

REVIEW ARTICLE

Frequency lowering

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Abstract

Background and Aim: It has been several decades since the technology of frequency lowering (FL) has been proposed. However, primary research has revealed no benefits regarding the use of this technique. Currently, new methods for FL and improvement of perception of speech and fricative sounds have led to the application of these methods by numerous companies to produce hearing aids. In this study, through reviewing the findings of recent studies we introduced several FL techniques used in various companies.

Recent Findings: Results of studies conducted since the year 2000 on FL technology suggested that this technology could be used to improve speech perception in cases of high frequency hearing loss. Today, the majority of hearing aid manufacturers use different FL methods.

Conclusion: While the setting principles of FL methods are still vague, improved hearing of fricative sounds has been associated with increased use of this technique by researchers. FL technique has its own benefits and setbacks, understanding of which would facilitate the use of FL techniques and adjustment of hearing aids for hearing-impaired individuals.

Keywords: Frequency lowering; transposing frequency; frequency compression; non-linear

frequency; compression; linear transposing frequency

Introduction

Hearing loss is a common phenomenon, which is present in 1-3 infants per 1000 [1]. Considering acquired hearing loss during adulthood, this number increases in adulthood. In addition, hearing loss is more observed in high frequencies (HFs), compared to low frequencies (LFs), which leads to the ability of receiving LFs, but having difficulties in receiving HFs [2]. Limitation in hearing high frequency sounds varies depending on the form and severity of hearing impairment. In this regard, individuals with ski slope or severe to profound hearing loss are more prone to limited perception of HF sounds. This limitation is associated with not benefiting from HF signs and their information in speech. As a result, people with these types of hearing impairment have difficulties in speech perception and communication [3,4]. Limited hearing of HF sounds could result in some problems in children, such as delay in the learning process and natural growth of speech and language of infants. Inaccurate and delayed speech learning process also causes difficulties in speech production of children. Moreover, this situation can have several adverse impacts on the life style, education process, and social interactions of children [5]. Although the programs for early detection of hearing loss have led to the detection of this impairment during the first few months of birth (before six months), there are

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still many children suffering from this condition [6]. Limitation in obtaining high frequency speech information has a negative effect on the number of learned words, as well as meaning and content of speech [7]. In addition, lack of hearing HFs could cause difficulties in hearing the surrounding sounds, such as alarms, telephone ring, car horn, and bird chirp. Hearing some of these sounds is crucial for individual's safety, whereas some other sounds are pleasant to hear. People with ski slope or with severe to profound hearing loss are deprived from these types of sounds [8,9]. Another hearing problem in these cases is deficiency in hearing the phonemes, such as /θ/, /f/, /t/, /sh/, /ʃ/, and /z/. They also may not be able to differentiate between some phonemes, including /ʃ/ and /s/. This lack of ability to hear or differentiate some of the phonemes could result in inaccurate speech perception or grammar problems [10-14].

In cases with severe to profound hearing loss or those with ski slope hearing loss, the problem is in the structure of the inner ear and damage to the inner hair cells, which is called dead region [14]. When there is dead region (DR), information that reaches this section of the cochlear cannot produce action potential due to lack of hair cells. Therefore, the auditory nerve is not able to transmit the HF information to the brain. This phenomenon leads to the hearing of the main signal as a noise or in a distorted way [15]. Reinforced acoustic excitation is also not able to improve the function of this region. In addition, a distorted signal can adversely affect the sound quality and speech perception of the individual [16].

Nevertheless, hearing enhancement devices must be used in hearing-impaired individuals to create a sense of hearing. One of the most important challenges for audiologists is to provide proper equipment for individuals with severe to profound or ski slope hearing loss (especially if the case is an infant). The commonly used hearing aids cannot provide sufficient gain for receiving HF sounds for many reasons; firstly, all the conventional hearing aids have low output in the HF region (especially higher than 4000 Hz) [17]. Secondly, the

conventional hearing aids have a limited frequency bandwidth, while advancement in technology has led to the production of hearing aids with broader bandwidth, limited perception of HFs remain a major problem in this regard. This bandwidth limitation is more crucial in children, who need to be able to hear voices with higher frequencies to produce speech [18].

Thirdly, the incidence of HF acoustic feedback might increase due to enhanced gain. Although the problem with the feedback is mainly solved in hearing aids designed with the recent advanced technologies, this problem is not completely resolved [19], and fourthly, an unwanted acoustic resonance is created in the tubes or output of hearing aid receiver, leading to hearing distorted sounds [17,19].

Therefore, the conventional hearing aids cannot provide optimal amplification for individuals with hearing impairment. An alternative method is to use devices designed to change the frequency of HF sounds to an audible level, which is best known as frequency-lowering technique [20].

The majority of studies conducted before the year 2000 draw on two traditional methods, which are less applied today. In addition, a small number of individuals were evaluated in the mentioned studies; however, their results were indicative of improvement/lack of improvement in speech perception of the participants [20]. From 2000 onwards, other FL techniques were evaluated due to progress in technology, faster processing systems of hearing aids manufactured by various companies, and adopting a new perspective towards FL by manufacturers. Therefore, to carry out this study, we searched all the articles on the final and conventional methods, which were published from 2000 onwards in Scopus, PubMed, and Google Scholar Databases.

Frequency lowering techniques

Many methods have been used for FL, all of which have one aim in common that is to transfer the HF sounds to frequencies that can be heard better by hearing-impaired individuals [20].

In general, FL is divided into five different techniques. The first is in fact the most primary technique called “channel vocoders”, in which speech signals pass several band-pass filters and get evaluated.

In each band-pass filter, high frequency envelope push signal is restored by a number of narrow band noises or pure tone generators; afterwards, it is modulated in low frequency, and then presented to the hearer. One of the benefits of this method is its adjustable setting. Nevertheless, this technique has been used in none of the hearing aids manufactured by various companies. The major drawback of this method is lack of differentiation between voiced and voiceless sounds. Moreover, the quality of output signal is not equal to speech signal [20].

The second technique is known as “slow playback”, in which speech signal is recorded online and analyzed. The process system of FL is activated in case of frequency components above 2.5 kHz in input signal; otherwise, the system remains inactivated. Afterwards, the recorded sound is adjusted for each individual and played at a lower speed. Frequency is declined due to lower speed of signals. This technique is used in the hearing aids manufactured by the AVR Sonovation company, first in the form of pocket hearing aids, and then behind the ear hearing aids. The advantage of this technique is maintenance of harmonic dependency between the frequency components. However, given the longer presentation of output signal, there is a lack of synchronicity between input and output speech signals, which might lead to the elimination of some parts of the main signal [20-22].

Frequency transposition

The third FL technique is called “frequency transposition” (FT), designed to move HFs toward LFs. This technique was first applied by the Oticon company. Hearing aid input sounds up to 3000 Hz were amplified without any change in frequency. However, frequencies within the range of 4000-8000 Hz were moved toward frequencies lower than 1500 Hz by a processing system [20].

Another frequency transposition method was

proposed by Velmans in 1973, in which the whole frequency response region of the hearing aid is divided into low and high bands and the cut-off frequency is 4000 Hz. Frequencies higher than 4000 Hz are reduced to 4000 Hz by a processing system, combined with low-band reinforced sounds and presented as output signal [19].

Robinson proposed another method in 2007, in which the starting point of frequency transposition activity is determined based on the cochlear dead region. Therefore, this device can be adjusted based on the need of each individual. In addition, sounds with higher frequencies would be transferred to lower frequencies. The transition system is activated when the input signal has high frequency [20,23].

Another known frequency transposition technique was introduced by the commercial name of Audibility Extender, manufactured by the Widex Company in 2006. The activity point of frequency transposition system is introduced by the name of START frequency. An audiogram is used to estimate the START frequency; therefore, this device can be adjusted based on the need of each individual. START frequency is the threshold of inaudible region. The first frequency above 1600 Hz, which has a threshold more than 70 dB HL and slope of more than 10 dB/octave for frequencies within the range of 500-4000 Hz, is considered as the START frequency. Moreover, the START frequency can be manually adjusted within the range of 630-6000 Hz at one-third octave intervals. Two octaves higher than the START frequency are processed and analyzed in the hearing aid and the frequency area with the highest severity is selected and moved one octave lower. In this method, the transferred frequencies are added to the unprocessed frequencies of the main low frequency, which are below the start point, and then presented to the ear of the hearer from the hearing aid output. The presence of the main LF information, which are only reinforced, cause the heard sound to be normal. However, some information might be omitted due to the overlap of some sections of the main signal by the transferred signals. Moreover, the presence of

HF noise in the surrounding could be heard due to the moving of frequency to lower or mid-frequencies. This can lead to the mask of main frequencies of speech signal.

Nevertheless, since the frequency transposition system is only activated if HFs are the main dominant signals and is not always active, the general information is preserved and the sound would be heard in a normal way [24,25].

Audibility Extender is a static method, the most improved version of which is known as Enhanced Audibility Extender and acts adaptively. Application of voice detector algorithms prevents the moving of HF background noise. In addition, the processed moved sounds have more gains in order to better differentiate the sounds in the new system. A signal-dependent system is also active, which leads to the differentiation of lowered voice phonemes from voiceless phonemes. Another added system to the Enhanced Audibility Extender helps with preserving the harmonics of voice phonemes similar to the main signal, which results in more natural sounds. In this method, bandwidth is also more widened [25].

The FL technique was proposed by the Starkey hearing aid company with the name "spectral IQ". In general, this function is inactive and could be activated based on the choice of the audiologist. Even after the selection, the FL acts only when the HF is the dominant input signal. Adjustments are automatically made based on the severity of hearing loss and audiogram shape, which are different in each person. The start point is where the HFs are not audible and must decrease, and the target area is the place the reduced frequencies are moved to. The frequency region with the lowest rate is called corner frequency, also known as processing START frequency. Software determines the start point through the calculation of corner frequency. If a frequency with 20 dB difference is observed in the audiogram curve, that area is regarded as corner frequency. If the slope of audiogram is not within this limit, the HF border with a threshold of 70 dB is considered as the target frequency region. Spectral gain also refers to the amount

of gain for transferred sounds, which is calculated based on the required gain of the origin area. What distinguishes this method from others is the difference in the width of the area of origin and the target region, which depend on the form and severity of hearing loss [26].

Frequency compression

Frequency compression is also one of the frequency lowering techniques (the fourth method), performed in two ways. The first way is linear, in which all frequency components in the frequency band are compressed with a fixed factor. This compression is conducted toward sounds with lower frequencies in all the frequency areas (e.g. high, mid, and low frequencies). Therefore, frequencies of formant peaks in the main speech signal are compressed with a constant ratio. While the general form of the signal remains the same, it will be slightly compressed. Nevertheless, the pitch of the signal is lowered and the sound becomes unnatural. Consequently, this method was not commercially used in hearing aids [20].

The second type is another conventional non-linear frequency compression method with the brand name of SoundRecover, designed by the Phonak Company in 2007. In this method, a cutoff frequency point is selected as the start point of compression, which can be adjusted based on the audiogram shape of each person; the compression system is always active. Since only the frequencies higher than the cut-off point are compressed in this technique, sound quality remains normal. Given the lack of frequency transfer and compression of high frequencies, no frequency overlaps with other frequencies in this method, which leads to the resolving of information omission problem observed in other techniques. However, it should be mentioned that the compression of frequencies higher than the cut-off point leads to the changing of the harmonic ratio of speech frequency components. The lower the frequency of the cut-off point, the more compression of frequencies and the more changes in the

harmonic ratio [27].

Another method proposed by the Phonak Company in 2016 is known as the SoundRecover2 technique, which underwent some modifications, compared to the primary version. In this method, two cut-off points are adaptively used. At each moment, only one of the cut-off frequency points is active. Adaptive nature of this method means that based on the range of input signal frequency, the start point of the frequency compression algorithm is automatically selected. If the frequency energy of the input signal is within the range of low frequencies, an HF cut-off point is selected in order to increase the audibility of sounds. On the other hand, if high-frequency input signals are dominant, an LF cut-off point is selected (less than 1500 Hz). The switching is performed automatically. This leads to the use of a lower compression ratio so that the frequency ratio of harmonics is preserved better. Bandwidth of the hearing aid activity is also increased to 11 kHz. Moreover, it provides four different modes with various pre-determined clarity-comforts to manually adjust the settings of the device [28].

The Belton Company has used the FL method with the brand name of SoundShifter. In this company, LF is similar to the non-linear frequency compression (NFC) system; however, unlike the latter, it is mostly inactive. Four pre-determined adjustment modes, including off, mild (4 kHz), medium (3.5 kHz), and strong (2.5 kHz), are included in the software in order to select the start point of frequency compression and compression ratio, which are both determined before the adjustments for the audiologist. The compression ratio for the mild mode is 1.3 and for the strong mode is 2 [29]. The frequency compression method is also used in GN Resound hearing aids, known with the brand name Sound Shaper [30]. In the Hansaton group, the frequency compression method is used with the name of Sound Restore. In addition, the Unitron Company used the frequency compression technique similar to the Phonak Company. The frequency compression method was also applied by the Siemens Company.

Composition

A new type of frequency lowering (FL) method was proposed by the Oticon Company in 2016, regarded as the composition technique (the fifth method). This FL technique is known with the brand name of Speech Rescue and designed based on maximum audible output frequency (MAOF).

A multi-layered technique is used in this method. At first, the HF region is evaluated and then divided into two or three sections. Afterwards, the start point of LF is determined and collected in narrow regions with low signals. In practice, the HF sections are taken from a range of 3000 Hz and transferred to two or three narrow sections within the range of 800-1600 Hz in the region of lower frequencies [31].

Discussion

The aim of all the FL methods is to make the HF sounds audible to hearing-impaired individuals. Hearing aids, which are programmed based on frequency compression system or frequency transposition, have numerous regulatory parameters, provided based on the audiogram and severity of hearing loss. The results of the mentioned studies were indicative of improved hearing of fricative sounds, which are presented in Table 1. In these studies, words and/or sentences were used as stimulant. Higher scores were obtained by the participants regarding the responses to words and sentences, which were indicative of better speech perception [37,39,51-53]. In a study by Alnahwi in 2015, the frequency compression and frequency transposition methods were compared in individuals with hearing loss using speech stimulants (e.g. monosyllabic, words, consonants, and sentences) in the presence of noise. According to the results, application of frequency transposition technology facilitates the detection of fricative words, leading to improved distinguishing of consonants. In this systematic review, it was concluded that 53% of studies considered the use of frequency compression system appropriate for adults (compared to frequency transposition system, 39%). On the other hand, 91% of studies on frequency compression

Table 1. Summary of studies using frequency transposition and non-linear frequency compression methods

Author/s	Year	Frequency lowering technology	Number of participant	Degree of hearing loss	Stimulus	Result
McDermott and Dean [32]	2000	T	6	Steeply sloping	Monosyllabic words	No improvement
Sakamoto et al [33]	2000	NFC	5	Sever to profound	Sentences	No improvement
Simpson et al [34]	2005	NFC	17	Moderate -profound	Monosyllables	8 participants showed improved
Simpson et al [35]	2006	NFC	7	Steeply sloping	Monosyllables , sentences in noise	No improvement
Kuk et al [36]	2007	T	13	Moderately sloping, moderate to severe above 2KHz	Nonsense	3-6% improvement
Robinson et al [23]	2007	T	7	Dead region(0.8- 1.5 kHz)	Nonsense	17% improvement in 2 participants
Nyffeler [37]	2008	NFC	11	Moderate-severe to profound	Sentences in noise	26% improvement
Glista et al [38]	2009	NFC	13	Moderate- profound	Ling test, consnsnt, vowel, plural word	8 participants showed improvement
Smith et al [39]	2009	T	6	sloping	CNC word, phonemes	Improvement
Wolfe et al [40]	2009	NFC	12	Moderate- severe	Plural test	Improvement
Glista et al [41]	2009	NFC	11	Moderate- profound	Ling test, consonant, vowel, plural word	All showed improvement
Auriemmo et al [42]	2009	T	10	Sloping, normal-moderate in low and severe to profound in high frequencies	nonsense	Improvement in fricative articulation and recognition of vowel & consonants
Kuk et al [43]	2009	T	8	Severe- profound	nonsense	Improvement in fricative, decrease of phoneme confusion
Wolfe et al [44]	2010	NFC	15	Moderate to moderately severe	nonsense	Improved
Bohnert et al [45]	2010	NFC	11	Severe- profound	Speech in noise	7 participant showed improvement
Gou et al [46]	2011	T	7	>100,<100 dB HL	nonsense	Improvement in speech recognition
Uys et al [47]	2012	NFC	40	Severe- profound	music	Improvement
Dansory et al [48]	2013	T	10	Severe- profound		Improvement in speech recognition and articulation
Alexander [49]	2016	NFC	28	Mild-moderately severe	Nonsense in noise	Improvement 33-50%
Bentler et al [50]	2014	NFC	66	Mild- severe	monosyllable	No improvement
Uys and Latzel [51]	2015	NFC	9	Severe- profound	Music and HINT	Improvement
Hillock-Dunn et al [52]	2015	NFC	17	Vary in degree and shape	Spondee word in noise and babble	Bandwidth is important
Wolfe et al [53]	2016	NFS	14	Severe- profound	Plurals word	Improvement

T; transposition, NFC; non-linear frequency compression, HINT; hearing in noise test

reported better hearing of HFs in children after the intervention (compared to the frequency transposition system, 70%) [54].

A study was conducted by Souza et al. to evaluate the effects of FL technology, using NFC technique, on the intelligibility of sentences and quality of sounds in adults with mild to moderate hearing loss after language learning. The participants were among individuals with ski slope hearing loss, aged 60-92 years, and homogenous with the subjects of the control group in terms of age and natural hearing ability. Sentences were evaluated in silence and babble noise using different signal to noise ratios. According to the results of the mentioned study, moderate compression, which is the result of placing the cut-off frequency point in higher frequencies, had little impact on speech intelligibility. Individuals with greater HF hearing loss gained more benefit from NFC. When the compression is high (low frequency cut-off point), understanding of sentences also reduces. This condition is more affected in noisy environments. In quiet surroundings, more compression led to reduced sound qualities reported by hearers, especially by those with better HF threshold. In noisy environments, the quality of sound was decreased, whereas there was little change in compression parameters. It was also reported that NFC gain in adults is affected by compression adjustment parameters [55].

Glista et al. introduced two methods to evaluate the performance of FL. In the first method, live sound and the /sh/ and /s/ sounds were used. On the other hand, 1.3 high frequency band-pass octave filter was applied in the second method. The problem with live sound was that different speakers with different genders in an uncalibrated environment were using it, which changed the final results. Application of the second method was associated with unnatural sound and frequency bandwidth limitation, which was due to the fact that the maximum output frequency was 6300 Hz [39]. In a study by Scollie et al., adjustments guide and protocol settings for FL signal process were published. According to these researchers, when children cannot hear the sound /s/ (especially when produced

by a female), while using their hearing aids, application of hearing aids made with FL technology can be beneficial. In addition, use of aided response and/or level of hearing the fricative sounds can help validate the effectiveness of hearing aids [56].

According to Alexander, when the cut-off frequency is selected at 1.6 kHz, increased compression ratio can lead to decreased differentiation of consonants and vowels. On the other hand, increased cut-off frequency, even with high compression ratio, had no impact on the differentiation of consonants and vowels. In that study, 28 participants with mild to severe hearing loss were evaluated using nonsense syllabic stimulants in a noisy environment. In the severe group, a moderate correlation was observed between the second formant (caused by changes in NFS) and distinguishing of vowels [49].

Use of a slight compression ratio leads to less variations in the frequency range (from moderate to high), resulting in improved hearing of speech and surrounding sounds. In fact, the problem of frequency compression is resolved in the new method known as SoundRecover2 [49,53]. In addition, wider frequency band of hearing aid leads to improved understanding of HF sounds [40-57].

In a study by Wolfe et al., children who used sound recover 1 accepted SoundRecover2 easily, and their acclimatization did not take a long time [53]. In another study by Kuk et al., it was demonstrated that acclimatization could happen in two weeks using the frequency transfer technology [36].

Peltier et al. conducted a study to evaluate 74 individuals, who were using hearing aids with the technology of linear octave frequency transposition (LOFT) and indicated that partial or complete suppress of tinnitus was experienced by 60 participants after a few months of daily use of the device. The amount of suppress was different in these reports regarding age, as well as duration and location of tinnitus. Measurements were based on audiometric and psychoacoustic evaluations. A slight obvious correlation was observed with the amount of hearing loss, whereas no such correlation was

observed with the audiogram slope. While individuals have different tinnitus pathologies, greater suppress was found in the group of tinnitus with sudden deafness etiology. 23 cases had history of exposure to noise. In this group, tinnitus suppress was only reported a few days after using the LOFT hearing aid. The tinnitus would return when the LOFT hearing aid was not used. On the other hand, the tinnitus would suppress after a few days of using the hearing aid again. The NFC hearing aid was used for a few participants, which led to no tinnitus suppression [58].

Conclusion

While the proper setting principles of FL methods are still unclear, improved hearing of fricative sounds has led to the suggestion of this technique by researchers. Access to appropriate hearing input sounds, in terms of intensity and frequency in people with hearing loss, especially children, is of paramount importance. Usually, individuals with hearing impairments have difficulties hearing HF sounds, leading to speech problems in these people. In this regard, the FL technique is used to resolve this problem. Each method has its own advantages and drawbacks, better understanding of which can help with adjusting each hearing aid based on the needs of people with specific hearing impairments.

If a hearing-impaired individual is able to hear HFs sound while using the hearing aid, there is no need for FL technology. On the other hand, lack of hearing the HF sounds can be a major cause of using the FL techniques, which improves the hearing of HF sounds and enhances speech perception in such people.

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