PTA value is then used to predict initial cut-off frequency and compression ratio values. The frequency compression ratio is then derived from the cut-off frequency. However, the information regarding the calculation of cut-off frequency was not available in literature. Figure 2.5 depicts the criteria chosen to select the cut-off frequency for different degrees of hearing loss based on the HF-PTA.

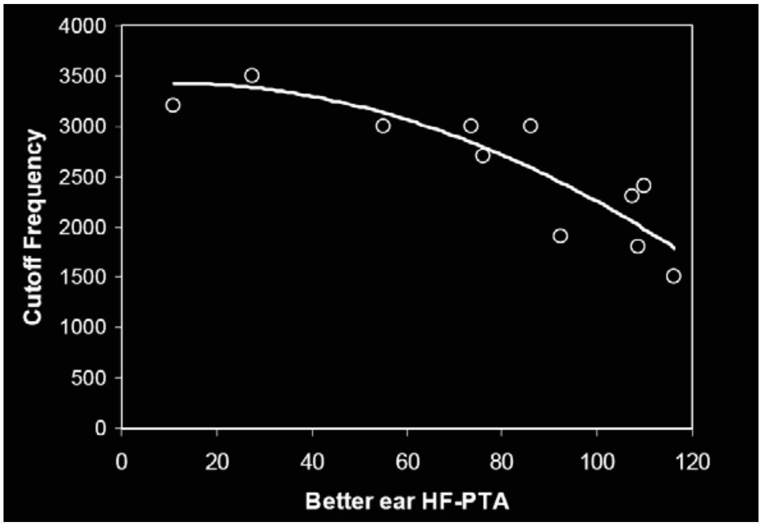
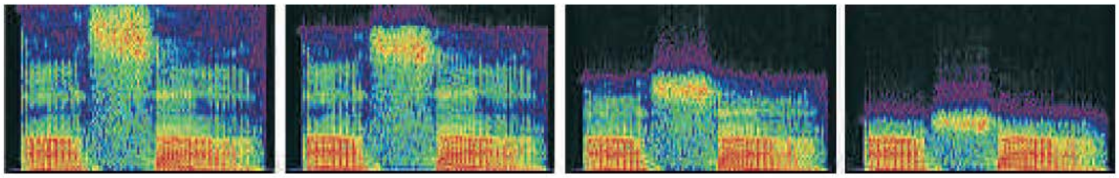


Fig. 2.5: The criteria chosen for the selection of the cut-off frequency (Bagatto, 2008).

The compression ratio effectively determines the strength of the frequency compression processing above the cut-off frequency. The Figure 2.6 depicts how the frequency compression is active at different compression ratios. It is shown that at all the compression ratios there is no overlapping of the compressed and the non-compressed speech signal at all compression ratios.


Original

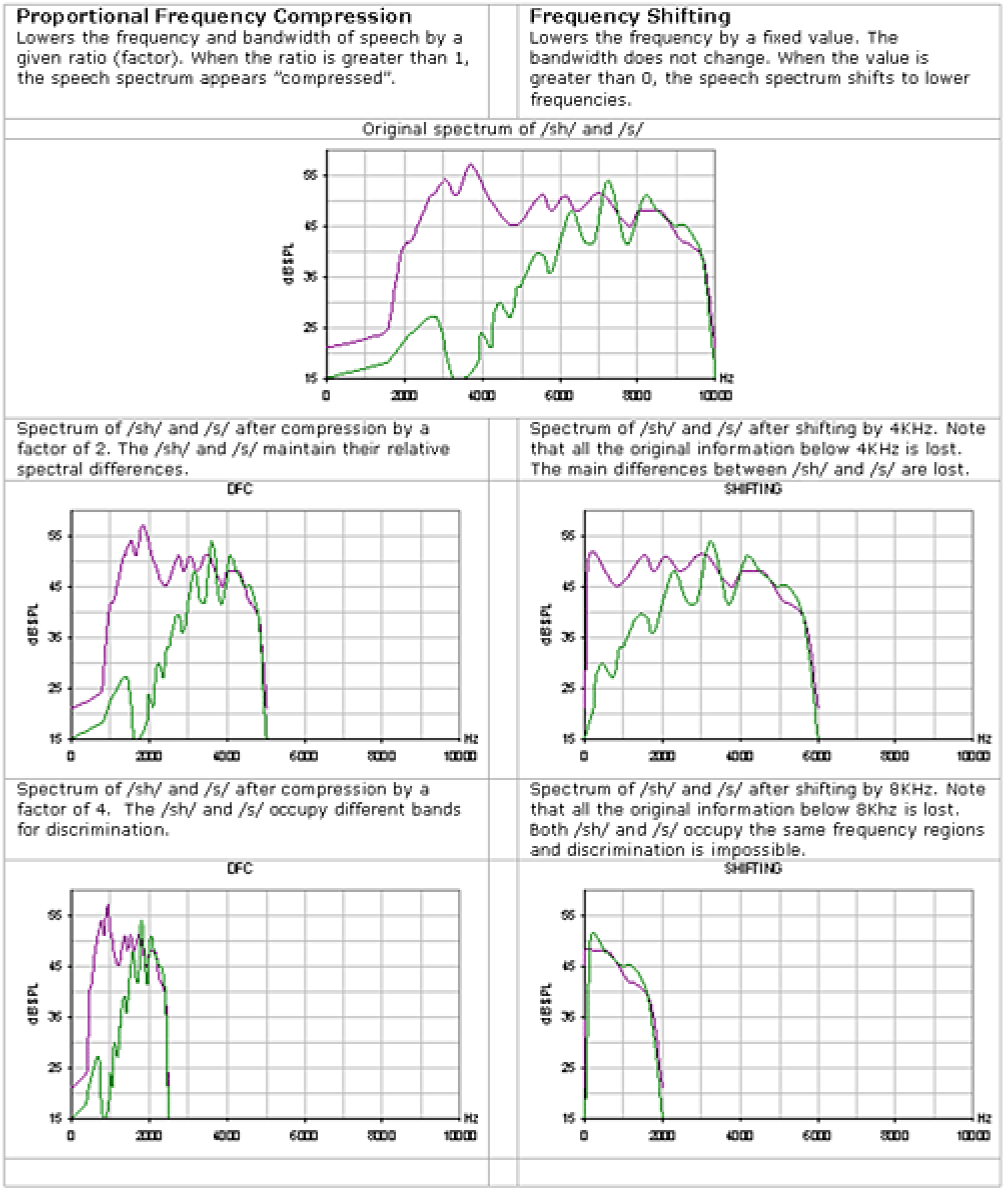
Cut-off frequency 4000 Hz
Compression ratio 1.5:1

Cut-off frequency 2000 Hz
Compression ratio 2:1

Cut-off frequency 1500 Hz
Compression ratio 4:1

Fig. 2.6: The spectral representation of the effect of different compression ratios of 1.5: 1, 2:1 and 4:1 on the speech signal (McDermott & Glista, 2008).

Figure 2.7 shows the difference in the two strategies of frequency compression and frequency lowering with respect to the spectrum of / s / and / ʃ /. It shows that even with the compression factors of 2 and 4 the spectral differences of / s / and / ʃ / are maintained while the main difference between / s / and / ʃ / are lost when shifted by 4 kHz and 8 kHz and hence making the identification of / s / and / ʃ / difficult.



Proportional Frequency Compression Lowers the frequency and bandwidth of speech by a given ratio (factor). When the ratio is greater than 1, the speech spectrum appears "compressed".	**Frequency Shifting** Lowers the frequency by a fixed value. The bandwidth does not change. When the value is greater than 0, the speech spectrum shifts to lower frequencies.

Original spectrum of /sh/ and /s/

Spectrum of /sh/ and /s/ after compression by a factor of 2. The /sh/ and /s/ maintain their relative spectral differences.	Spectrum of /sh/ and /s/ after shifting by 4KHz. Note that all the original information below 4KHz is lost. The main differences between /sh/ and /s/ are lost.
Spectrum of /sh/ and /s/ after compression by a factor of 4. The /sh/ and /s/ occupy different bands for discrimination.	Spectrum of /sh/ and /s/ after shifting by 8KHz. Note that all the original information below 8Khz is lost. Both /sh/ and /s/ occupy the same frequency regions and discrimination is impossible.

Fig. 2.7: The pictorial representation of the difference between the strategies for frequency lowering (Davis, 2005).

The Figure 2.8 depicts the original signal, effect of a high frequency hearing loss, and the differences between frequency transposition and frequency compression.

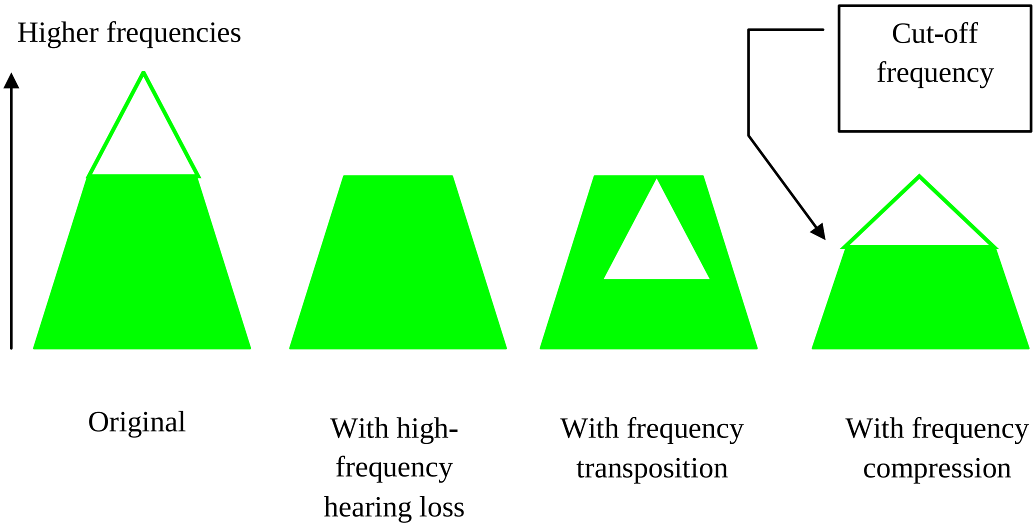


Fig. 2.8: A schematic representation of two types of frequency lowering technology; high frequency information is represented by the open triangle (Simpson, Hersbach & McDermott 2005).

- Original - The white triangle at the top represents the highest frequencies in a normal hearing person.
- With high frequency hearing loss- the high frequencies in the top open triangle and can no longer be heard.
- With frequency transposition -The high frequencies are shifted down, retaining the same shape. They are either mixed with or replace the lower frequencies in the lower part of the mountain.

- With frequency compression - A frequency that is slightly lower in frequency than the top of the second picture is chosen as the cut-off frequency. The frequencies above this cut-off frequency are compressed so the triangle fits on top of the cut-off frequency and now the top of the triangle representing high frequencies is within the range of audible frequencies (second picture). The shape is squashed a bit, but only near the top (higher frequency area). There is no overlapping or mixing.

Hurtig (1991) found excellent recognition of vowels by listeners with normal hearing after only 15 minutes of practice when proportional frequency shifting was used to lower the frequency of the speech tokens. For this reason, proportional frequency lowering, or frequency-compression schemes, might offer some promise as a method for remediation of speech perception difficulties of listeners with high-frequency sensorineural hearing loss. Many listeners with sensorineural hearing loss report that they have more difficulty understanding speech produced by female talkers than speech from males, further suggesting that proportionally frequency-lowered speech may have some utility in improving their speech recognition.

Turner and Hurtig (1999) examined proportional frequency compression as a strategy for improving speech recognition in listeners with high-frequency sensorineural hearing loss. Non-sense syllables spoken by a female and a male talker were used as the speech material. Both frequency compressed speech and the control condition of unprocessed speech were presented with high-pass amplification. For the material spoken by the female talker, significant increases in speech recognition were observed in slightly less than one-half of the listeners with hearing impairment. For the male-talker material, one-fifth of the listeners with hearing impairment showed significant recognition improvements. The results indicate that while high-pass amplification is still the most effective approach for improving speech recognition of listeners with high-frequency hearing loss, proportional frequency compression can offer significant improvements in addition to those provided by amplification for some clients.

An advantage of this method is that frequency ratios are preserved. In other words, the relationship between the frequencies of different formant peaks in speech remains constant. These ratios may be particularly important cues for the recognition of vowels in speech (Neary, 1989).

Simpson, Hersbach, and McDermott (2005) evaluated the performance of an experimental frequency compression hearing device using tests of speech understanding in quiet in individuals with moderate-to-severe sensorineural hearing loss and sloping audiograms. Their recognition of monosyllabic words was tested using the experimental device in comparison with conventional hearing aids. Of the 17 subjects, eight showed a significant score improvement, whereas, one subject showed a significant score decrease. Some of the improvements may have resulted from the better audibility provided in the high frequencies by the experimental device in comparison with the conventional aids. However, a subsequent study found that increasing the high-frequency gain in the conventional aids did not produce equivalent perceptual benefits.

Simpson, Hersbach, and McDermott (2006) studied the efficacy of an identical frequency-compression scheme in a group of seven subjects, all of whom had steeply sloping hearing losses. No significant differences in group mean scores were found between the frequency-compression device and a conventional hearing instrument for understanding speech in quiet. The authors attributed to the poor performance with the non-linear frequency compression to the presence of suspected cochlear dead regions. Testing in noise showed improvements for the frequency-compression scheme for only one of the five subjects tested. Subjectively, all but one of the subjects preferred the sound quality of the conventional hearing instruments. The authors concluded that frequency compression provided limited benefit to individuals with steeply sloping sensory neural hearing loss with suspected dead regions.

Fabry, Launer, and Derleth (2007) opined that frequency compression has proven to be effective in only half of the patients with steeply sloping hearing loss due to their inability to "re-map" the way high-frequency sound is perceived when it shifts to another frequency region. This may be due, in part, to frequency compression thresholds and ratios being set too low and too high, respectively, and warrants further investigation. Regardless, frequency compression, in combination with open fittings and directional microphones, may serve as an appropriate non-invasive amplification benchmark prior to implantation.

As there are equivocal evidences regarding the usefulness of high frequency amplification in individuals with high frequency sensorineural hearing loss, there is a need to validate the efficacy of providing frequency compression in individuals with high frequency sensorineural hearing loss.

Chapter 3

METHOD

The present study investigated the speech perception abilities of individuals having high frequency sensory neural hearing loss with, and without cochlear dead regions, using Non-Linear Frequency Compression (NLFC).

Participants

Twenty four individuals with bilateral sensorineural hearing loss were selected for the study. The data were collected from twenty nine ears of these participants. The participants were divided into two groups.

- Group I, which included 13 participants (N=15 ears) having sloping sensorineural hearing loss without any cochlear dead region. The slope of the hearing loss in the test ear was 10-15 dB threshold increase per octave. The participants were in the age range from 32 to 72 years (mean: 57.61 years; SD : +/-8.78 years)
- Group II which consisted of 11 participants (N=14 ears) having sloping sensorineural hearing loss with the presence of cochlear dead region. The slope of the hearing loss in the test ear was 15-30 dB/octave. The participants were in the age range of 35 years to 76 years (mean: 49.81 years; SD: +/-13.98 years). Cochlear dead region can be defined as a region in the cochlea where the IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected (when it is sufficiently intense) by off-place or off-frequency listening (Moore, 2004).

- The participants did not complain of middle ear problems or neurological disorders.
- Native speakers of Kannada language.
- Naïve hearing aid users.

Material

Speech identification test consisting of words with high frequency speech sounds in Kannada developed by Mascarenhas (2001) was used. The words in the list consisted of speech sounds predominantly above 2 k Hz. The test consisted of three word lists (each with twenty five words) and three sentence lists (each with nine sentences).

Recording of Stimulus

The word lists and sentence lists were recorded using the software Adobe Audition software (Version 1.0) in the computer. The material was recorded by a native female speaker of Kannada with normal vocal effort. The unidirectional microphone was kept at a distance of 5-6 inches from the mouth of the speaker. The sampling rate was 16,000 Hz and the sampling frequency was 41,000 Hz. After recording, all the words and sentences were normalized. A calibration tone of 1000 Hz was included before each list.

Instrumentation

- A calibrated diagnostic dual channel audiometer Madsen OB-922 (Version 2) to administer pure tone, speech audiometry and aided performance.

- A calibrated GSI-Tymp Star Middle Ear Analyzer (Version 2) to rule out middle ear problems.
- Threshold Equalizing Noise (Hearing Level) test or TEN(HL) CD, developed by Moore, Glasberg, and Stone (2004) to confirm the presence or absence of a cochlear dead region.
- A personal computer for running the TEN(HL) test CD through the auxillary input of the audiometer.
- A digital BTE hearing aid which had the following features was used along with a stock ear mold :
    1. Sound Recover – A feature to restore audibility of high frequency sounds. It has the facility of frequency compression with adjustable cut-off frequency (1.5 kHz to 6 kHz) and compression ratio (1.5:1 to 4:1). Sound Recover takes all frequencies above a given cut-off frequency and compresses them to into the adjacent frequency range with more audible hearing thus making the inaudible high frequency sounds more audible.
    2. Bass Boost: Users with significant hearing loss are dependent on low frequency audibility. The Bass Boost feature (from 0 to + 6 dB) provides extra low frequency gain and output.
    3. Sound Flow Standard: In real-time, it continuously and instantly optimizes hearing instrument settings to the changing environment such as calm situations, speech in noise, etc. automatically.
    4. 2+2 dedicated program accessible through a programming switch.

5. Whistle Block Technology: Precise, aggressive phase cancellation that blocks feedback without distortion. Additional function allows accurate distinction between true feedback from naturally occurring highly correlated signals (music, etc.)
6. Noise Block Processing
7. Omni Directional Microphone
8. Audiogram Direct: Audiogram Direct enables the fitter to measure the client's hearing directly through the hearing aid, taking into account the properties of the individual ears and the chosen model. It then provides a fast and accurate starting point for the fitting. Audiogram Direct is also ideal for use with off-site visits.
9. Volume Control and Tac tronic Switch.

The features of the hearing aid used in the present study were-

1. Sound Recover
2. Bass Boost
3. 2+2 Dedicated program
4. Volume Control, Tac tronic Switch

- A personal computer along with iPFG (version 2.1 a) software was used to program the hearing aid. Appropriate cable was used to connect the hearing aid to the programming interface to the HIPRO Box. The HIPRO was in turn connected to the PC having the iPFG software.

Test environment

The testing was done in an air conditioned sound treated single/double room.

Procedure

The testing was done in three phases

Phase I: Categorization of participants into those having cochlear dead region and without cochlear dead region

Phase II: Hearing Aid Fitting without and with non-linear frequency compression (NLFC)

Phase III: Evaluating the efficacy of frequency compression through

3.1 Speech Identification Score

3.2 Ling six sound identification

3.3 Quality Judgment

Phase I

Step 1: Routine audiological testing including pure tone audiometry, speech audiometry, and immitance evaluation were carried out for each participant. Later the TEN (HL) test was administered to categorize participants with and without cochlear dead regions.

The steps followed to select high frequency sloping sensory neural hearing loss were:

- Pure tone audiometry was done for all the participants. Air conduction thresholds were estimated between 250 Hz to 8000 Hz at audiometric frequencies under TDH-39 headphones encased in MX-41 AR ear cushion. The bone conduction thresholds were estimated between 250 Hz to 4000 Hz using B-71 bone vibrator.

Modified Hughson Westlake method (Carhart & Jerger, 1959) was used to estimate the threshold.

- Speech audiometry was administered for all the participants in which Speech Recognition Threshold (SRT), Speech Identification Scores (SIS) and Uncomfortable Loudness Level (UCL) for speech were measured.
- Tympanometry with a 226 Hz probe tone was carried out for all the participants. Reflexometry was carried out in which the ipsilateral and contralateral thresholds were estimated for all the participants at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

After the initial diagnosis of sloping sensory neural hearing loss, the participants were administered the TEN(HL) test (Moore, Glasberg, & Stone; 2004) for the identification of dead region in the cochlea.

The Threshold Equalizing Noise (Hearing Level) or TEN(HL) CD was played using a laptop computer and the stimuli were presented via the Madsen OB-922 (Version 2.0) through TDH-39 ear phones. Test frequencies were 0.5, 0.75, 1, 1.5, 2, 3, and 4 kHz. The TEN (HL) level is specified as the level of a one-ERB_N wide centered at 1 kHz. ERB_N stands for Equivalent Rectangular Bandwidth Noise of the auditory filter determined by using young individuals with normal hearing at moderate sound levels (Glasberg & Moore, 1990; Moore, 2003). Levels of the TEN noise were 50 and 70 dB/ERB_N (50, 70 dB SPL) for all participants. A TEN level of 70 dB HL / ERB_N was used for most of the frequencies and a lower level of 50 dB HL/ ERB_N was used for frequencies with lesser degree of (< 50 dB HL) hearing loss.

The level of the signal and the TEN was controlled using the attenuators in the audiometer. The TEN(HL) test was carried out as described by Moore, Glasberg, and Stone (2004), using a procedure similar to manual audiometry, that is modified Hughson-Westlake procedure (Carhart & Jerger, 1959), except that masked thresholds were measured using a 2-dB final step-size as recommended by Moore, Glasberg, and Stone (2004).

The TEN noise and pure tones were played in same channels of the audiometer. Prior to testing, calibration was done in which the normal hearing individual was supposed to detect the tone in noise presented at 50 dB HL. The noise level was kept constant at 50 dB HL. The level of tone was adjusted using the level adjustment knob of the audiometer. The normal hearing individual was asked to indicate whether he / she heard the tone in the presence of TEN which was presented continuously at a fixed level of 50 dB HL and the intensity of the tone was varied, for equal loudness. The level adjustment knob for the tone was decreased if the participant was able to hear the tone and the level adjustment knob was increased if the participant was not able to hear the tone. An up and down procedure for changing the level adjustment knob of the audiometer was done until the participant was able to detect the tone in the presence of TEN when both the tone and TEN were presented at 50 dB HL. TEN noise was presented ipsilaterally, and masked thresholds were obtained for each test frequency.

Once the calibration was performed, the masked thresholds were compared to ascertain the presence of cochlear dead regions. The presence or absence of a cochlear dead region was based on the criteria suggested by Moore, Glasberg, and Stone (2004). The criteria to signify a dead cochlear region were:

1. If the masked threshold in the TEN was 10 dB or more than the TEN level/ ERB_N and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was assumed to be present at that frequency.
2. If the masked threshold in the TEN was less than 10 dB above the TEN level/ ERB_N , and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was assumed to be absent.
3. In case the TEN(HL) level could not be made high enough to elevate the absolute threshold by 10 dB or more, then the results were considered inconclusive. This would happen because the noise that would have been required was judged as too loud or because the maximum output of the audiometer was reached. A "no response (NR)" was recorded when the participant did not indicate hearing at the maximum output level of the audiometer. Participants with inconclusive results were discarded from the study.

The edge frequency, that is, the frequency from which a cochlear dead region starts, was noted down for all the participants. This test was administered for all participants and they were assigned to either the group without cochlear dead region (Group I) or with cochlear dead region (Group II) depending on the presence or absence of a cochlear dead region.

Phase II

A. Hearing Aid Fitting

The hearing aid was connected to the HIPRO using appropriate programming cables. The HIPRO was connected to the personal computer in which the programming software iPFG 2.1a was installed. The following steps were followed for the fitting of hearing aid for each participant:

1. From the ‘Client Menu’ of the iPFG 2.1a software, the ‘Personal Data’ was selected to enter the details of the participant.
2. Later the ‘audiogram data’ was selected in which the pure tone thresholds of each participant from 250 Hz to 8000 Hz for air conduction and from 250 Hz to 4000 Hz for bone conduction of the test ear were entered.
3. From the ‘Instructions’ menu, hearing aid detection was accessed. The specific test hearing aid with frequency compression feature was selected from the ‘hearing instrument selection’ menu.
4. From the ‘Pre-Fitting’ menu, NAL-NL1 fitting formula was selected.
5. From the ‘Fitting’ menu, the hearing instrument response was re-calculated for each participant using NAL-NL1 and extended bass boost range was enabled by +3 dB for optimizing the performance as it gives extra low frequency gain and output amplification.
6. As there were two test hearing aid models, one was programmed with default ‘initial fit’ settings of non-linear frequency compression (NLFC-IF), as suggested by the software. The other hearing aid was programmed for the ‘fine tuned’ settings of non linear frequency compression (NLFC-FT).

   To enable the ‘initial fitting’,

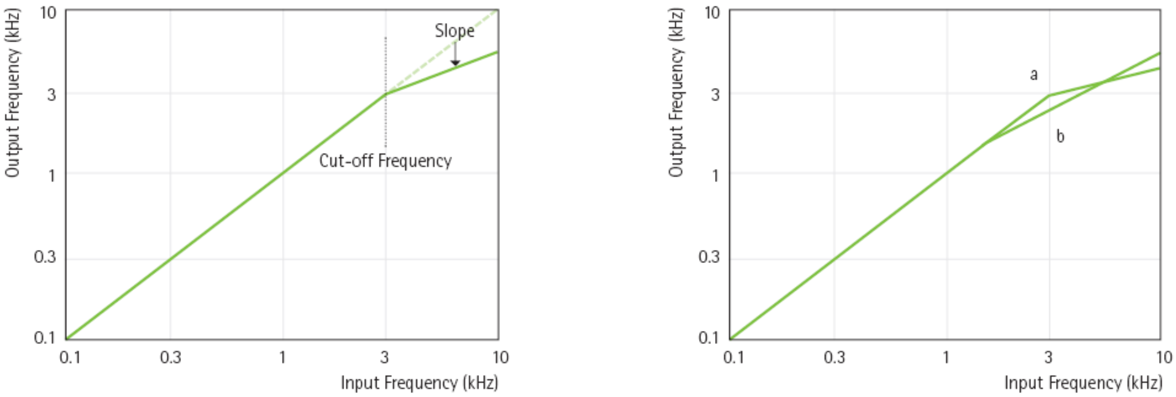
   a. The ‘Level 1’ of the experience / loudness item was selected as the participants were naïve hearing aid users.

b. The occlusion control was set to ‘off’ position, as the participants did not complain of any occlusion of own voice.
c. One hearing aid was programmed with Program 1 without frequency compression (WNLFC) and Program 2 for calm situations with frequency compression with initial fit. These settings were as prescribed by the programming software which was the ‘Initial Fit’ Settings (NLFC-IF). The optimal settings of the frequency compression are determined automatically by iPFG 2.1a software based on the audiometric configuration, thus making the inaudible high frequency sounds audible to the listener. Another hearing aid was programmed with Program 1 for calm situations with fine tuning of the Frequency Compression by choosing the ‘Manual Fine Tuning’ of the Fitting main menu. The fine tuning was done by selecting ‘Sound Recover’ parameter and adjusting the frequency compression parameter. The sound recover is the frequency compression algorithm wherein the high frequencies are compressed into an adjacent frequency range.

To ‘fine tune’ or optimize the frequency compression parameter, the cut-off frequency (range being 1.5 kHz to 6 kHz), and the ratio of frequency compression (range being 1.5:1 to 4:1) were manipulated in such a way that the participant was able to discriminate between /s/ and /ʃ/ appropriately. The frequency at which the participant identified the two phonemes correctly at least 50% of the time being presented was considered as the cut-off frequency of the high frequency response of the hearing aid. If the client was not able to identify the phonemes through auditory mode alone, then training was given for a brief period of about ten minutes along with the visual modality. Later, the fine tuning was continued with the auditory modality alone.

The testing with the NLFC activated was done in two conditions

1. The default settings of non-linear frequency compression as determined by the software. The gain, cut-off frequency and compression knee-point determined by the software was saved as the settings of program 2 in the first hearing aid.
2. The fine tuning of NLFC in the hearing aid was done by manipulating two adjustable parameters of frequency compression from the 'sound recover' feature in the software. In this feature, the Cut-off Frequency and the Compression Ratio of the NLFC were adjustable. This manipulation of frequency compression is illustrated in Figure 3.1.



A B

Fig. 3.1: Cut-off frequency of NLFC. A. The compression being applied after the cut off frequency; B. The difference in compression being applied as a consequence of different cut- off frequencies, the cut off frequencies being a and b.

The fine tuning of the ratio of frequency compression parameter was done by the following steps:

1. If the participant was able to identify both the phonemes /s/ and /ʃ/ with the initial fit setting of the frequency compression, the parameter was adjusted to weaker settings step-by-step. In other words, the cut-off frequency was increased, i.e., the strength of frequency compression was decreased when the participant was able to identify the phonemes at the default cut-off frequency till he/she was able to identify both the phonemes.
2. If the participant was not able to identify one or both the phonemes correctly, the frequency compression parameter was made stronger step-by-step. In other words, the cut-off frequency was decreased, i.e., the strength of frequency compression was increased when the participant was not able to identify the two phonemes. An up and down procedure was used until consistent correct responses were obtained from the participants when the phonemes were presented randomly. This was done each time by testing the identification ability for /s/ and /ʃ/. The frequency compression ratio at which he/she was able to identify correctly atleast for 50% of the time it being presented was used. If any participants were not able to identify the two phonemes even after fine tuning of the cut-off frequency and compression ratio, the cut-off frequency at which the maximum number of times the participant identified the phonemes were finalized as the cut-off frequency and compression ratio of the participant. This fine tuned cut-off frequency and frequency compression ratio of the NLFC was stored in as Program 1 (P1) of the second hearing aid. Thus, in one of the hearing aids, two programs Program 1 (P1) and Program 2 (P2) were set -
    - P1 without NLFC

- P2 with NLFC at default settings as recommended by ‘initial fit’ feature of the iPFG software.

In the other hearing aid, fine-tuned NLFC settings were stored as P1.

Finally, while ‘Saving the program’ into the hearing aids, the volume control was disabled, delayed start-up (boot up delay) was selected and Tac tronic switch for the program selection was enabled.

After programming the hearing aid, Speech Identification Score and Quality Judgment were evaluated. All the participants were tested in four conditions.

1) Unaided condition
2) Hearing aid without Non-Linear Frequency Compression
3) Hearing aid with Non-Linear Frequency Compression enabled - Initial fit setting
4) Hearing aid with Non-Linear Frequency Compression enabled - Fine tuned setting

For each participant, if the non-test ear was the poorer ear, then the testing was done without masking. However, if the non-test ear was the better ear, then the better ear was masked with speech noise at 65 dB using ER-3A insert ear phone fitted with an appropriate ear tip. This was done to avoid the participation of the non-test ear in the test.

Phase III: Hearing Aid Verification

A. *Steps to measure Speech Identification Score (SIS)*

The participants were made to sit comfortably on a chair in the test room at a distance of one meter from the loud speaker of the audiometer at 45^0 A on the aided ear side. The recorded word list was presented through a laptop computer routed through the Madsen OB-922 (Version 2.0) audiometer in the control room. The presentation level was set at 40 dB HL. Level adjustment was done for the calibration tone so that the VU-meter deflections averaged ‘0’. The SIS was obtained in quiet condition.

The order of testing the participants was unaided testing followed by aided testing in which the enabling and disabling of the Non-Linear Frequency Compression feature, was randomized across and within the participants to avoid any order / learning effect. The participants were given a break during the data collection, if required.

The list of high frequency words and sentences were presented at 40 dB HL to obtain the SIS in the unaided and aided conditions.

1. *Unaided Condition*

This was done without a hearing aid being worn by each of the participant.

2. *Aided Condition*

Three aided conditions were evaluated for each participant from both the groups.

1. With Non-Linear Frequency Compression disabled
2. With Non-Linear Frequency Compression enabled - Initial Fit setting
3. With Non-Linear Frequency Compression enabled - Fine Tuned setting

As there were three lists of words and sentences, none of the words or sentences list was repeated for any participant during the data collection.

The participants were instructed to repeat the recorded words that he /she heard which were presented through a personal laptop computer and routed the auxiliary input of the audiometer. The responses were noted down in the International Phonetic Alphabet by the tester. The total number of correct responses was noted down for each test condition for each participant.

For the purpose of the study, scoring for words and sentences were done. For word identification, the response was considered incorrect if he/she failed to repeat or if it was repeated incorrectly. For sentences, it was taken as a correct response only if the participant repeated the entire sentence verbatim. The response was considered as incorrect if any word was missed or reworded or any phoneme in a word being replaced by another phoneme. Each correct response was given a score of ‘one’. The total number of correct responses was calculated after testing in each condition, for a maximum score of 25 for words and 9 for sentences.

Further, the ability of the participant to identify the Ling six sounds (/a/, /i/, /u/, /s/, /ʃ/, /m/) was done for each condition at 40 dB HL and the sounds which were not identified by the participant were noted down. The sounds were presented in random order. This was done using monitored live voice through the audiometer. For each correct identification, a score of ‘one’ was given and ‘zero’ for each incorrect identification. All the sounds were presented once and the responses were noted down. If any client found difficulty in identifying the phonemes, then the sounds were presented once more. After the presentation, the identification scores were converted to percentage scores.

B. Quality Judgment

The participants were asked to rate the hearing aid in terms of its quality of speech output in all the four conditions tested. For this, the recorded Kannada passage was routed through the audiometer at 40 dB HL. The participants were instructed to rate on six parameters of quality. The instructions were made simple in Kannada and it was explained to the participant.

The parameters and the rating scale for evaluating the quality judgment were -

- Loudness : from 0 to 10
- Clearness : from 0 to 10
- Sharpness : from 0 to 10
- Fullness : from 0 to 10
- Naturalness : from 0 to 10
- Overall impression : from 0 to 10

Each parameter was rated on a 10 point scale as follows

0 – very poor
2 – Poor
4 – Fair
6 – Good
8 – Very Good

10 – Excellent

The participants were asked to rate the odd numbers if they found the quality to be intermediate between two points.

Thus, for each participant the following data were collected in each of the four test conditions (unaided, aided without NLFC, aided with initial fit NLFC, and aided with fine tuned NLFC)

1. SIS for words
2. SIS for sentences
3. Identification of Ling six sounds
4. Quality Judgment.

These data were tabulated for statistical analysis.

Chapter 4

RESULTS AND DISCUSSION

The study was conducted with an aim to find out the efficacy of one of the latest technology in hearing aids, the non-linear frequency compression (NLFC), in individuals with and without cochlear dead regions. The present study also aimed at studying the subjective quality ratings of speech with NLFC among the participants.

The data were collected from two groups of participants having sloping sensorineural hearing loss, Group I with participants not having cochlear dead region and Group II with participants having cochlear dead region. The parameters measured were the speech identification scores and quality of speech in four test conditions.

1. Unaided condition
2. Aided without NLFC (WNFC)
3. Aided with NLFC programmed in initial fit settings (NFC - IF)
4. Aided with NLFC programmed in fine tuned settings (NFC - FT).

The data for the above parameters were analyzed using Statistical Package for the Social Sciences (SPSS for windows, Version 16) software. The following statistical tools were used to analyze the collected data:

4.1 Descriptive statistics, the mean and standard deviation, for the two groups with and without cochlear dead regions in the four different test conditions.

4.2 Mixed ANOVA (Repeated measures ANOVA) for the four conditions with group as between subject factor to study the effect of the four different conditions, i.e., for unaided condition, without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings, the effect of groups and interaction between the conditions and groups.

4.3 Bonferroni’s Multiple Comparison to study the pair-wise comparison on the parameters for unaided condition, without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings for both the groups.

4.4 Independent samples t-test was done to check the group differences within each condition, i.e., for unaided condition, without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings across both the groups.

4.5 One-way repeated measures ANOVA to find out the effect of speech identification scores for unaided condition, without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings within the two groups.

4.6 The percentage correct scores were calculated for the identification of Ling’s six sounds for the three aided conditions.

The above done tests were done separately for words and sentences.

4.7 Friedman’s test was done to find out the effect of the different subjective ratings of quality across the three aided conditions and within each group.

4.8 Mann Whitney-U test to find the differences in the subjective rating across the groups, for quality in three test conditions, i.e., without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings.

Performance for words and sentences in different test conditions

The mean and standard deviation of performance of words and sentences in terms of SIS was obtained for unaided condition, without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings across the two groups. The mean and standard deviation of Group I (N=15 ears without DR) and Group II (N=14 with DR) for the SIS in the four test conditions have been tabulated in Tables 4.1 and 4.2.

Table 4.1

Mean and standard deviation (SD) of groups with cochlear dead regions (Group I) and without cochlear dead regions (Group II) in the four different conditions for words and sentences

			Test conditions			
			Unaided	*Without NLFC*	*With NLFC- initial fit settings*	*With NLFC- fine tuned settings*
Words Max. Score = 25	Group I	Mean	3.53	14.47	15.93	17.40
		SD	5.12	2.97	2.66	2.75
	Group II	Mean	6.00	11.50	11.21	11.71
		SD	6.52	6.25	5.86	5.88
Sentences Max. Score = 9	Group I	Mean	2.0667	6.27	7.007	7.0000
		SD	2.46	1.91	1.36	1.20
	Group II	Mean	3.57	5.79	5.86	5.79
		SD	3.82	2.97	3.21	2.86

From Table 4.1, it can be seen that as expected the mean SIS for the group without a cochlear dead region tended to increase from the unaided condition to aided conditions. Among the three aided conditions, performance was better with NLFC being activated. But the same trend was not seen for the group with a cochlear dead region, wherein, the mean scores increased from the unaided condition, but little change was observed within different aided conditions. The standard deviation decreased for the aided conditions than in the unaided condition in the group without a cochlear dead region, but it remained almost the same for the group with a cochlear dead region. This observation was true for both words and sentences.

For Group I, among the aided conditions, the performance for words was best with NLFC- fine tuned settings followed by NLFC-initial fit settings, then without NLFC. However for the Group II, the mean SIS values revealed that the performance improved in the aided condition, but remained similar in all the three aided conditions for words. For sentences, the performance in the aided condition improved when compared to unaided condition in both the groups.

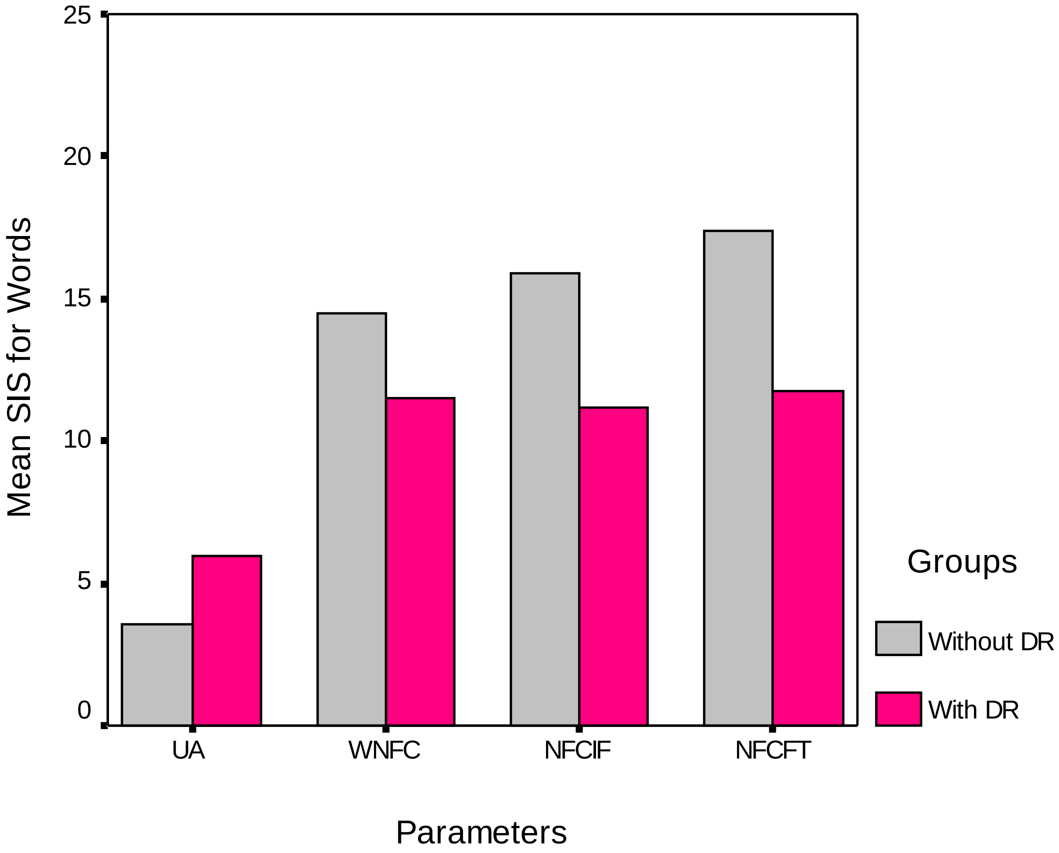


Fig. 4.1: The Mean SIS for words under four conditions, UA - Unaided, WNFC - Without NLFC, NFC-IF - With NLFC Initial Fit settings, NFC-FT - With NLFC Fine Tuned settings.

A slight variation in the mean word scores in the two groups of participants across the three aided test conditions for both the groups was noted. In order to find out if these performances were significantly different, mixed ANOVA was performed.

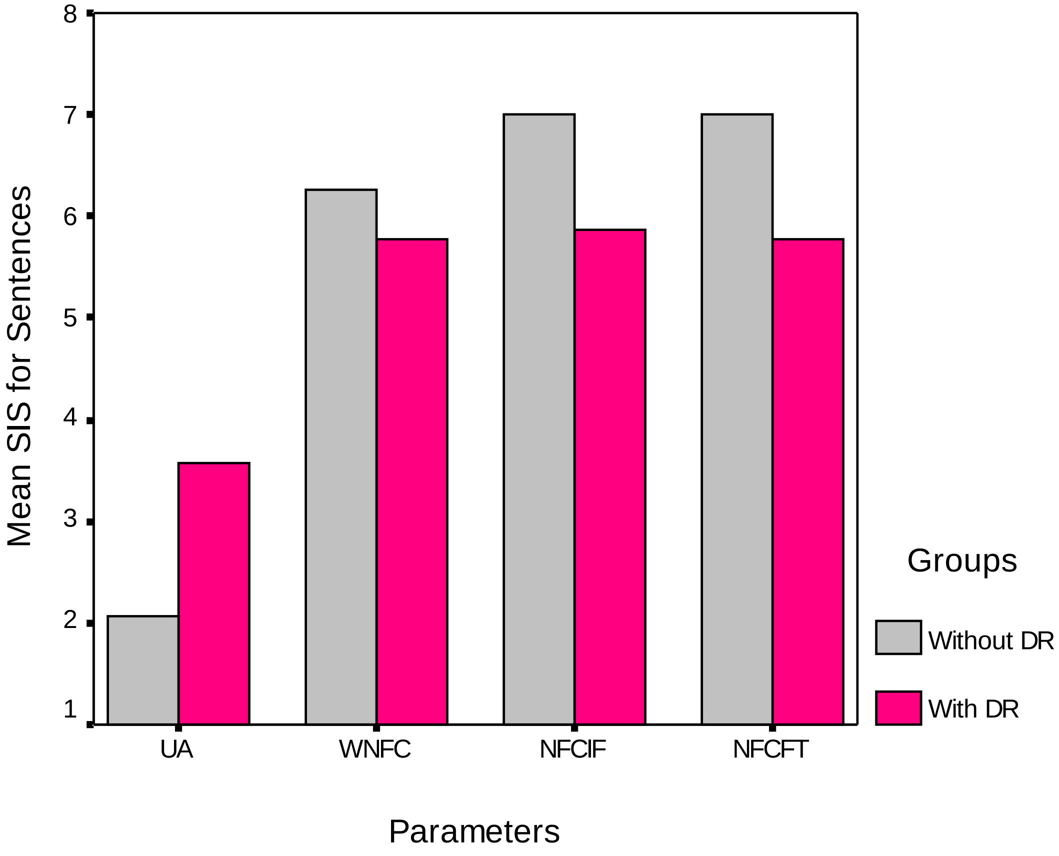


Figure 4.2: The Mean SIS for sentences for four conditions, UA - Unaided, WNFC - Without NLFC, NFC-IF - With NLFC Initial Fit settings, NFC-FT - With NLFC Fine Tuned settings.

The Figure 4.2 depicts the mean scores for all the four conditions for sentences as stimuli. It can be seen that the mean scores were higher for Group I (without DR) than Group II (with DR) in all the three aided conditions. Among the three aided conditions, in Group I, the performance for NLFC initial fit settings and NLFC fine tuned settings yielded the similar improvement followed by without NLFC while little difference was observed in the mean scores for Group II.

Effect of different test conditions on SIS

Mixed ANOVA was done to find out if there was a significant difference in performance between the four different test conditions and two groups of participants. The results revealed a significant difference for the four conditions [($F (3, 81) = 98.753$, $p < 0.001$)] while no significant difference was seen between the two groups of participants [($F (1, 27) = 2.683$, $p > 0.05$)]. Since there was a significant interaction between the conditions and groups, separate analysis was done for both the groups and for different conditions [($F (3, 81) = 16.042$, $p <0.001$)]. From the Bonferroni's test, a significant difference between the unaided condition and all the aided conditions at 5% level of significance was noted, which was as expected. Among the aided conditions, a significant difference was found between with NLFC-fine tuned settings and without NLFC. Whereas, there was no significant difference between the pairs with NLFC-initial fit settings and with NLFC- fine tuned settings. The NLFC-initial fit settings and without NLFC conditions were not statistically significant even at 5% level of significance.

Effect of different conditions across the two groups of participants for words and sentences

Independent samples t-test for SIS for words was done to check the group differences within each condition. The results showed no significant difference between the unaided condition [$t (27) = 1.137$, $p > 0.05$,] and the condition in which the NLFC was deactivated [$t (27) = 1.651$, $p > 0.05$] across the two groups for words even at 5% level of significance. However, there was a significant difference between the NLFC-initial fit settings [$t (27) = 2.826$, $p < 0.05$] and fine tuned settings [$t (27) = 3.376$, p

<0.05] across the two groups at 5% level of significance. Similarly, independent samples t-test was done for sentences under the four conditions, across the two groups. The results showed a different trend altogether. There was no significant difference across the four test conditions, i.e., for unaided condition [$t(27) = 1.270$, $p > 0.05$], without NLFC [$t(27) = 0.523$, $p > 0.05$], with NLFC-initial fit settings [$t(27) = 1.264$, $p > 0.05$], and with NLFC- fine tuned settings [$t(27) = 1.510$, $p > 0.05$] between the two groups even at 5% level of significance.

Comparison of unaided and three aided conditions across the two groups

The mean scores for all the four conditions for words as stimuli are shown in Figure 4.1. It can be seen that the mean scores were higher for Group I (without DR) than Group II (with DR) in all the three aided conditions. Among the three aided conditions, the NLFC-fine tuned settings yielded the maximum scores in Group I followed by NLFC-initial fit settings and finally without NLFC. Little difference can be seen for the Group II across all the three aided conditions. To investigate if these differences in the mean SIS under the different test conditions were significantly different, one way repeated measures ANOVA was performed.

One way repeated measures ANOVA was done to compare the SIS between the unaided condition and the three aided conditions in both the groups. The conditions which showed a significant difference were further analysed for pair-wise comparison using the Bonferroni's post-hoc test. Again, as expected, results of the analysis showed that for Group I significant difference was found only for the NLFC fine tuned settings and without NLFC at 5% level of significance. No significant difference was found for the NLFC-initial fit settings and without NLFC; and also for NLFC-initial fit settings and NLFC fine tuned settings even at 5% level of significance. The same trend was found for both words and sentences in the Group I [F (3, 42) = 70.432, $p < 0.05$].The trend seen for Group II was different with no significant difference for any of the aided test conditions, for both words and sentences, even at 5% level of significance [F (3, 39) = 32.195, $p > 0.05$].

To summarize the results of Bonferroni’s post-hoc test, significant results was seen for both words and sentences as stimuli was seen only for Group I for NLFC-fine tuned and without NLFC settings whereas no significant different was found for any pairs in the Group II at 5% level of significance.

The results support that of the studies on speech perception through non-linear frequency compression by Simpson, Hersbach, and McDermott (2005, 2006) which reported a significant improvement for individuals with gradually sloping hearing loss but no improvement for individuals with steeply sloping hearing loss was reported. They attributed the cause for lesser improvement in steeply sloping hearing loss to the presence of a “cochlear dead region”. An improvement might have been present if the amplification was given within half to one octave above the estimated edge frequency (Vickers, et al., 2001). There are studies which show that reduction of hearing aid gain in the frequency range of dead regions may be desirable in some listeners who have them (Preminger, 2004). Probably in the present study, an improvement in Group II might have been noticed if amplification was restricted to within half to one octave above the estimated edge frequency, as reported by Vickers et al., 2001.

Kluk (2005) concluded that if for subjects with DRs, a larger than normal region of the auditory cortex is devoted to the analysis of frequencies just below *fe*, then it is possible that this auditory cortex re-organization makes subjects with DRs more effective at extracting “useful” information from lower frequencies in the speech. The frequency lowering strategies like non-linear frequency compression shifts the inaudible high frequency information to the lower frequencies where there is more useful hearing. So, it may be possible that the individual with a cochlear dead region may benefit better if the higher frequencies are shifted to the frequencies around the edge frequencies where it is more effective in extracting the information.

The identification of Ling’s six sounds in four test conditions

The results showed that the maximum correct identification was observed for /a/ followed by /u/ for Group I, wherein, the participants got 100% scores in all the four test conditions including the unaided also. Even though the percentage scores improved for / i /, / s /, / ʃ / and / m / in the aided conditions compared to unaided condition there was a little difference across the three aided test conditions. The findings throw light on the fact that the participants without a cochlear dead region do benefit from the amplification for the identification of Ling’s sounds. But the participants without a cochlear dead region did not benefit from the NLFC, being enabled at both initial fit settings and fine tuned settings, when compared to NLFC disabled condition for the identification of / i /, / s /, / ʃ / and / m /.

It was observed that for the Group II with a cochlear dead region, the identification was best for the sound / a / where the percentage scores was 100% in all the four test conditions irrespective of aided and unaided. The amplification increased the identification scores for / i /,   / u / and / m /, whereas, the identification scores remained poor for / s / and / ʃ /. The identification score for the / i /, / u / and / m/ remained the same across all the aided conditions. The percentage scores for both the groups for the identification of Ling's six sounds is tabulated in the Table 4.2.

Table 4.2

Percentage scores for the identification of Ling's six sounds, for both the groups

Condition	*Group*	*/ a/*	*/ i /*	*/ u /*	*/ s /*	*/ ʃ /*	*/ m /*
Unaided	Group I	100%	0%	100%	0%	6.7%	86.7%
	Group II	100%	0%	71.4%	0%	0%	85.7%
Without NLFC	Group I	100%	73.3%	100%	33.3%	60%	100%
	Group II	100%	35.7%	92.9%	0%	0%	100%
With NLFC- initial fit settings	Group I	100%	73.3%	100%	33.3%	53.3%	100%
	Group II	100%	35.7%	92.9%	0%	0%	100%
With NLFC- fine tuned settings	Group I	100%	80%	100%	33.3%	60%	100%
	Group II	100%	35.7%	92.9%	0%	0%	100%

The result of identification of Ling's six sounds is graphically represented in Figure 4.3 for Group I and Figure 4.4 for group II.

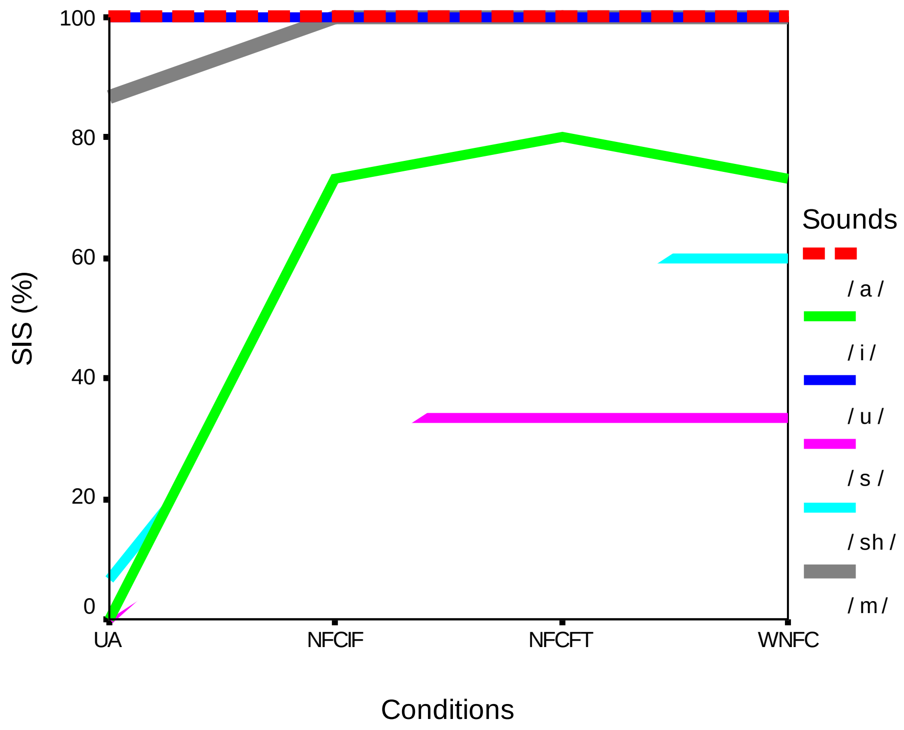


Figure 4.3: Line Graph depicting the percentage scores for the identification of Ling's Sounds, UA - Unaided, WNFC - Without NLFC, NFCIF - With NLFC Initial Fit settings, NFCFT - With NLFC Fine Tuned settings.

Figure 4.3 depicts the percentage of correct identification of the Ling's six sounds in Group I, without cochlear dead region. It can be seen from the graph that maximum scores were obtained for / a/ and / u / for all the test conditions and the least for / s /. Among the conditions, better identification was observed for NLFC - fine tuned than WNFC and NLFC - initial fit settings and slight improvement was seen for the identification of / ʃ / for without NLFC and with NFC- fine tuned settings compared to NLFC - initial fit settings. While for / m / and / s /, the identification was same across all the three aided conditions.

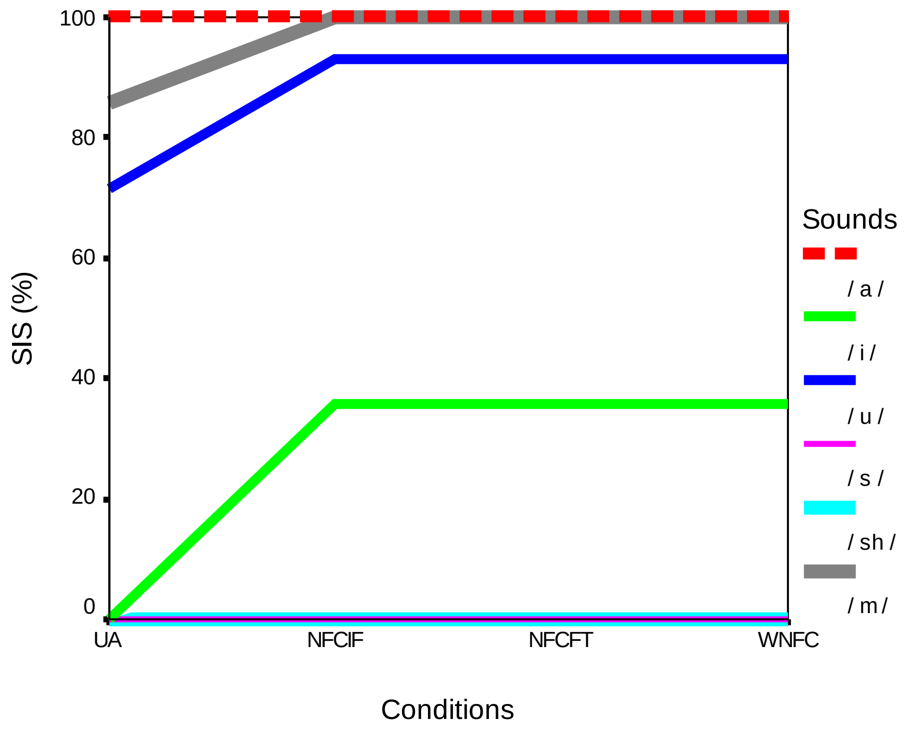


Figure 4.4: Line Graph depicting the percentage scores of the identification of Ling's Sounds, UA - Unaided, WNFC - Without NLFC, NFCIF - With NLFC Initial Fit settings, NFCFT - With NLFC Fine Tuned settings.

Figure 4.4 depicts the percentage of correct identification of the Ling's six sounds in Group II, with cochlear dead region. It can be seen from the graph that maximum scores were obtained for / a/ for all the test conditions and the least for / s / and/ ʃ / for all the test conditions. Among the aided conditions, no difference were observed in the identification of / u /, / m / and / i / while no score improvement was observed in the identification of / s / and/ ʃ / in the aided conditions compared to the unaided conditions.

From the above results, it can be inferred that the identification of vowels / a / and / u / which is a mid frequency and low frequency vowel respectively, and also / m /

which is low frequency nasal consonant was aided by the amplification. Whereas, the increase in the percent correct scores for the high frequency vowel was comparatively lesser than the other two vowels. The poorer scores were found for the Group II with participants having a cochlear dead region when compared to Group I comprising of participants without any cochlear dead region.

In Group I, for consonants, the identification was better for / m / which is a low frequency nasal consonant when compared to / s / and / ʃ / which are high frequency fricatives. This may be expected as the individuals with sloping high frequency hearing loss have difficulty perceiving fricatives which have significant energy well above 2000 Hz with peak energies in the range of 4500 Hz to above 8000 Hz (Boothroyd & Medwetsky, 1992; Pittman, Stelmachowicz, Lewis, & Hoover, 2003). And within the two fricatives, / ʃ / had better identification scores than / s /. This can be reasoned out by considering the energy concentration of / s /, i.e., between 4-8 kHz which is more towards the higher frequency side when compared to / ʃ /, i.e., below about 3 kHz (Heinz and Stevens, 1961). So evidently, / ʃ / would have been more audible than / s / for these individuals with a high frequency sensorineural hearing loss. However, such a trend was not observed for the Group II having participants with a cochlear dead region, wherein, the there was no improvement in the identification of the fricatives between the unaided and aided conditions.

To summarize, the NLFC improved the identification of fricatives slightly in Group I comprising of participants without a cochlear dead region. The high frequency amplification did benefit the Group I having participants without a cochlear dead region.

However, the NLFC did not aid in the identification of fricatives in the Group II with participants with a cochlear dead region. This may be due to the non-functioning or absent inner hair cells in the Group II because of which the benefit from high frequency amplification is less. This is in support with the literature which reports limited benefit for individuals with high frequency amplification in individuals with a cochlear dead region (Gordo & Iorio, 2007; Baer, Moore, & Kluk, 2002; Mackersie, Tracy, & Davis, 2004; Vickers, Moore, & Baer, 2001) while improvement in performance for individuals without a cochlear dead region (Gordo & Iorio, 2007). This may be due to the fact that at frequencies where dead region is present, those individuals will not receive usable speech cues despite "sufficient" aided gain (Preminger, Carpenter, & Ziegler, 2005).

The above mentioned results on consonant recognition is contrary to the results obtained by the investigators Scollie, Glista, Bagatto, and Seewald (2008) in which they found an improvement in the tests on high frequency sound recognition like / tʃ /, / d /,/ f /, / d3 /, / k /, / s /, / ʃ /, / t /, / z / for both children and adults. The contradictory results may be attributed to the fact that in their study, testing was done with binuaral fitting and after the participants had worn the hearing aids for a minimum period of two weeks. The research has shown that the subjective preference of frequency lowering stratergy like frequency transpostion can be improved by training and with longer period of use (McDermoot & Dean, 2000; Ribeiro & Migueis, 2008). The improvement in the objective performance in another study may be attributed to the longer period of experience with the frequency lowered speech with non-linear frequency compression (Scollie, Glista, Bagatto, & Seewald, 2008).

Quality Judgements

Six parameters for the judgement of quality were evaluated as the participants were asked to rate the quality in all the three aided conditions, i.e. without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings. Within each condition, these six parameters were rated on a six point scale.

The Figure 4.5 depicts the mean ratings for all parameters of quality across all the three aided conditions. It shows that the maximum score or rating obtained for any parameter is ‘6’.

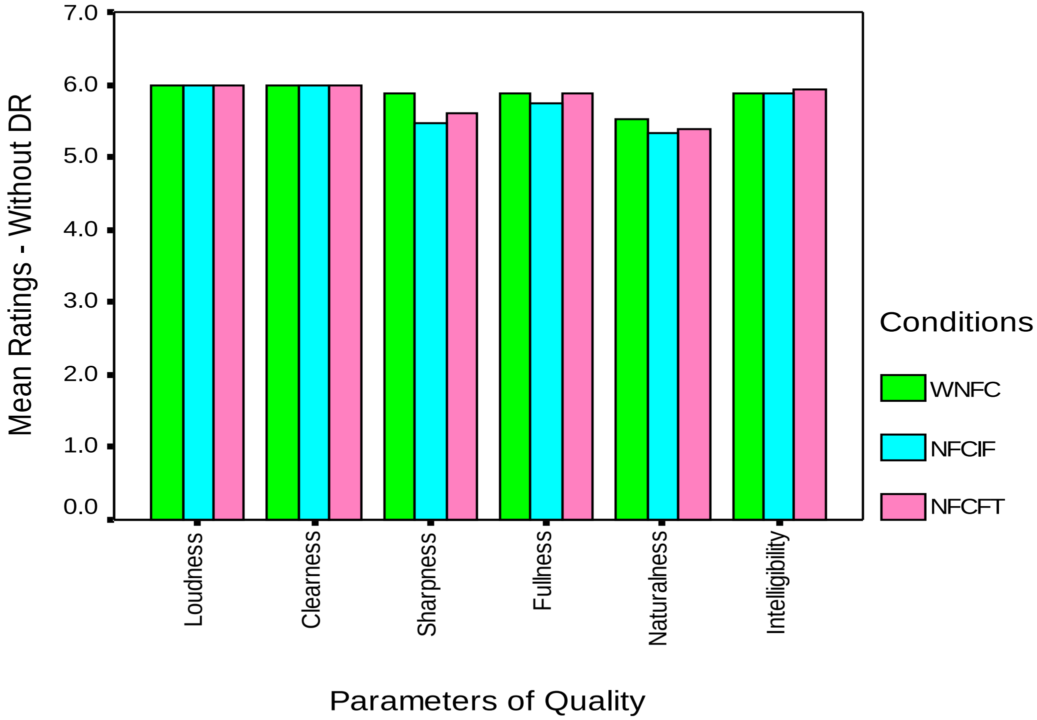


Fig. 4.5: The mean ratings of the subjective quality across the aided conditions for six parameters for Group I, UA - Unaided, WNFC - Without NLFC, NFCIF - With NLFC Initial Fit settings, NFCFT - With NLFC Fine Tuned settings.

From Figure 4.5, it can be observed that in the group without dead regions,

- Comparable ratings were got for the parameters ‘loudness’ and ‘clearness’ for all the three conditions
- For ‘sharpness’, ‘fullness’ and ‘naturalness’, the NLFC initial fit settings yielded slightly poorer rating than that provided by NLFC-fine tuned settings and without NLFC, i.e., highest rating was for without NLFC condition, and the least rating was for NLFC initial fit settings.
- Little differences in the ratings for ‘intelligibility’ were seen across conditions.

From this, it can be inferred that, the participants without cochlear dead region found the frequency compressed speech ‘little sharp’ and ‘unnatural’ among the parameters of quality. This may be attributed to the frequency compression and also due to lack of acclimatization to the frequency compressed speech. The participants would have accepted the quality better probably after a few days of use or training as reported for frequency transposed speech (McDermoot & Dean , 2000, Ribeiro & Migueis, 2008).

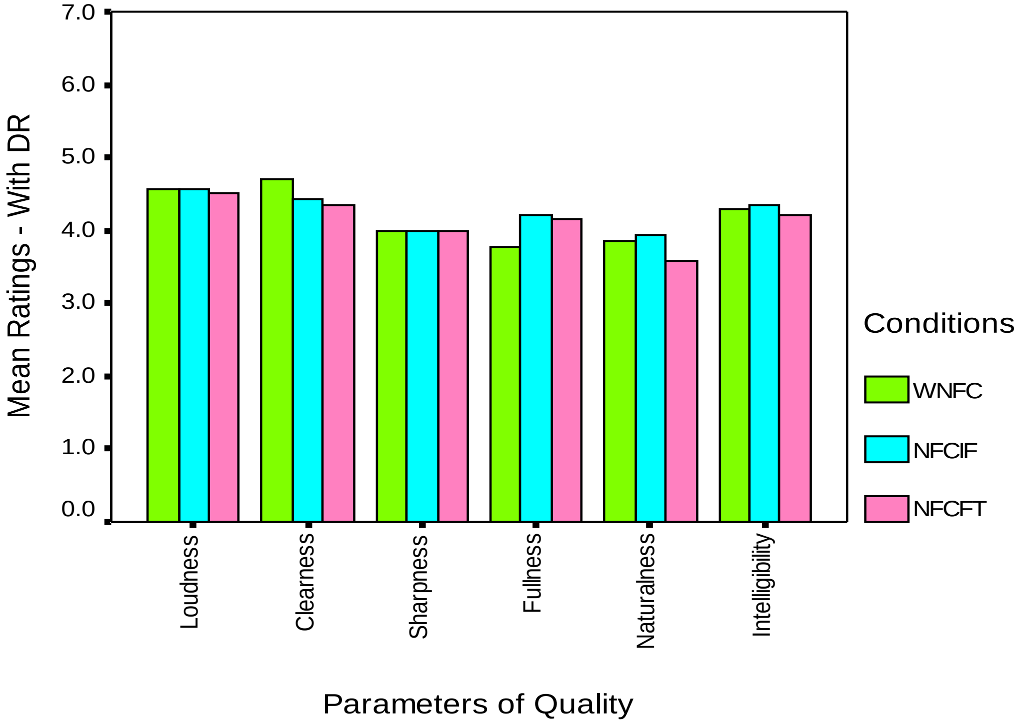


Fig.4.6: The mean ratings of the subjective quality across the aided conditions for six parameters for group II, WNFC - Without NLFC, NFCIF - With NLFC Initial Fit settings, NFCFT - With NLFC Fine Tuned settings.

The Figure 4.6 depicts the mean quality ratings for all the parameters across all the three aided conditions, for Group II. It reveals that the maximum score obtained for any condition was are ‘5’. The mean ratings of Group II were less when compared to Group I.

- The ratings for ‘loudness’ and ‘overall intelligibility’ were almost same across all the three aided conditions.
- ‘Clearness’ was rated the best without NLFC while the other two conditions yielded similar ratings.
- ‘Sharpness’ got equal rating across all the three aided conditions.
- For ‘fullness’, the maximum rating was for NLFC-initial fit settings followed by NLFC-fine tuned settings and finally without NLFC.
- Poorest rating was obtained for ‘naturalness’ especially in NLFC fine tuned condition.

These results reveal that mean scores of subjective quality rating was higher for the Group I - without cochlear dead region, when compared to Group II - with cochlear dead region. This finding support that reported by Preminger, Carpenter, and Ziegler, (2005) which showed the subjects with no dead region was similar to the normative group in APHAB sub-scales, whereas, the subjects with dead region scored poorer. In other words, the group that closely resembled the “successful” hearing aid users in subjective hearing aid performance was the no dead region group.

Friedman’s Test was carried out for both the groups separatetly, for all the three aided conditions, i.e., without NLFC, with NLFC-initial fit settings, and with NLFC- fine tuned settings. It revealed no significant difference in each of the groups for all the parameters between the three aided test conditions ($p > 0.05$). Among the three aided conditions, NLFC - fine tuned settings yielded the poorer scoring compared to NLFC-initial fit settings and without NLFC.

Mann-Whitney U test was done to investigate the significant difference between the quality ratings by participants in the two groups across the three aided conditions for each of the six parameters of quality. The results of Mann-Whitney U test are tabulated in Table 4.3.

Table 4.3

Results of Mann-Whitney U test across the three aided conditions for the six parameters of quality between the two groups.

Conditions	*Quality parameters*	*/Z/*	*Significance (2-tailed)*
Without NLFC	Loudness	3.87	0.000
	Clearness	3.30	0.001
	Sharpness	3.76	0.000
	Fullness	4.32	0.000
	Naturalness	3.50	0.000
	Overall intelligibility	4.23	0.000
With NLFC – initial fit settings	Loudness	3.87	0.000
	Clearness	3.60	0.000
	Sharpness	2.76	0.006
	Fullness	3.37	0.001
	Naturalness	2.39	0.017
	Overall intelligibility	3.91	0.000
With NLFC – fine tuned settings	Loudness	3.87	0.000
	Clearness	3.87	0.000
	Sharpness	3.07	0.002
	Fullness	3.75	0.000
	Naturalness	3.60	0.000
	Overall intelligibility	4.45	0.000

As shown in the Table 4.3, the results of Mann-Whitney U test showed significant difference across the three aided conditions for all the six parameters of quality between the two groups.

From the results of the present study, the following can be inferred:

1. The groups without a cochlear dead region receive benefit from high frequency amplification compared to the group without a dead region.
2. Frequency lowering strategies like non-linear frequency compression is of limited use for individuals with cochlear dead region whereas it improves the speech identification performance of individuals without dead region.
3. Individuals with a dead region received poorer benefit in terms of the subjective quality of the speech from a hearing aid when compared to the individuals without a dead region.

Chapter 5

SUMMARY AND CONCLUSION

The study aimed at investigating the speech perception abilities of individuals having sloping sensorineural hearing loss with or without cochlear dead regions, using Non-Linear Frequency Compression (NLFC). All the participants were naïve hearing aid users.

The study was conducted in three phases:

Phase I: Categorization of participants into those having cochlear dead region (Group II) and without cochlear dead region (Group I) by administering TEN (HL) test

Phase II: Hearing Aid Fitting with out and with non-linear frequency compression (NLFC)

Phase III: Evaluating the efficacy of frequency compression through

1. Speech Identification Score for words and sentences
2. Ling Six Sound Identification
3. Quality Judgment

The above measurements were done in three aided conditions. They were hearing aid program without NLFC, hearing aid program with NLFC in default setting (as recommended by the fitting software) and hearing aid program with NLFC in 'fine tuned' setting.

The results were analyzed using appropriate statistical tools like descriptive statistics, Mixed (Repeated measures ANOVA), Bonferroni's Multiple Comparison, Independent samples t-test, One-way repeated measures ANOVA, Friedman's test and Mann Whitney-U test.

The results revealed that:

1. There was a significant difference in Group I, without cochlear dead region for without NLFC and NLFC-fine tuned settings, no significant difference for any other aided conditions. The same trend was seen for both words and sentences. However, no significant difference was found for any test conditions in Group II with a cochlear dead region, for both words and sentences.
2. The Ling sound identification improved for all the aided condition for Group I with no significant difference in the scores across the three aided conditions. But no significant improvement was found for the Group II for the identification of Ling sounds for the high frequency sounds like / s / and / ʃ /, while slight improvement was seen for the identification of vowels.
3. For the quality ratings, the mean scores of rating were lower for the Group II than Group I. The results showed significant difference across the three aided conditions for the six parameters of quality between the two groups while there was no significant difference

From the present study, it can be concluded that high frequency amplification does help individuals with sloping hearing loss without a cochlear dead region. Also, frequency lowering strategies like NLFC, with the compression ratio optimized can be of help in speech understanding in individuals with sloping sensorineural hearing loss without a cochlear dead region. Unlike the individuals without cochlear dead region, individuals with cochlear dead region did not seem to benefit either with any high frequency amplification or NLFC. However further research is required to validate the benefits of NLFC in individuals without cochlear dead region. In individuals with cochlear dead region, research needs to be focused on use of other frequency lowering techniques and comparing different frequency lowering techniques.

Clinical Implications

- The present study throws light on the limited benefit from amplification for individuals with sloping hearing loss with cochlear dead region. Their amplification needs are different from those with sloping hearing loss without dead regions.
- Frequency lowering strategies, such as non-linear frequency compression, are beneficial for individuals without cochlear dead regions. Thus, prescription of such technology should be done with caution for individuals with a sloping hearing loss.

Future Directions for Research

- To study the efficacy of frequency lowering techniques on individuals with and without cochlear dead region whose audiograms are matched.
- To investigate the efficacy of NLFC in different slopes of high frequency sensorineural hearing loss.
- To study the effect of a period of use and experience on speech perception and quality of speech with NLFC.

- To compare the efficacy of different frequency lowering strategies.
- To study on a larger sample of participants from each group.
- To study effect of NLFC on the speech identification scores for the group with cochlear dead region, with frequency compressed speech given within half to one octave of the estimated edge frequency. This is because, in literature, it has been reported that the discrimination ability is enhanced near the edge frequency of the dead region (Thai-Van, Micheyl, Moore, & Collet, 2003).

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