Comparison of three different frequency-lowering technologies in Arabic speaking hearing loss children

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Introduction
Frequency-lowering is the generic term that refers to current technologies that take high-frequency input signals, typically considered speech sounds, and deliver them to a lower frequency region for improved speech understanding. Manufacturers of hearing aids (HAs) introduced frequency-lowering techniques to compensate in part for the perceptual effects of high-frequency hearing impairments, which include linear frequency transposition scheme, nonlinear frequency compression, and spectral IQ.

Objectives
To find which of the three frequency-lowering technologies is more beneficial in amplifying high-frequency sounds in children with high-frequency hearing. We also aimed to find which technology gives the best aided Arabic speech score in our Egyptian children patients.

Patients and methods
A total of 10 children with moderately severe to profound high-frequency sensory neural hearing loss using conventional methods of amplification were included. Aided threshold and word discrimination score were done four times using conventional HA once and other three trails using HAs with different frequency-lowering technology.

Results
Significant differences were found between conventional amplification and the three frequency-lowering technologies, where the spectral IQ was considered the best regarding functional gain and speech discrimination abilities.

Conclusion
Spectral IQ is better for children as a fitting strategy, giving more gain in the high frequencies and better speech identification.

Introduction and rationale

Frequencies above 3 kHz contribute ~25% of the audible speech cues required for recognition of spoken language [1]. The highest frequency speech fricative /s/ is one of the most common consonant sounds in the English language. The peak energy of /s/ when spoken by a child or female talker will fall between 6300 and 8300 Hz [2]. Restoration of audibility for individuals with severe or profound high-frequency hearing loss is often constrained by limited hearing aid (HA) bandwidth, feedback oscillation, and poorly prescribed gains. Besides, even when audibility of high-frequency speech sounds can be restored, some patients with severe to profound hearing loss may not benefit from amplification and may reject the amplified sound quality. These outcomes are attributed to dead regions, within the portions of the cochlea [3]. In a dead region, the effective result of listening to amplified speech within the frequencies of dead regions has been described as 'information overload'.

This information overload is thought to be perceived as distorted by the hearing impaired patient [4].

Frequency lowering is the generic term used to refer to current technologies that take high-frequency input signals, typically considered to be speech sounds, and deliver these sounds to a lower frequency region for improved speech understanding [5,6]. The perceptual benefits potentially include improved ability to resolve and discriminate between sounds, as well as to detect them [7].

Different methods for accomplishing this manipulation are present, namely frequency transposition [5] and frequency compression [6]. These methods are

incorporated in two HAs by major HA manufacturers. The Widex linear frequency transposition (LFT) scheme functions by shifting components of sounds which are present within a source octave into a predetermined target octave [7], and the Phonak nonlinear frequency compression (NLFC) scheme in which high-frequency information is moved to lower frequencies by compressing the energy in high-frequency HA channels into a narrower frequency range. The highest frequencies are shifted and compressed to the greatest extent, whereas lower frequency information is shifted to a progressively lesser extent. The processing has two adjustable parameters: the cutoff frequency and the frequency compression ratio [6].

On the contrary, spectral IQ uses a technique called spectral feature identification to monitor acoustic input to the HA. Spectral feature identification identifies and classifies acoustic features of high-frequency sounds. Once appropriate high-frequency features are detected, spectral IQ uses a sophisticated processing technique to replicate (or translate) those high-frequency features at a lower, audible frequency [8].

The importance of high-frequency amplification task becomes even more apparent when considering the development of speech and language skills in the hearing-impaired pediatric population. Researchers suggest that children require audibility of a broad bandwidth of speech for optimal access to high-frequency speech cues and that hearing loss can impede normal development of affricate and fricative production [9].

In our study, we tried to find which of the three frequency-lowering technologies were more beneficial in amplifying high-frequency sounds of children with high-frequency hearing. We also aimed to find which technology gives the best aided Arabic speech score in our Egyptian children patients.

Patients and methods
Patients

(1) Twenty children (40 ears) (eight females and 12 males), with an age range of 7.5–10 years and mean age of 8.2±1.7 years with moderately severe to profound high-frequency sensory neural hearing loss were include in the study (Fig. 1). Notice that patients were tested four times, that is, they are one group of 20 ears was tested as four groups).

Figure 1
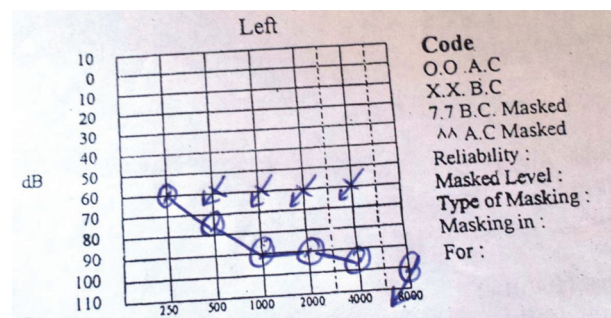
Showing pure tone audiometry of one case with moderately severe to profound sloping sensorineural hearing loss.

(2) All children were using bilateral fully digital HAs with conventional amplification as early childhood for 4.5–6 years (5.1±0.3) with regular speech therapy started after the start of HA use.
(3) Good language command was necessary for a child to be included in the study.
(4) Children with multiple disabilities, children with poor intellectual functions (low IQ), and children with poor language development were excluded from the study.

Methods
All children were subjected to the following:

(1) History taking.
(2) Otoscopic examination.
(3) Pure tone audiometry using audiometer Orbiter 922 (Madsen LTD, Otometric, Hungary) via headphone TDH 39.
(4) Stanford Bient intelligence scale version V.
(5) Speech reception threshold using Arabic Bisyllabic Words for children [10].
(6) Speech discrimination scores using Arabic Phonetically Balanced Words for children (PB-KG) [10]. Four lists were used, one for each pair of HAs to avoid learning effect. All lists are standardized with equal difficulty.
(7) Words were considered right if correctly discriminated, and subsequently pronounced completely known speech defects were considered right (e.g. if child utter /g/ as /d/ so words containing /g/ was considered right, even if /g/ was replaced by /d/, as the child is not able to correctly utter the phoneme even he can hear it well).
(8) HAs used were programmed to suit the audiogram of each patient based on the default settings of the fitting software.

(9) Verification of HA amplification was done using the following:
  (a) Maximum peak output (MPO): it was determined for each pair of HA with the frequency lowering disabled.
  (b) Listening check was performed before finishing the fitting process with frequency lowering. If subjective feedback indicates difficulty with speech sound distinctions (especially /s/ and /ʃ/), fine tuning was continued until good differentiation between these phonemes is attained. Comfortable live voice of the examiner was used which was kept as constant, when examining each pair of HAs, as possible.
(10) Aided audiometry and aided speech reception threshold and discrimination (SD) scores were done four times with three different HA pairs. The first with their original binaural HAs, and then using three different pairs of HAs [Widex Menu with frequency extender (Denmark), Phonak Naida Q30 (Phonal Sonova, Switzerland) with sound recover, and Starkey X series 70 (Starkey Hearing Technologies' Companies, US) with spectral IQ] (Fig. 2).
(11) All HAs were programmed to match as closely as possible the gain and amplitude-compression characteristics recommended for each audiogram by the DSL i/o prescription. In addition, signal-processing features such as feedback cancelation, noise reduction, and occlusion compensation were disabled, and an omni-directional microphone configuration was selected.
(12) For all types of HAs, children were permitted to use the new pair of HA for a continuous period of 3 h (a period of acclimatization to the new sound generated by the new technology), and each pair is tried in a separate session in random order to use HA pairs in different order in different children.
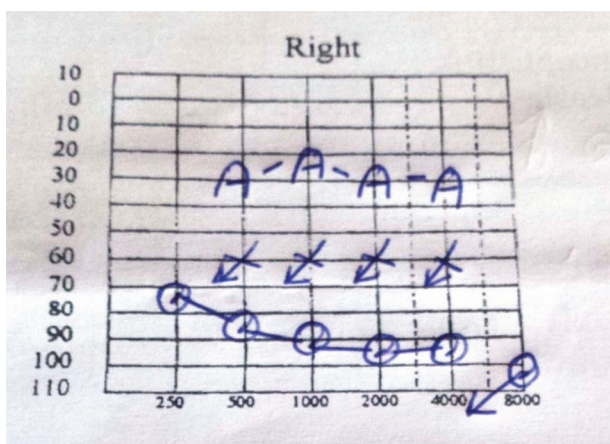(13) Here, we are not testing the benefits of the HA as much we examine HA different performance so a period of acclimatization is enough especially in children with rapid brain reorganization.
(14) During wearing HAs, children were permitted to attend a phonetic secession for 1 h and two other hours of ordinary life conversation with their parents. Then comparison was made between the three pairs and between them and their own HAs.
(15) For the possibility of the presence of dead region, comparison was done within the same patient. So, if a dead region is present, its effect is the same for the four comparisons. This occurs either when testing the patient with his/her own HA or when testing the same patient with each pair of HAs.

Statistical analysis

t-Test, one-way analysis of variance, and pairwise comparison using Tukey honest significant difference test were used. Original HAs results were listed as 'group 1', frequency extender (LFT) results were listed as 'group 2', sound recover HAs (NLFC) results were listed as 'group 3', and finally, spectral IQ results were listed as group 4.

All children and their parents were thoroughly counseled about the procedure, stating the values, the hazards, and the aim of the study. A written consent was obtained and signed by each participant.

Results

Average age of children submitted in this study was 6–9 (7.3±1.2) years, and the average duration of HAs usage experience was 4–6.3 years (5.2±1.1).

They were 12 male and eight female.

In the current study, audiometric results of the study group patients were plotted in Table 1 that shows moderately severe to profound sensorineural hearing loss. Comparison between aided threshold using conventional HA and LFT HA demonstrates a significant difference between aided thresholds in the high frequencies (Table 2).

Comparison between aided threshold using conventional HA and NLFC HA demonstrates a

Figure 2

Showing audiogram of one patient with severe sensorineural hearing loss and aided response using pair of linear frequency transposition hearing aids.

significant difference between aided thresholds in the high frequencies (Table 3). Comparison between aided threshold using conventional HA and spectral IQ HA demonstrates a significant difference between aided thresholds in all aided thresholds except at 500 Hz (Table 4).

Table 5 showed the comparison between the three different frequency-lowering techniques; significant differences were found at all frequencies except 500 Hz.

Once we had determined that differences exist among the means, pairwise comparisons by Tukey honest significant difference were done to determine which means differ and yield a matrix. Significant difference was found between LFT and NLFC and between spectral IQ and both LFT and NLFC. Only nonsignificant difference was found between LFT and NLFC when testing at 4000 Hz (Table 6).

Significant difference was found among all groups regarding aided speech discrimination scores (Table 7). On the contrary, only significant differences were found between spectral IQ and NLFC and LFT whereas nonsignificant difference was found between LFT and NLFC (Table 8).

Table 1 Pure tone audiometry average in the study group

Frequency	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Mean	65.3	79.52	89.4	98.48	100.56	NH
SD	10.1	8.2	5.3	10.2	10.56	–

NH, not heard.

Table 2 Aided free field threshold using conventional hearing aids and linear frequency transposition

Frequency (Hz)	Conventional HA	LFT HA	t	P
500	25.34±7.312	25.2±12.3	0.0639	0.9497
1000	31.43±6.242	30.32±4.234	0.9546	0.3518
2000	40.3±7.6	25.3±3.254	12.4226	<0.0001*
4000	52.3±10.3	29.75±4.4352	13.7206	<0.0001*

HA, hearing aid; LFT, linear frequency transposition. *Significant.

Table 3 Aided free field threshold using conventional hearing aids and nonlinear frequency compression

Frequency (Hz)	Conventional HA	NLFC HA	t	P
500	25.34±7.312	20±10.1	2.745	0.0129*
1000	31.43±6.242	25.32±6.3234	4.372	0.0003*
2000	40.3±7.6	29.3±4.5314	8.1989	<0.0001*
4000	52.3±10.3	33.3±3.3541	12.4957	<0.0001*

HA, hearing aid; NLFC, nonlinear frequency compression. *Significant.

Table 4 Aided pure tone audiometry using conventional hearing aids and spectral IQ

Frequency (Hz)	Conventional HA	Spectral IQ HA	t	P
500	25.34±7.312	23.63±9.1	1.2334	0.2325
1000	31.43±6.242	19.88±5.6534	8.7548	<0.0001*
2000	40.3±7.6	21.5±3.6334	15.0136	<0.0001*
4000	52.3±10.3	23.5±3.6635	18.3996	<0.0001*

HA, hearing aid. *Significant.

Table 5 Analysis of variance testing for multiple measures was used to compare the three different hearing aids aided thresholds response

Frequency (Hz)	LFT	NLFC	Spectral IQ	F	P
500	25.2±12.3	20±10.1	23.63±9.1	1.270	0.289
1000	30.32±4.234	25.32±6.3234	19.88±5.6534	18.202	0.000**
2000	25.3±3.254	29.3±4.5314	21.5±3.6334	20.594	0.000*
4000	29.75±4.4352	28.25±3.3541	23.5±3.6635	12.31	<0.0001*

LFT, linear frequency transposition; NLFC, nonlinear frequency compression. *Significant. **Highly significant.

Discussion

The inability to restore audibility of high-frequency speech was an established obstacle in hearing care until shifting of high-frequency information into lower frequency regions in which hearing loss is less severe and cochlear integrity is superior was introduced. In other words, moving high-frequency speech information to lower frequencies should improve audibility in patients with sloping high-frequency hearing loss.

In the present study, when we compared conventional amplification-aided threshold with LFT-aided threshold, significant improvements at high frequencies of 2000 and 4000 Hz with LFT HA were found. Meanwhile, statistically nonsignificant difference was found in the lower frequencies of 1000 and 500 Hz. Besides, NLFC HA showed a lower aided threshold in all tested frequencies. Lastly, comparing conventional amplification with spectral IQ revealed significantly lower threshold in frequencies above 1 kHz. Finally, in the current study, speech discrimination scores showed significant improvement with the three frequency-lowering technologies. Spectral IQ hearing showed the best response, whereas there was no difference between LFT-aided and NLFC-aided speech discrimination scores.

This good performance of Starkey HA may be related to the spectral IQ nature of action which allows HAs to maintain a comparatively broadband, undistorted

frequency distribution, while simultaneously restoring high-frequency speech audibility [8].

LFT technology demonstrates that in the LFT scheme, the contents of the source octave are analyzed periodically to identify a dominant spectral peak. The frequency of that peak is determined, and the amount of lowering is calculated so that the selected frequency is shifted down by one octave. Other frequency components in the source octave are shifted by an equal number of hertz. For example, if the peak frequency is 4 kHz, the extent of the downward shift is 2 kHz, resulting in the peak component being lowered to 2 kHz. At the same time, a source component at 5 kHz would be lowered by 2–3 kHz. Note that, in general, only the frequency of the peak is shifted by exactly one octave. Consequently, it is possible that some components in the source octave would fall outside the target octave after shifting [5,11]. This technology has improved the aided response in the high frequency but to less amount compared with the other technology.

Phonak NLFC scheme is based on different principles. The processing has two adjustable parameters: the cutoff frequency and the frequency-compression ratio. The amount of lowering is progressive, such that frequencies which are much higher than the cutoff shift by a larger amount than frequencies only slightly above the cutoff [6]. For example, the selected frequency-compression ratio of 1.7 : 1 would result in a component at 1.7 octaves above 2.3 kHz being lowered to a frequency one octave above 2.3 kHz (i.e. 4.6 kHz). The transfer function relating input to output frequencies is completely determined during fitting by selection of the aforementioned two parameters [6,7]. Signal components processed by the NLFC scheme do not overlap any other components present at the same time. Together with components below the cutoff frequency, signals that have been compressed in frequency are amplified and additionally processed

Table 6 Pairwise comparisons by Tukey honest significant difference test at 1000 and 2000, and 4000 Hz

	NLFC	Spectral IQ
LFT	$P<0.05$*	$P<0.01$*
NLFC		$P<0.01$*

Honest significant difference=4.17, 2.93, and 4.08, respectively. LFT, linear frequency transposition; NLFC, nonlinear frequency compression. *Significant.

Table 7 Aided speech discrimination test results

	LFT	NLFC	Spectral IQ	Conventional HA	F	P value
Mean (%)	62.8	63.8	70.8	54.8	14.6251	0.0000*
SD	8.443	5.287	1.932	3.795		

HA, hearing aid; LFT, linear frequency transposition; NLFC, nonlinear frequency compression. *Significant.

Table 8 Pairwise comparisons by Tukey honest significant difference test in aided speech word discrimination honest significant difference=6.61

	NLFS	Spectral IQ	Conventional
LFT	NS	$P<0.05$*	$P<0.05$*
NLFC		$P<0.05$*	$P<0.01$*
SIQ			$P<0.01$*

LFT, linear frequency transposition; NLFS, nonlinear frequency compression; SIQ, spectral IQ. *Significant.

as usual. The previous leads to improve its threshold in all tested frequency, but no significant improvements in word discrimination score when compared to LFT.

Spectral IQ uses a technique called spectral feature identification to monitor acoustic input to the HA. Spectral Feature Identification identifies and classifies acoustic features of high-frequency sounds. Once appropriate high-frequency features are detected, spectral IQ uses a sophisticated processing technique to replicate (or translate) those high-frequency features at a lower, audible frequency. This unique process goes beyond the simple lowering of acoustic input; new features are created in real time, resulting in the presentation of audible cues while minimizing the distortion that occurs with other technologies [8]. Spectral IQ preserved the configuration of audiogram from one side, preventing excess gain for low frequencies and thus prevents upward spread of masking sparing at the same time the ability for speech discrimination. The above may be the cause of better speech discrimination score.

Conclusion

We found that the three FL technologies gave better aided threshold and better aided speech discrimination score compared with conventional HA. Using Arabic word spectral IQ gives the best performance. However, we recommended further study comparing the three technologies, but after longer time of use of each one.

Conflicts of interest
There are no conflicts of interest.

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