IJHSR International Journal of Health Sciences and Research
www.ijhsr.org ISSN: 2249-9571

Original Research Article

Benefits of Bimodal Stimulation in Children with Cochlear Implant: Role of Nonlinear Frequency Compression Strategy in Acoustic Hearing

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Received: 30/01/2016 *Revised: 24/02/2016* *Accepted: 26/02/2016*

ABSTRACT

The present study aimed to determine whether the application of nonlinear frequency compression (NFC) strategy in hearing aid (HA) would provide additional perceptual benefits compared to conventional strategy when used in conjunction with cochlear implant (CI) in children. A total of 16 children in the age range between 8.6 and 11.11 years with cochlear implant using bimodal stimulation participated as subjects. Word recognition performance was assessed in quiet and noisy environments under one monaural cochlear implant alone (CI alone) and two bimodal (CI+HA) listening conditions, i.e. CI+HA with NFC strategy and CI+HA with conventional strategy. The results revealed that children obtained significantly higher ($p<0.05$) word recognition performance in quiet environment compared to noisy environment under monaural CI alone and bimodal CI+HA listening conditions. The word recognition performance improved under both the bimodal listening conditions, i.e. either the hearing aid was fitted with NFC strategy or the conventional strategy compared to monaural CI alone listening condition in both quiet and noisy environments. However, a statistically significant ($p<0.05$) improvement was observed especially in noisy environment. In addition, there was no statistically significant difference ($p>0.05$) in terms of this bimodal benefit between two bimodal listening conditions. Hence, it can be concluded that the application of NFC strategy in acoustic hearing provided perceptual benefits when used in conjunction with cochlear implant. However, there were no additional perceptual benefits which can be credited particularly to the use of NFC over conventional strategy. This supports the position that low-frequency acoustic information contributes to the bimodal benefit.

Key words: cochlear implant, bimodal stimulation, word recognition performance, non-linier frequency compression strategy, conventional strategy.

INTRODUCTION

Cochlear implants are able to improve overall performance of both adults and children with severe-to-profound hearing loss by providing them with auditory information that is not adequately obtainable through conventional HA technology. Providing binaural hearing is a vital component of aural rehabilitation as binaural hearing helps to localize sounds and understand speech better in adverse listening situations. [1,2] Bilateral auditory input is essential for binaural hearing, and it has been a topic of debate for many years with regard to hearing aid fitting. Now it has become a standard clinical practice to provide binaural amplification (hearing aids) for individuals with bilateral hearing loss. This debate is now ongoing with regard to CI also. The CI recipients have two options for bilateral stimulation, i.e. use a CI in one ear and a HA in the non-implanted ear known as bimodal stimulation or use a CI in each ear known as bilateral cochlear implantation. [3]

In recent years, there has been an increase in the amount of research on the potential benefits that might arise from bilateral activation in CI recipients. [4-8] Although bilateral cochlear implantation is becoming a more common recommendation, it cannot be an option or may not be recommended for all recipients due to health issues that prevent a second surgery, financial barriers, worry about second surgery, waiting for future technology or, in some cases due to a notable amount of residual hearing in the non-implanted ear. In such cases, the least-expensive and non-invasive method known as bimodal stimulation can be a better option.

Significant advances over the years in CI technology, speech coding strategies, surgical techniques, and increasingly positive outcomes have led to relaxation in the candidate selection criteria for cochlear implantation. [9]As a result most of the cochlear implant recipients will have some amount of usable residual hearing in their non-implanted ear to benefit from continued use of hearing aid. The mid-and high-frequency hearing must still be profound to be considered as candidates for CI, the low-frequency hearing can be moderate for adults and severe for children. [10] Although, HAs often fail to provide adequate performance for these individuals, a satisfactory access to low-frequency information can be provided through HA. [11]

The published literature on assessing the benefits of wearing a hearing aid in the non-implanted ear, i.e. bimodal stimulation is quiet positive and there have been rare cases in which the performance with bimodal stimulation was worse than that with CI alone. [12] Most of the studies have been carried out on subjects using conventional HAs as bimodal devices and reported that the low-frequency acoustic information provided by the HA combined with mid-and high-frequency information provided by CI contributes to this bimodal benefit. [13] However, a number of innovative devices and sound processing schemes have been designed in some recent hearing aids to make the inaudible high-frequency speech information audible for individuals with high-frequency sloping and/or severe-to-profound hearing loss by using frequency-lowering techniques. [14]

Recently two major manufacturers of HAs introduced two distinct frequency-lowering techniques that were designed to compensate in part for the perceptual effects of high-frequency hearing impairments. Frequency transposition and frequency compression techniques are the two main types of frequency-lowering technologies available today. Frequency transposition (e.g. linear frequency transposition) shifts the signal down the frequency axis by a fixed amount. On the other hand, frequency compression (e.g. non-linear frequency compression) technology compresses the output bandwidth of the signal by a specified ratio. Although these schemes process sound signals in very different ways, studies investigating their use by both adults and children with hearing impairment have reported significant perceptual benefits. [15] The introduction of frequency-lowering strategies in some recent HAs raises the possibility that additional perceptual benefits may be obtained when this type of signal processing strategy is used simultaneously with a CI. [14] Hence, there is a need to investigate whether the additional high-frequency acoustic information provided by the frequency lowering strategy in a HA provides additional perceptual benefits for children using bimodal stimulation.

A study by [14] evaluated speech recognition performance of eight adults with monaural CI using HA with nonlinear frequency compression (NFC) in their contra lateral ear. The results revealed that the speech perception was better under bimodal listening conditions (whether NFC was enabled or NFC was disabled in the

HA) in comparison with HA alone and CI alone conditions. However, there was no statistically significant difference between NFC enabled and NFC disabled conditions in the HA when used along with CI. Hence, there were no perceptual benefits attributable specifically to the use of NFC when the HA was used along with the CI. However, according to the subjective ratings provided by these CI users, the simultaneous use of an HA with NFC was readily accepted. Similarly [16] evaluated speech recognition performance of nine adults with monaural CI using HA with linear frequency compression (LFC) in their contra lateral ear. The results revealed that the speech perception was better in bimodal conditions (whether LFC was enabled or LFC was disabled in the HA) in comparison with HA alone and CI alone conditions. There was no statistically significant difference between LFC enabled and LFC disabled conditions in both objective and subjective measures under bimodal listening conditions. However, none of the participants reported any negative responses when the LFT was used in conjunction with the CI indicating no binaural interference.

Although there were no perceptual benefits attributable specifically to the use of NFC or LFT when used simultaneously with the CI, the use of NFC was readily acceptable on subjective ratings in the first study, and none of the participants reported any negative responses when LFT was used in the later study. Since both the studies were carried out on adult subjects, we decided to examine whether children using bimodal stimulation would derive benefits from a HA utilizing NFC.

MATERIALS AND METHODS

A repeated-measures experimental design was used to evaluate the benefits of bimodal stimulation in children with CI as a function of the type of signal processing strategy used in the HA. This was accomplished by measuring the word recognition performance under monaural CI alone and bimodal CI+HA listening conditions in both the quiet and noisy environments.

Participants

A total of sixteen Telugu speaking (Telugu, a South Central Dravidian language that is the state language of Andhra Pradesh) pre-lingual hearing-impaired children, who received monaural CI were considered for the present study. The subjects had a mean age of 9.10 years and mean pure-tone threshold average of 95.93 dB HL in the non-implanted ears. The subjects had a minimum auditory experience (including pre-implant bilateral hearing aid usage) of 6 years which includes a minimum of 4 years of post-implant hearing. The auditory experience with pre-implant hearing aid usage of the participants ranged between 2.3 and 4.1 years with a mean duration of 2.9 years. The auditory experience with post-implant ranged between 4.3 and 6.3 years with a mean duration of 4.7 years. The mean auditory experience with bimodal stimulation was 21.93 months. Ten of the subjects were implanted with Nucleus CI 24 RE (CA) implant and six were implanted with Nucleus CI 24 RST implant with freedom speech processor. The subjects were using high-power six cannels digital hearing aid with nonlinear frequency compression (NFC) strategy in their non-implanted ears.

Hearing aid fitting

The hearing aids were fitted to each child by programming the HA using NAL-RP fitting formula as recommended by [17] In addition the two parameters such as the cut-off frequency and the compression ratio were determined. The default parameter values of cut-off frequency and the compression ratio were calculated automatically by the fitting software based on the audiogram of the child.

The test procedure

Word recognition score (WRS) testing was administered on each subject in a sound-treated audiometric room under free-field condition where the ambient noise levels were within permissible limits. WRS testing was performed in two monaural and four bimodal listening conditions on each child such as (1) CI alone in quiet environment (2) CI alone in noisy environment (3) CI+HA with NFC strategy enabled in quiet environment (4) CI+HA with NFC strategy enabled in noisy environment (5) CI+HA with NFC strategy disabled (i.e. conventional setting) in quiet environment (6) CI+HA with NFC strategy disabled (i.e. conventional setting) in noisy environment. A battery for assessing speech recognition performance by children in Telugu developed by **[18]** was used as test stimuli. The stimulus was presented at 65 dB SPL in quiet and +10 dB SNR in noisy listening conditions. The noise was four-talker babble presented at 55 dB SPL and mixed with the speech material. The stimulus was played on a CD player, which was routed through a Diagnostic Clinical Audiometer and delivered through a single loud speaker placed in front of the child at a distance of one meter and at an angle of 0^0 azimuth.

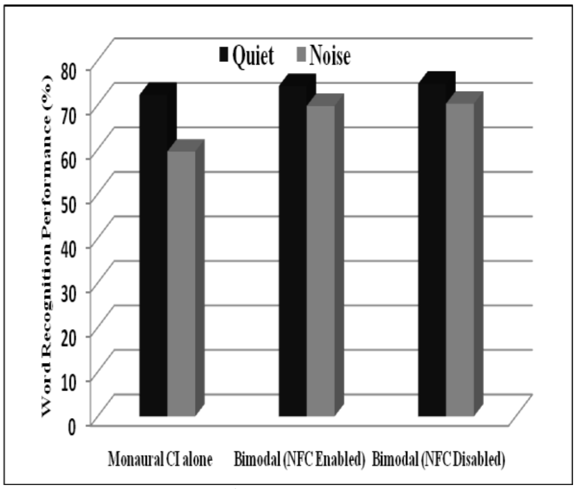
Statistical analysis: The mean and standard deviation (SD) values of WRS under monaural CI alone and two bimodal CI+HA listening conditions (i.e. CI+HA with NFC enabled and CI+HA with NFC disabled) in both quiet and noisy environments were calculated. The obtained data were subjected to one-way ANOVA to find out significant difference in the mean values of WRS between listening conditions.

RESULTS AND DISCUSSION

The mean and SD values of WRS under monaural CI alone and two bimodal CI+HA listening conditions (i.e. CI+HA with NFC strategy enabled and CI+HA with NFC strategy disabled) in both quiet and noisy environments obtained by 16 subjects using NFC strategy in their hearing aid were calculated. Table 1and Graph 1 show the mean values of WRS obtained by the subjects under CI alone and bimodal CI+HA listening conditions in quiet and noisy environments.

Table 1: Mean values of WRS between two bimodal listening conditions in quiet and noisy environments

Listening Condition	Word Recognition Score (%)				Significance value
	Quiet		Noise		
	Mean	SD	Mean	SD	
Monaural CI Alone	72.25	10.55	59.50	9.75	p<0.05
CI+HA (NFC Enabled)	74.25	10.45	69.75	9.55	
CI+HA (NFC Disabled)	74.75	10.65	70.25	9.65	



Graph 1: Mean values of WRS between two bimodal listening conditions in quiet and noisy environments

The subjects obtained mean WRS of 72.25%, 59.50%, 74.25%, 69.75%, 74.75% and 70.25% under CI alone in quiet, CI alone in noisy, CI+HA (conventional setting) in quiet, CI+HA (conventional setting) in noisy, CI+HA (NFC setting) in quiet, and CI+HA (NFC setting) in noisy environments respectively. The obtained data were subjected to one-way ANOVA to find out significant difference in mean values of WRS obtained within and between listening conditions. The results revealed that there was a statistically significant difference (p<0.05) between and within listening conditions. Hence, the data was further subjected to LSD Post-Hoc analysis to find out significant difference in the mean values of WRS between listening conditions.

The results revealed that there was a statistically significant (p<0.05) effect of noise and bimodal listening conditions on word recognition performance. The subjects obtained significantly higher ($p<0.05$) word recognition performance in quiet environment compared to noisy environment under both the monaural CI alone and bimodal CI+HA listening conditions. Although, there was a significant effect of noise on word recognition performance, this effect was less under both the bimodal listening conditions compared to monaural CI alone listening condition. The subjects obtained significantly lower ($p<0.05$) word recognition performance under monaural CI alone listening condition compared to two bimodal CI+HA listening conditions in noisy environment. The two bimodal CI+HA listening conditions (i.e. CI+HA with NFC enabled and CI+HA with NFC disabled) resulted in an improved word recognition performance compared to monaural CI alone listening condition under both quiet and noisy environments. However, a statistically significant ($p<0.05$) improvement in word recognition performance under both the bimodal listening conditions were observed especially in the presence of noise. It was further observed that although both the bimodal CI+HA listening conditions (i.e. CI+HA with NFC enabled and CI+HA with NFC disabled) resulted in a significant ($p<0.05$) bimodal benefit especially in the presence of noise, there was no statistically significant difference ($p>0.05$) between two bimodal CI+HA listening conditions in terms of this bimodal benefit.

From the above findings it can be inferred that the bimodal stimulation is beneficial for children with CI irrespective of differences in the type of signal processing strategy used in the bimodal device in the present study. The use of NFC strategy in hearing aid resulted in a significant bimodal benefit. However, the benefits were similar to those benefits obtained when the hearing aids were used with conventional strategy. The additional high frequency acoustic information provided by the NFC strategy has not resulted in further bimodal benefit.

DISCUSSION

There was a statistically significant effect of noise on the word recognition performance which was demonstrated by a significant reduction in word recognition performance under monaural CI alone and bimodal CI+HA listening conditions in noisy environment under both the bimodal listening conditions. This is because the electrical stimulation used in the CI has limitations compared to acoustic amplification. [13, 19,20] The shallow insertion of electrode array in the cochlea severely limits the transfer of low-frequency spectral information and prevents the lower harmonics of pitch to be encoded approximately in the “right place” of the cochlea. [12] As a result the low-frequency pitch information which aids in separating the voices by making use of fundamental frequency (F0) cues is poorly transmitted through electric stimulation used in CI. [19-21] The spectral resolution provided by the CI is limited compared to the more precise spectral resolution provided by acoustic hearing when listening to speech. [22]A limited spectral resolution or little spectral information may be sufficient to understand speech in quiet environment. However, limited spectral resolution has a direct negative consequence on the ability to understand speech in the presence of background noise. A much finer spectral resolution is required in order to understand speech in the presence of background noise than that required to understand speech in a quiet environment. [23] Hence, even though the CI users are able to achieve significantly higher levels of speech recognition performance in quiet environment, the presence of background noise continues to significantly degrade speech recognition performance for even the best CI performers. [19, 20,24]

Although there was a significant effect of noise on word recognition performance under both monaural CI alone and bimodal CI+HA listening conditions, the effect of noise was reduced under bimodal CI+HA listening condition compared to monaural CI alone listening condition. The bimodal CI+HA listening condition resulted in an improved word recognition performance compared to monaural CI alone listening condition especially in the presence of noise. As expected the bimodal advantage especially in the presence of noise could have risen from combining the low-frequency acoustic information delivered through the HA with electrical information delivered via the CI. The low-frequency residual acoustic hearing is often superior to electrically stimulated hearing. Although CI can provide good detection of low-frequency sounds, the acoustic hearing, provided by either a normal hearing or HA is able to provide more accurate low- frequency information as compared to CI. [20] The low-frequencies in the speech provided by HA contain information on the fundamental frequency (F0) of the speaker's voice and formants. The F0 cues improve speech recognition in the background of competing speakers even at poor signal-to-noise ratios. [25] The low-frequency pitch information also provides information on voice onset time (VOT) cues which contributes in the distinction of voiced versus voiceless consonantal sounds on the segmental level. [26] On the other hand, the mid-and high-frequency information provided by the CI can provide valuable linguistic information related to the place of articulation and manner of articulation of consonants. [10] Hence, the low-frequency pitch information provided by acoustic hearing might complement the mid-and-high-frequency information provided by the electric hearing through CI to enhance speech intelligibility. [13]

Another reason for the bimodal advantage could be that the acoustic stimulation provided by the HA might have provided the subjects to access the finer spectral and temporal pitch cues in the speech signal that are not well resolved by the CI. [27] The frequency resolution provided by the electrode array is limited compared with the more precise frequency resolution provided by acoustic hearing. The spectral resolution of residual low-frequency acoustic hearing presumably is better than that of electric hearing provided by the CI. [19, 28,29] This advantage of spectral resolution in low-frequency acoustic hearing may provide relative benefits in perceiving spectral features of speech sounds, therefore, may lead to improved speech recognition in the presence of noise. [12,30] The low-frequency information is represented neither by the place of stimulation nor by the pattern of firing of temporal fine structure in CI. [13] The neural responses are highly synchronized to the sound waveform only for low-frequency sounds, [31] and hence, it is likely that combining low-frequency fine-timing information through HA and high-frequency information through CI would be more effective in providing temporal cues. [13] A similar argument has been made by many investigators in discussing the potential benefits of using a HA in an implanted ear with a short-electrode array (monaural-bimodal stimulation). They suggested that preserving low-frequency hearing in the implanted ear by inserting a short electrode array and stimulating the apical areas of same cochlea with acoustic information through HA together might provide listeners better spectral and temporal resolution of speech signal compared to using a long electrode array alone. [27,30]

The most common type of sensorineural hearing loss is a loss of hearing sensitivity that increases along with an increase in frequency. As the degree of hearing loss increases, the amount of speech information that can be extracted from an audible signal decreases. However, the degradation of speech information is less severe at low-frequencies compared to high-frequencies even when the degree of hearing loss is greater. This is consistent with the research evidence that the degradation is less severe at the lower-frequencies than at the high-frequencies even though the amount of speech information that can be extracted from an audible signal decreases with increased hearing loss. On an average, an individual with a 100-dB hearing loss at 500 Hz can extract about half the information available to a normal-hearing person from the same amount of audible signal. [32] Thus, the spectral and temporal resolutions are relatively preserved in the low-frequencies compared to the high frequencies. [19,28,33] Although conventional hearing aids provide insufficient gain in the high-frequency region, a satisfactory access to the low-frequency information can be provided even with greater degree of hearing loss. [10] A similar argument has been advanced by [21] regarding the potential benefits of using a HA in the non-implanted ear in CI recipients. They have suggested that although speech perception by using a HA alone is not possible, the low-frequency pitch information provided by acoustic hearing complements the mid-and high-frequency information provided by electric hearing to enhance speech intelligibility.

Similarly, additional perceptual benefits were expected when the HA was set to the NFC strategy compared to the conventional strategy. The subjects showed significant bimodal benefit in the presence of noise whether they were fitted either with the NFC strategy or the conventional strategy in the HA. It was further found that there was no significant difference between the two bimodal listening conditions in terms of this bimodal benefit. The additional high-frequency acoustic information provided by the NFC strategy has not resulted in further perceptual benefits compared to the conventional strategy. In other words there were no additional perceptual benefits observed which can be attributable especially to the use of NFC over conventional strategy. This suggests that the CI provides much superior mid-to-high frequency information compared to acoustic amplification for children with severe-to-profound hearing loss. This supports the position that the low-frequency acoustic information provided by the HA combined with electrical hearing provided by the CI contributes to this bimodal benefit.

CONCLUSIONS AND RECOMMENDATIONS

A statistically significant improvement in word recognition performance was found under both the bimodal listening conditions, i.e. either the HA was fitted with NFC strategy or the conventional strategy especially in the presence of noise. Additional perceptual benefits were expected when the HA was set to NFC strategy compared to conventional strategy. However, there were no additional perceptual benefits which can be credited particularly to the use of NFC over conventional strategy. Although NFC is designed to make inaudible high-frequency information to be audible, the CI might have might have provided a much superior mid-and high- frequency information compared to hearing aid with NFC. Thus the present study supports the position that the low-frequency acoustic information provided by the HA combined with electrical information provided by the CI contributes to this bimodal benefit. Although no additional perceptual benefits which can be credited particularly to the use of NFC over conventional strategy, none of the subjects showed binaural interference or any negative responses. Further research should focus on comprehensive evaluation methods both qualitative and quantitative for this type of stimulation and develop more generalized fitting guidelines for NFC before concluding that the conventional HA is better choice over HA having NFC for obtaining bimodal benefits.

ACKNOWLEDGEMENTS

Authors sincerely thank all the children for their participation, and their parents for their constant interest and support throughout the study.

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How to cite this article: Kumar SBR, Mohanty P. Benefits of bimodal stimulation in children with cochlear implant: role of nonlinear frequency compression strategy in acoustic hearing. Int J Health Sci Res. 2016; 6(3):258-266.

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