Edge frequency effect on speech recognition in patients with steep-slope hearing loss

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Aim
The aim of this study was to evaluate the effect of edge frequency on speech recognition after nonlinear frequency compression (NFC) using Arabic consonant speech discrimination lists.
Patients and methods
The study was conducted on 20 adult literate patients with bilateral steep-slope high-frequency sensory–neural hearing loss. Patients were subjected to history taking, ear examination, puretone audiometry, and threshold equalizing noise (HL) test to estimate cochlear dead regions. They were divided into four groups according to the edge frequency. Speech recognition was evaluated using modified Arabic consonant discrimination lists before and after amplification with NFC at three settings that differed in cutoff frequency of compression using the same hearing aid. Free field aided thresholds were obtained in every setting.
Results
Patients showed improvement in aided thresholds when the cutoff frequency was lowered. Speech recognition evaluation showed that the extent of dead regions has a marked impact on patients' speech recognition score. Patients with the lowest edge frequency obtained the worst speech recognition score and least benefit from lowering the cutoff frequency, unlike those patients with the highest edge frequency who had better speech recognition and benefitted more from the highest cutoff frequency.
Conclusion
Identifying edge frequency in NFC is important, especially in those patients with steep-slope configuration, as the lower the edge frequency, the poorer the performance. In contrast, satisfactory amplification is reached when the cutoff frequency is at or near the edge frequency.

Keywords:
cochlear dead region, nonlinear frequency compression, steep sloping sensory–neural hearing loss, threshold equalizing noise (hl)

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Introduction

Patients with steep-slope hearing loss have difficulties in hearing high-frequency speech, such as /f/,/s/ and /sh/, which lie around a frequency bandwidth that extends from 1000 Hz to over 7000 Hz [1].

The benefits from conventional hearing aids can be limited by acoustic feedback, discomfort resulting from excessive loudness, or the output abilities of the amplification system itself. Furthermore, in some cases, even when high-frequency information can be made audible, it may not be discriminated when dead region (DR) exists [2,3].

The extent of a DR is described in terms of the characteristic frequencies of the functioning inner hair cells or neurons immediately adjacent to the DR. This is referred to as the edge frequency (*fe*) [4,5].

These DRs can be diagnosed from psychophysical tuning curves or more easily with the threshold equalizing noise (TEN) test. The TEN test is based on whether a puretone is falsely detected in a cochlear DR. Thereby the test introduces masking noise to mask regions close to the DR and consequently prevents off-frequency signal detection [6].

The amount of vibration produced by the tone at this remote region will be less than that in the DR, and so the noise will be very effective in masking it. Thus, the signal threshold is expected to be markedly higher than normal [6,7].

For patients with this type of impairment, amplification could be useful for frequencies up to about 1.7 times the *fe* of the DR [8,9].

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Therefore, technology has added new circuitry to compress high-frequency bands into lower ones through the use of hearing aids with nonlinear frequency compression (NFC). The scheme divided incoming signals into two broadbands based on a chosen cutoff frequency. Signal components below the cutoff frequency were amplified with appropriate frequency shaping and amplitude compression but without frequency shifting. Signal components above the cutoff were compressed in frequency in addition to undergoing amplification [10].

The NFC applies progressively larger shifts to components having increasingly high frequencies. Consequently, a wide range of high-frequency input signals resulted in a narrower range of output signals [10].

Speech recognition outcomes with NFC typically vary from no mean difference to improvement. Variability has been observed both within groups of patients in the same study [10,11] and across studies [12–15]. The NFC parameter selection for each participant could contribute to the observed variability.

Patients and methods

This study was conducted on 20 adult patients suffering from bilateral symmetrical steep-slope high-frequency sensory–neural hearing loss of at least 20 dB per octave with normal to moderate loss at 250–500 Hz with high-frequency DR(s) diagnosed with the TEN test.

Each of the patients in this study was subjected to the following protocol of evaluation:

(1) Complete history taking, otoscopic examination to exclude external or middle-ear pathology, and audiological evaluation including puretone audiometry and immitance measures.
(2) TEN (HL) test for determining cochlear DRs:
The TEN test was provided through a compact disc (CD). The signals from the CD were fed through a two-channel audiometer (Madsen Astera audiometer, Denmark) that was connected to a computer system. Threshold was measured for puretone presented in ipsilateral broadband noise using the recorded CD, the noise on one channel and test tones on the other channel. Both channels are routed to one ear. The auditory threshold is reached in descending manner (10 and 5 dB search method) where the threshold is the lowest puretone level detected in 50% of trials. Then the masked threshold is measured in the presence of a continuous background noise. Possible frequencies for the test tone are 500, 750, 1000, 1500, 2000, 3000, and 4000 Hz. A DR at a particular frequency is indicated by a masked threshold that is at least 10 dB above the absolute threshold and 10 dB above the nominal noise level [16].
(3) Speech audiometry:
  (a) Phonetically balanced word discrimination lists [17]: Speech reception thresholds and speech recognition scores (SRS) were obtained by monosyllabic and bisyllabic phonetically balanced word discrimination lists.
  (b) Modified Arabic consonant discrimination lists [18]: Prerecorded sensible and non-sensible word lists (SWL and NSWL) were used for speech recognition evaluation.
  The words were presented to the patient at the level of 40 dB HL above the speech reception threshold in unaided condition and at the level of 65 dB HL in the aided condition. The patient had to choose the word he or she heard from a closed set of words that differed from the test word in only one consonant, either initial or final, which is the tested consonant, and the test score was reported as a percentage of the correct responses.
(4) Fitting the hearing aid:
General settings:
  (a) The ear with better threshold and less cochlear DR was selected, and the right ear was selected if both were symmetrical for better manipulation.
  (b) Ear molds were made with parallel (1.7–2 mm) vent according to low-frequency thresholds.
  (c) The hearing aid used in this study was Bolero Q50 SP with NFC algorithm.
  (d) All batteries were checked to ensure that they was fully charged before the test.
  (e) The patient was placed 1 m from the sound field loudspeaker in an acoustically sound-treated room.
  (f) The fitting formula was NAL-NL2.
  (g) Three different sittings were tested on each patient using three different cutoff frequencies while the compression ratio remained nearly fixed.
  Hearing aid verification was done by obtaining aided thresholds for frequencies 250, 500, 1000, 2000, and 4000 Hz, respectively.
  Speech performance was evaluated with the NFC algorithm using modified Arabic consonant speech discrimination lists, and scores were obtained at the three different settings.

Statistical analysis

Data were analyzed using the statistical program for social sciences package, version 20.0.

Results

Hearing threshold assessment

Descriptive analysis results of the puretone thresholds in dB HL using TDH-39 headphones of all studied ears at frequencies 250, 500, 1000, 2000, 4000, and 8000 Hz are shown in Table 1.

Eleven cases had no response at 8000 Hz and six cases at 4000 Hz, with a maximum stimulation of 110 and 120 dB HL, respectively, and they were assigned a mean value of 120 dB HL.

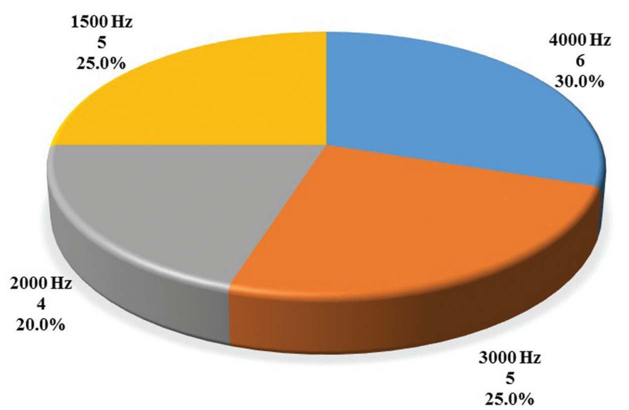
Distribution of studied cases according to the extent of the dead region

Selected cases were subdivided according to the extent of DRs in terms of their *fe* into four classes using the TEN test: patients with *fe* 4000 Hz, patients with *fe* 3000 Hz, patients with *fe* 2000 Hz, and patients with *fe* 1500 Hz (Fig. 1).

Table 1 Distribution of patients according to puretone thresholds

Frequency (Hz)	Range (dB HL)	Mean±SD	Median
250	20–40	27.75±5.95	25
500	20–45	35.00±8.11	40
1000	30–100	63.75±17.76	70
2000	60–120	89.50±13.66	90
4000	90–120	107.75±10.32	105
8000	90–120	111.75±10.92	120

Figure 1



Distribution of patients according to edge frequency.

The right ear was selected for the study in 15 cases and the left ear in five cases. Selection was based on ears with better hearing thresholds.

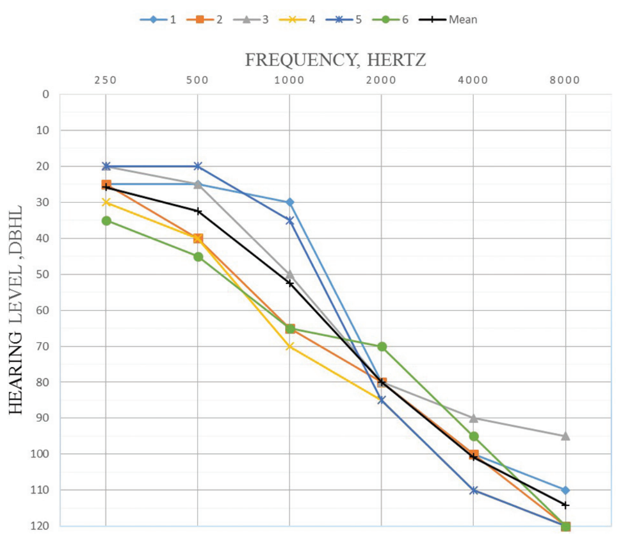
(1) Audiometric thresholds for the studied cases in each of the four groups are presented in Figs 2–5, with each symbol and line presenting different cases, with the black line representing the group mean.
(2) Parametric settings of the studied cases using NFC algorithm are presented in Table 2. By using the NFC algorithm every case was subjected to three different parametric settings as regards cutoff frequency for compression and compression ratio.

Aided threshold assessment

All, patients with *fe* 4000 Hz showed improvement in aided thresholds in the three settings compared with unaided thresholds, as shown in Fig. 6.

All patients with *fe* 3000 Hz showed improvement in aided thresholds in the three settings compared with unaided thresholds, except for one case that showed

Figure 2

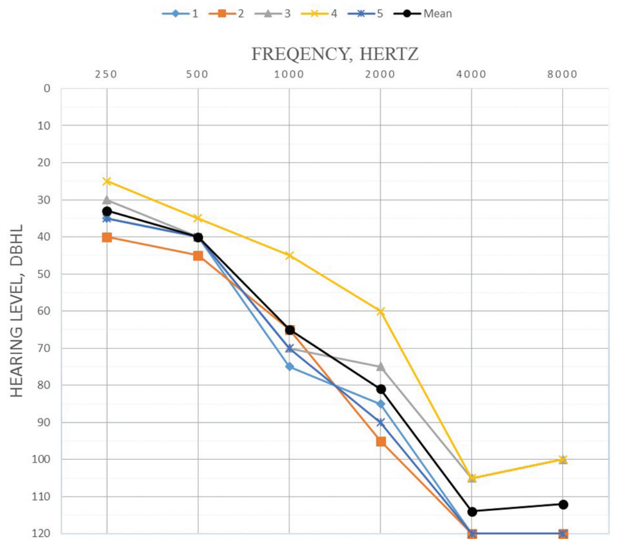


The audiometric thresholds for patients with *fe* 4000 Hz, with the black line representing the group mean.

Table 2 Parametric settings of studied cases using nonlinear frequency compression algorithm

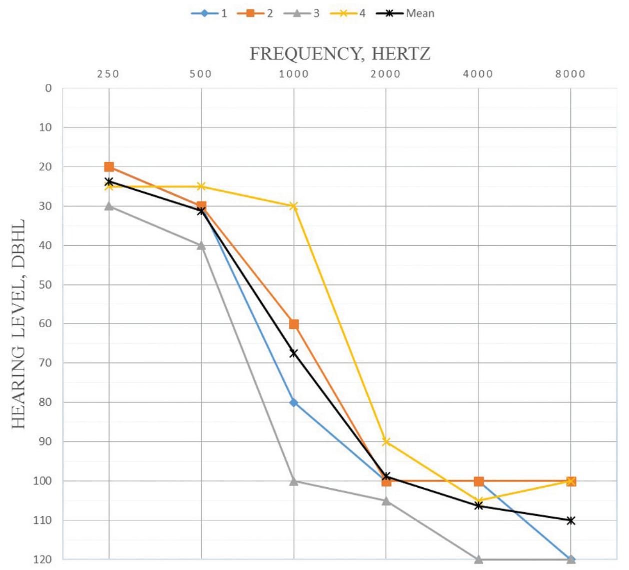
	First setting		Second setting		Third setting	
	Cutoff frequency (KHz)	Compression ratio	Cutoff frequency (KHz)	Compression ratio	Cutoff frequency (KHz)	Compression ratio
Mean±SD	2.96±0.06	1.98±0.06	2.17±0.05	1.99±0.04	1.5	2

Figure 3



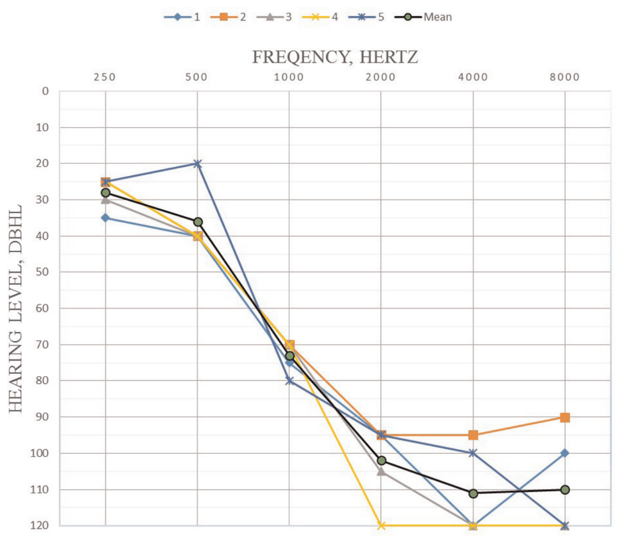
The audiometric thresholds for patients with *fe* 3000 Hz, with the black line representing the group mean.

Figure 4



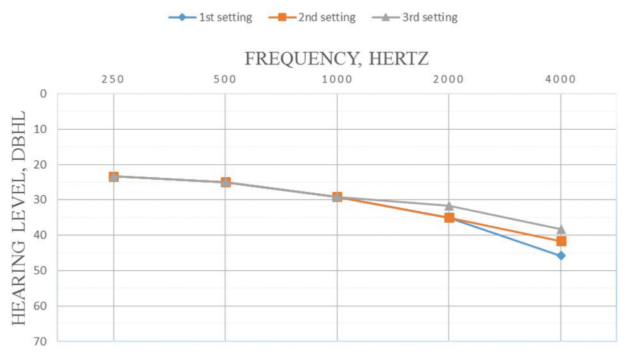
The audiometric thresholds for patients with *fe* 2000 Hz, with the black line representing the group mean.

Figure 5



The audiometric thresholds for patients with *fe* 1500 Hz, with the black line representing the group mean.

Figure 6



The group mean aided thresholds for patients with *fe* 4000 Hz at the three settings.

no response for the tested frequency of 4000 Hz in the first setting, as shown in Fig. 7.

In patients with *fe* 2000 Hz also, one case showed no response for the tested frequency of 4000 Hz in the first setting and were assigned a mean value of 120 dB HL, as shown in Fig. 8.

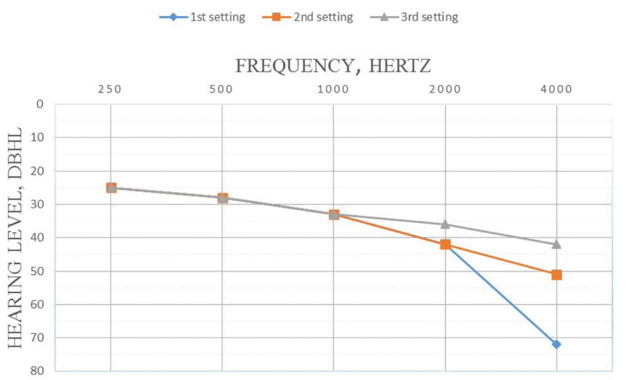
Three out of the five patients with *fe* 1500 Hz showed no response for the tested frequency of 4000 Hz in the first setting and one case showed no response for the same frequency in the second setting. These patients were assigned a mean value of 120 dB HL (Fig. 9).

Speech recognition scores

When patients were subjected to unaided speech recognition test, there was a statistically significant difference between the four studied groups as regards SWL, NSWL, and average of the two word lists ($P<0.001$, 0.002, and 0.001, respectively), with best performance for studied cases with *fe* 4000 Hz, as shown in Fig. 10.

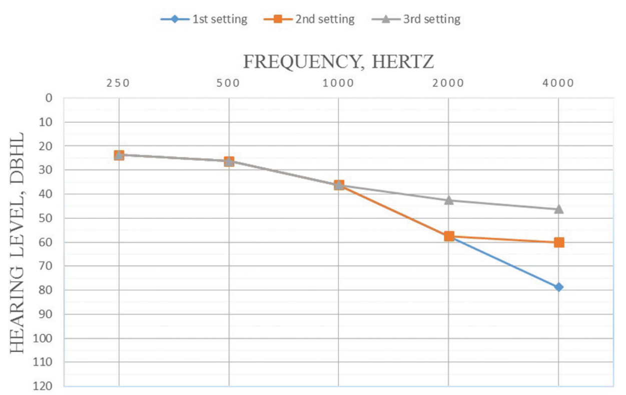
A comparison between the patients' SRS before and after amplification with H.A programmed at the three settings in each of the four studied groups according to SWL showed statistically significant differences between the three settings compared with the unaided condition, except for the first setting in patients with *fe* 1500 and 2000 Hz, as shown in Table 3 and Fig. 11. According to NSWL, there was a statistically significant difference between the different

Figure 7



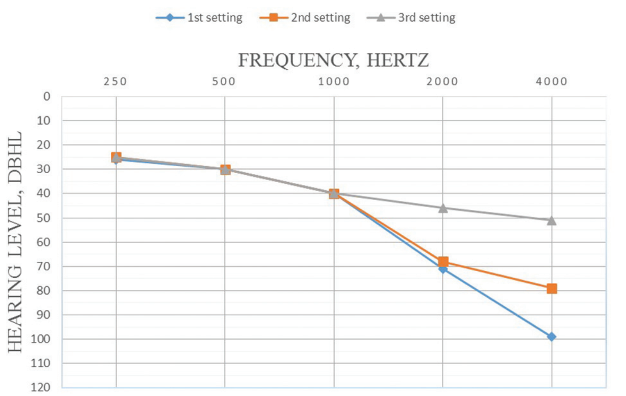
The group mean aided thresholds for patients with *fe* 3000 Hz at the three settings.

Figure 8



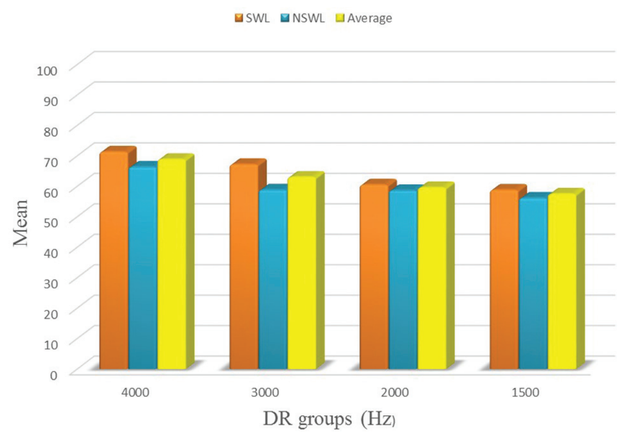
The group mean aided thresholds for patients with *fe* 2000 Hz at the three settings.

Figure 9



The group mean aided thresholds for patients with *fe* 1500 Hz at the three settings.

Figure 10



Distribution of the four groups according to unaided speech recognition. DR, dead region; NSWL (non-sensible word) list, SWL (sensible word list) and the average of the two lists.

settings and unaided condition in the four groups, except for the third setting in patients with *fe* 3000 and 4000 Hz and the first setting in patients with *fe* 1500 and 2000 Hz, as shown in Table 4 and Fig. 12.

Discussion

Patients with steep-slope hearing loss often represent a challenge when we consider them for amplification because of physical limitations of the hearing aid itself and physiological limitations if DRs are present.

At present, there are no standards for clinical management of cochlear DRs. Some investigators have specified amplification characteristics to be used with patients having DRs, but there is no agreement and different studies have arrived at contradictory recommendations. While some recommend limiting amplification to a range up to 1.7 times the *fe* of the DR [8,9], others advise the use of prescribed settings and recommend against limiting high-frequency amplification [19]. As a result of these conflicting recommendations, it remains uncertain how clinicians should direct their treatment strategies, if at all, for hearing aid patients with DRs.

The present study was conducted on patients with bilateral steep-slope hearing loss to evaluate the effect of such hearing loss configuration regarding the extent of DR on speech recognition and also to evaluate the influence of the starting frequency of DRs (*fe*) on selecting NFC parameters through studying the effect of different setting parameters on speech recognition.

The most consistent findings across the analysis of the speech performance for the studied cases are that the extent of DR has a marked impact on patients' speech recognition and identifying its *fe* is important for the selection of NFC cutoff frequency.

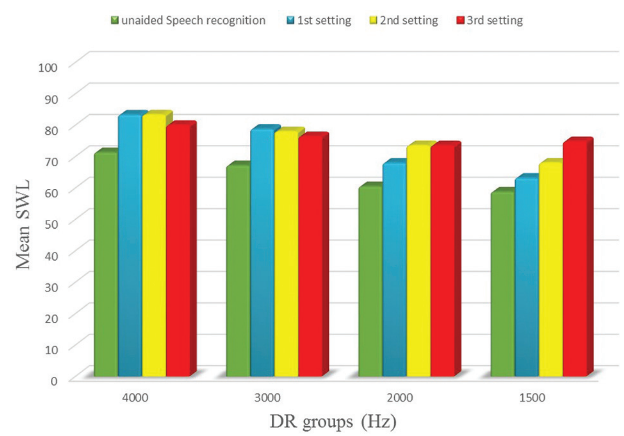
The TEN test was used for diagnosing DR(s) in the cochlea and identifying its *fe*. The newer version TEN

Table 3 Comparison between the different cutoffs in each group according to sensible word list

Dead region groups according to edge frequency (Hz)	Sensible word list				F	P
	Unaided speech recognition	First setting	Second setting	Third setting		
4000 Hz						
Minimum–maximum	68.0–74.0	78.0–86.0	78.0–86.0	76.0–84.0	76.053*	<0.001*
Mean±SD	71.33±2.42	83.33±3.01	83.33±2.73	80.0±2.83		
Median	71.0	84.0	84.0	80.0		
$P_{cont.}$		<0.001*	<0.001*	0.001*		
Significance between groups		P_1=1.000, P_2=0.327, P_3=0.183				
3000 Hz						
Minimum–maximum	60.0–74.0	72.0–82.0	70.0–82.0	66.0–82.0	23.944*	<0.001*
Mean±SD	67.20±5.93	78.80±4.15	78.0±4.69	76.40±7.80		
Median	70.0	80.0	80.0	82.0		
$P_{cont.}$		0.012*	0.016*	0.009*		
Significance between groups		P_1=1.000, P_2=1.000, P_3=1.000				
2000 Hz						
Minimum–maximum	60.0–62.0	66.0–72.0	72.0–76.0	72.0–76.0	51.971*	<0.001*
Mean±SD	60.50±1.0	68.0+2.83	73.50±1.91	73.50±1.91		
Median	60.0	67.0	73.0	73.0		
$P_{cont.}$		0.131	0.013*	0.013*		
Significance between groups		P_1=0.010*, P_2=0.133, P_3=1.000				
1500 Hz						
Minimum–maximum	52.0–62.0	58.0–68.0	64.0–72.0	68.0–80.0	35.596*	<0.001*
Mean±SD	58.80±4.15	63.20±4.60	68.0±3.74	74.80±4.82		
Median	60.0	62.0	70.0	76.0		
$P_{cont.}$		0.065	0.021*	0.013*		
Significance between groups		P_1=0.196, P_2=0.033*, P_3=0.006*				

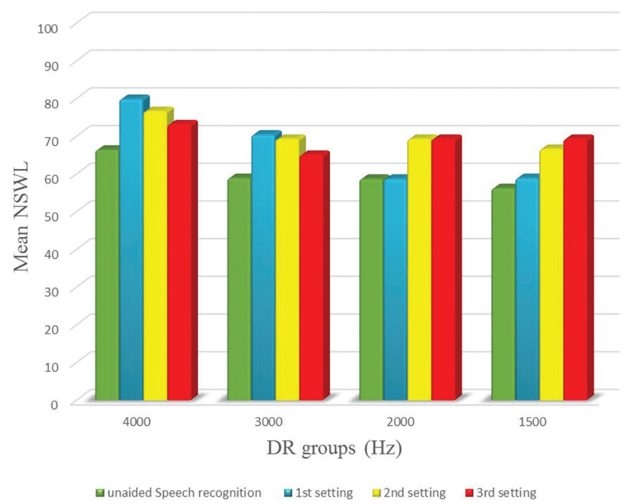
F, *F*-test (analysis of variance) with repeated measures and significance between groups using post-hoc test (adjusted Bonferroni). P_{cont}: *P* value for comparing between group control and each other group. P_1: *P* value for comparing between 3 and 2.2 KHz. P_2: *P* value for comparing between 3 and 1.5 KHz. P_3: *P* value for comparing between 2.2 and 1.5 KHz. *$P \leq 0.05$, statistically significant.

Figure 11



Distribution of the four DR groups presented by *fe* according to mean SWL at the three settings.

Figure 12



Distribution of the four DR groups presented by *fe* according to mean NSWL at the three settings.

(HL) was used instead of the older version TEN (SPL) to save time as the thresholds (unmasked and masked) were measured only once in dB HL.

Although it is not a rule, the presence of a steeply sloping high-frequency hearing loss is often associated with high-frequency DRs, as reported by Moore [5].

Mean audiograms of the tested ears showed that the presence of DR could be predicted when the absolute threshold for tested frequency exceeded 70 dB HL. This trend has been reported by Vinay and Moore [20] in a previous study when they were studying the prevalence of DRs in patients with sensory–neural

Table 4 Comparison between the different cutoffs in each group according to nonsensible word list

Dead region groups according to edge frequency (Hz)	Nonsensible word list				F	P
	Unaided speech recognition	First setting	Second setting	Third setting		
4000 Hz						
Minimum–maximum	63.46–69.23	78.85–80.77	65.38–82.69	61.54–76.92	19.474*	<0.001*
Mean±SD	66.35±2.02	79.81±0.05	76.60±5.89	73.08±6.08		
Median	66.35	79.81	77.88	75.96		
$P_{cont.}$		<0.001*	0.015*	0.141		
Significance between groups		P_1=1.000, P_2=0.233, P_3=0.349				
3000 Hz						
Minimum–maximum	50.0–67.31	61.54–84.62	59.62–78.85	53.85–82.69	13.319*	<0.001*
Mean±SD	58.85±6.74	70.38±9.18	69.23±8.27	65.0±11.81		
Median	57.69	69.23	65.38	59.62		
$P_{cont.}$		0.023*	0.003*	0.466		
Significance between groups		P_1=1.000, P_2=0.394, P_3=0.650				
2000 Hz						
Minimum–maximum	57.69–59.62	53.85–63.46	67.31–73.08	67.31–71.15	16.133*	0.001*
Mean±SD	58.65±1.11	58.65±4.58	69.23±2.72	69.23±1.57		
Median	58.65	58.65	68.27	69.23		
$P_{cont.}$		1.000	0.047*	0.002*		
Significance between groups		P_1=0.291, P_2=0.152, P_3=1.000				
1500 Hz						
Minimum–maximum	53.85–59.62	51.92–65.38	61.54–69.23	65.38–71.15	18.635*	<0.001*
Mean±SD	56.15±2.51	58.85±6.32	66.54±3.22	69.23±2.36		
Median	55.77	57.69	67.31	69.23		
$P_{cont.}$		1.000	0.008*	0.002*		
Significance between groups		P_1=0.113, P_2=0.083, P_3=0.310				

F, F-test (analysis of variance) with repeated measures and significance between groups using post-hoc test (adjusted Bonferroni). $P_{cont.}$: P value for comparison between controls and other groups. P_1: P value for comparing between 3 and 2.2 KHz. P_2: P value for comparing between 3and 1.5 KHz. P_3: P value for comparing between 2.2 and 1.5 KHz. *$P \leq 0.05$, statistically significant.

hearing loss, although DRs have been observed in individuals with better hearing thresholds when diagnosed using psychophysical tuning curves (e.g. Moore *et al.* [21]).

Regarding the effect of the extent of DRs on the total performance of patients with DRs on modified Arabic consonant discrimination lists (SWL and NSWL) represented as percent correct, the total average score of patients with DR at 4000 Hz only was 68.67%, that of patients with DRs extending from 3000 Hz and above was 63.85%, that of patients with DR extending from 2000 Hz and above was 59.81%, and that of patients with DR extending from 1500 Hz and above was 57.85%. The difference between the four groups was significant, with tendency to be worse with more extension of the DR as the *fe* reduces. This agrees with the results of El Ghazaly *et al.* [18], where patients with contiguous DRs in two to three frequency regions obtained less benefit from high frequencies, on average, than did patients with isolated DRs.

The degradation of the total performance while DRs become more extensive in steep-slope hearing loss configuration can be ascribed to the off-frequency phenomenon where speech information falling in a DR will be perceived by a lower-frequency region leading to misinterpretation of speech information. As speech is a broadband signal containing components that cover a wide frequency range, this might lead to some form of 'information overload' in low-frequency channels, impairing processing in these channels also.

After amplification with NFC, verification was done by obtaining audiometric aided thresholds for frequencies of 500, 1000, 2000, and 4000 Hz thresholds at the three different settings. The three settings were different only in cutoff frequency while cochlea region (CR) fixed nearly around 2 : 1 to facilitate comparison between the four selected groups.

Each of the four groups showed improvement in the aided thresholds compared with the unaided thresholds, mainly at 4000 Hz. The improvement was maximum in the third setting where cutoff frequency was 1500 Hz, as higher frequencies were lowered to healthier CRs. This improvement in aided thresholds agreed with the technique adopted by Glista *et al.*[14], Wolfe *et al.* [12], and Hazzaa *et al.* [22], who showed significant improvement in aided thresholds at 4000, 6000, and 8000 Hz in children with moderate SNHL using NFC.

Five of the studied cases gave no response in aided thresholds at 4000 Hz after programming for the first setting and/or second setting. This could be explained by referring to their audiograms where after compression using intended cutoff frequency and prescribed CR, 4000 Hz lowered to a CR where still no response or dead.

Analysis of variance was used for comparison of SRS in unaided condition and after fitting with the three NFC-prescribed settings.

In the studied cases with *fe* 4000 and 3000 Hz, patients showed the best performance when H.A was programmed on the first setting with the highest cutoff frequency (3000 Hz) with statistically significant difference in word recognition scores (WRS) compared with the unaided condition, and performance decreased with lowering of the cutoff frequency to 2200 Hz on the second setting and then to 1500 Hz on the third setting.

In patients with *fe* 2000 Hz, the highest WRS was obtained with H.A programmed on the second setting, with almost no change in the third setting.

In patients with *fe* 1500 Hz who had the most extensive DR among the studied cases, patients' WRS improved with a lowering of the *fe*, with the best score obtained with H.A programmed on the third setting.

Thus, in the present study patients with less-extensive DRs, excessive lowering led to degradation of speech performance, as seen in group 1 with *fe* 4000 Hz. Also, when H.A was programmed on the third setting, there was no statistically significant difference in WRS using NSWL compared with the unaided condition in this group.

This agrees with the findings of Souza and colleagues, who found that moderate amounts of compression, particularly with high cutoff frequencies, had minimal effects on intelligibility. Patients with the greatest high-frequency hearing loss showed the greatest benefit. Sentence intelligibility decreased with more compression. Listeners were more affected by a given set of parameters in noise. In quiet conditions, any amount of compression resulted in lower speech quality for most listeners, with the greatest degradation for listeners with better high-frequency hearing [23].

On the other hand, the third setting was beneficial for patients with more extensive DR as in patients with *fe* 1500 Hz who performed well with excessive lowering.

This agrees with the findings that suggest that the presence of high-frequency cochlear DRs may be associated with an increased ability to use low-frequency information [24,25].

Vestergaard measured the intelligibility of speech low-pass filtered at a number of cutoff frequencies for patients with high-frequency DRs with *fe* in the range of 750–1500 Hz, and with *fe* above 3000 Hz. For speech that was low-pass filtered at 1000 Hz, patients with *fe* in the range of 750–1500 Hz performed, on average, 10% better than patients with *fe* above 3000 Hz. This indicates that patients with low values of *fe* were able to make more effective use of low-frequency speech information than were patients with high values of *fe* [24].

Moore and Vinay [25] suggested that the presence of high-frequency cochlear DRs may lead to cortical reorganization and result in over-representation of low-frequency sounds, potentially enhancing the utility of low-frequency speech.

Our finding also agreed with that of Hornsby and colleagues, who studied different audiometric configurations and concluded that individuals with steeply sloping losses may make better use of information in severely low-pass filtered speech than may individuals with moderate-sloping or flat hearing losses. The reason for this differential benefit from low-frequency speech information is not clear. There is limited research suggesting that listening experience may affect the ability to make use of low-pass filtered speech information [26].

Alexander [27] concluded in his study on the influence of cutoff frequency and input bandwidth on consonant and vowel recognition that the use of a cutoff frequency less than 2200 Hz may degrade speech understanding, especially when combined with a high CR. This disagrees with our study as patients with *fe* 3000 and 4000 Hz improved with cutoff frequency 1500 Hz. This difference may be related to three reasons: the moderate CR (2 : 1) implemented in our study; the fact that he did not mention whether any of his studied cases were diagnosed with DR(s); and the vowel stimuli that he included in his speech materials.

Modified Arabic discrimination lists SWL and NSWL used for the speech recognition task in our study proved to be sensitive in identifying the impact of the extent of DR on speech recognition, as well as in evaluating NFC parameters, which showed improvement in performance compared with unaided conditions. However, McCreery *et al.* [28] suggested that the improvements observed with monosyllabic words containing one consonant in the initial or final position with NFC may overestimate the magnitude of improvements and recommended generalizability of the model of audibility to more realistic contexts.

Conclusion

(1) Modified Arabic consonant discrimination lists are sensitive in identifying the impact of the extent of a DR in terms of its fe on speech recognition in patients with steep-slope HL.
(2) The use of NFC technology in patients with steep-slope HL diagnosed with DRs proved to be applicable and effective.
(3) Identifying fe is important while selecting the cutoff frequency for NFC especially in those patients with steep-slope configuration, as more benefit is obtained while adjusting the cutoff frequency close to the fe.
(4) Patients with lower fe had more benefit from lowering the cutoff frequency provided a moderate amount of compression (CR) is selected.
(5) Selecting cutoff frequency below fe leads to degradation of speech performance.

Recommendations

(1) It is recommended to use larger sampling for different distributions of DRs to study acoustic and psychoacoustic performance using NFC amplification.
(2) It is also recommended to evaluate the effect of different cutoff frequencies of NFC on speech recognition in more realistic contexts.

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Conflicts of interest
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