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Frequency and intensity discrimination in children with cochlear implants

Nahed Mohamed Negm[1*], Trandil Hassan Elmahalawy[1], Enaas Ahmad Kolkaila[1] and Mona Ahmed Kotait[1]

Abstract

Background Frequency discrimination underlies more complicated auditory activities like speech comprehension and interpretation. However, intensity differences indicate how far apart noises are. This study aimed to evaluate and compare results of frequency modulation and difference limen for intensity in children with cochlear Implants (CI) as well as normal hearing children.

Results This case–control work was performed on 40 children, aged from 5–18 years, divided into two equal groups: a study group with unilateral CI and a control group with normal peripheral hearing. All patients were subjected to otological examination, audiological evaluation, frequency modulation difference limen (FMDL) and difference limen for intensity (DLI) tests. Patients with CI, as compared to normal hearing (NH) subjects, required significantly higher frequencies to discriminate FMDL and DLI respectively (P value = 0.001). At 2000 and 4000 Hz: FMDL had a significant diagnostic power for patients with CI (AUC = 0.980, 0.998 respectively, $P < 0.001$), at cut off 1.5, with 100% sensitivity and 100% specificity. While, at 4000 Hz: DLI had a significant diagnostic power for patients with CI (AUC = 0.999, $P < 0.001$), at cut off 1.5, with 100% sensitivity and 100% specificity.

Conclusion A statistically substantial variation was observed among CI and NH children in FMDL and DLI at all frequencies tested. Patients with CI required significantly higher frequencies to discriminate as compared to NH subjects. Frequencies at 2000 Hz and 4000 Hz possess the best specificity and sensitivity of FMDL. While frequency 4000 Hz possess the best specificity and sensitivity of DLI.

Keywords Pitch discrimination, Intensity, Frequency, Cochlear implants, Child

Background

A large auditory dynamic range (120 dB) is coded by cochlear implants (CI) into a small electrical dynamic range (10–30 dB) [1]. Auditory signals are observed to be compressed throughout signal processing by all readily accessible CI variants. To allow people utilizing CI to perceive a range of levels comparable to normal, several signal processing techniques are applied [2].

A basic auditory mechanism known as frequency discrimination underlies more complicated auditory activities including speech comprehension and interpretation [3]. The frequency modulation difference limen (FMDL) is commonly used for measuring it. Two frequency tones—one modulated and the other steady—are employed in this technique. It is up to the listener to judge whether the first or second tone is modified. This is dependent on the cochlear filtering that occurs [4, 5]. The place pitch mechanism plays a significant role in the CI-mediated transfer of information regarding frequency.

Whether of it is for speech or for non-speech stimuli, intensity discrimination is crucial. According to reports, people with normal hearing (NH) use intensity variations to judge the relative distance of sounds in their surroundings [6, 7]. Cochlear from retrocochlear lesions were distinguished using research investigating intensity discrimination among listeners with hearing loss [8].

*Correspondence:
Nahed Mohamed Negm
Nahedtssa_negm@hotmail.com
[1] Audio-Vestibular Medicine E.N.T. Department, Faculty of Medicine, Tanta University, Moawya Street, Tanta 31512, Egypt

Because they could be connected to modifications in the loudness growth function often seen when an impairment includes a cochlear component, alterations in intensity discrimination that precede hearing loss are of interest [9].

It has been shown that a variety of variables influence how well single electrodes respond to electrical pulse sequences that stimulate them. The rate of pulse [10], electrode arrangement [11], electrode position [12] and closeness to the modiolus are some of these variables [13].

The aim of this work was to evaluate frequency modulation difference limen and intensity difference limen in children with unilateral cochlear implants. Also, to compare results of these two tests in cochlear implant children and NH children.

Method

This case control work was performed in the period between September 2020 to June 2022 at Audio-Vestibular Medicine Unit at E.N.T Department, Faculty of Medicine, Tanta University, Tanta, Egypt, with ethical approval code number: 34080/9/20. A written consent was taken from parents of each participant in this study after explaining the tests and the objectives of the study.

Subjects

Forty children aged from 5 to18 years old were enrolled in this study. These included 20 children using unilateral CI with fully inserted electrodes of different devices (Medel, cochlear, Advanced Bionic) and aided sound field PTA threshold ≤ 35 dBHL at frequencies 500 – 4000 Hz, also with normal bilateral middle ear function. All participants had regular speech therapy for two years after CI. Control group included 20 children with Hearing threshold levels below 15 dBHL in any frequency in the ranging of 250 Hz to 8000 Hz are considered to be normal peripheral hearing. While all subjects outside the age group, with any general health problems (endocrinal, vascular, renal or neurological complaints), history of ototoxic drugs, unsatisfactory response to cochlear implant device as tested by warble tone in the free field, also, if speech discrimination score was ≤ 60% were excluded from this work.

Basic audiological testing includes pure audiometry of tone for air conduction at frequencies between 250 and 8000 Hz as well as conduction through bones at frequencies between 500 and 4000 Hz. This was done using AC40 interacoustics clinical audiometer. Speech recognition threshold (SRT) was done utilizing Arabic bisyllablic words appropriate to the subject's age and word recognition score (WRS) test utilizing Arabic phonetically balanced words appropriate to the subject's age. Also, Immittancemetry was used to measure the pressure of the middle ear with pressures that varied between + 200 to -400 mm H2O. Then, using the Interacoustics AT235h devices, ipsilateral auditory reflex threshold assessments were performed at pure frequencies of 500, 1000, 2000, and 4000 Hz.

For the study group, Basic audiological evaluation included aided-sound field threshold at octave frequencies from 500 to 4000HZ were measured with warble tone stimuli and averaged with the loudspeaker at zero azimuth to obtain the mean- aided sound field threshold, aided SRT using Arabic bisyllablic words appropriate to the subject's age with CI, aided (WRS) test using Arabic phonetically balanced words appropriate to the subject's age.

FMDL intended to establish the smallest change in frequency modulation that can be recognized. Modulation of pure tones was done by AC40 audiometer. In the study group, patients were seated at zero azimuth in front of a loud- speaker at a distance of approximately 1 m. In the control group, patients were seated at zero azimuth in front of a loud- speaker at a distance of approximately 1 m in FMDL and DLI tests. Instructions were provided as follows: you are going to hear two tons of different pitch; you should respond verbally until you hear one tone only. The signals were delivered in the free field at 40dBSL or the most comfortable level for sensitive patients.

FMDL was measured at 500Hz, 1000Hz, 2000Hz, 4000Hz. The frequency modulation was familiarized at a rate of 5% until 100% criteria of consistent responses was attained. The test process continued with the participant listening to a series of two tones that varied in modulation (5, 3, 2, 1, 0.8, 0.6, 0.4, 0.2, and 0%). The participant was asked to respond with "yes" whether they could audibly distinguish among modulated and unmodulated tones. Modulation was changed in an adaptive way, meaning that it was raised after one (no) answer and dropped after three (yes) replies. It is calculated how much modulation (also known as modulation depth) is needed to obtain a criteria response, such as 75% accuracy. In order to score, the FMDL was translated from a percentage of the main signal to a frequency variation in Hz [3].

The difference limen for intensity (DLI) was designed to determine the least discernible modulation shift. It was said that you would hear two tones with varying intensities and that you should answer vocally until you only heard one tone. The signals were broadcast in the open space at 30dBSL (rSRT), which is the level that sensitive patients find most comfortable. At 500Hz, 1000Hz, 2000Hz, and 4000Hz, DLI was detected. Starting with a heavily modulated tone until 100% criteria of consistent responses was attained, for example, familiarization to detect the extent of modulation was performed at 5%.

Following that, the test process included the participant listening to a series of two tones: an unmodulated tone and a tone with changing modulation (5, 3, 2, 1, 0.8, 0.6, 0.4, 0.2, and 0%). The participant was asked to respond with "yes" whether they could audibly distinguish among modulated and unmodulated tones. Modulation was changed in an adaptive way, meaning that it was raised after one (no) answer and dropped after three (yes) replies. It was calculated how much modulation was needed to get a criteria response, such as 75% accuracy. DLI was calculated as a percentage compared to the main signal, and the intensity variation was then converted to dB for scoring [14].

Statistical analysis

The IBM® SPSS statistical program, version 21 (IBM Inc., Chicago, IL, USA) was used to analyse the information. The one-sample Kolmogorov—Smirnov test was used to check the normality of data and data were nonparametric. Numerical data were non-parametric and so, median was presented, given that the data were nonparametric, the Mann–Whitney test was utilized to compare the various groups. Frequency and percentages (%) were used to illustrate qualitative parameters. Receiver operating characteristic (ROC) curve analysis was done to detect the sensitivity and specificity of the studied marker. Significant results were defined as two tailed P values < 0.05.

Results

Comparing the results of FMDL between CI cases and healthy children revealed that patients with CI required higher frequency modulations to discriminate (P value = 0.001) (Table 1).

Comparing the DLI test results between CI cases and healthy children revealed that patients with CI required higher intensity modulations to discriminate (P value = 0.001) (Table 2).

At 500Hz, FMDL test would significantly discriminate patients with CI (The area under (a ROC) curve (AUC) = 0.916, P value < 0.001), at cut off 0.90, with sensitivity of 95% and specificity 75%. At 1000Hz, FMDL% would significantly discriminate patients with CI (AUC = 0.979, P value < 0.001), at cut off 1.5, with sensitivity of 95% and specificity 100%. At 2000 and 4000 Hz, FMDL has a better diagnostic power for patients with CI (AUC = 0.980, 0.998 respectively, P < 0.001), at cut off 1.5, with specificity 100% and sensitivity of 100% (Fig. 1).

Table 1 FMDL (%) among children with CI and the group of controls (n = 40)

FMDL (%)		Study group (n = 20)	Control group (n = 20)	P value
500Hz	Median	2.0	0.80	0.001*
1000Hz	Median	2.5	0.80	0.001*
2000Hz	Median	3.0	0.60	0.001*
4000Hz	Median	3.0	0.60	0.001*

Data are presented as median

FMDL Frequency modulation detection threshold

* Significant as P value < 0.05

Table 2 DLI percentage between the group under the study and control group (n = 40)

DLI (%)		Study group (n = 20)	Control group (n = 20)	p value
500Hz	Median	2.5	0.80	0.001*
1000Hz	Median	3.0	0.80	0.001*
2000Hz	Median	3.0	0.60	0.001*
4000Hz	Median	3.5	0.60	0.001 *

Data are presented as median

DLI Difference limen for intensity

* Significant as P value < 0.05

At 500Hz, DLI test results would significantly discriminate patients with CI (AUC = 0.960, P value < 0.001), at cut off 0.90, with sensitivity of 95% and specificity 75%. At 1000Hz, DLI can significantly discriminate patients with CI (AUC = 0.995, P value < 0.001), at cut off 1.5, with sensitivity of 95% and specificity 100%. At 2000Hz, DLI can significantly discriminate patients with CI (AUC = 0.990, P value < 0.001), at cut off 1.5, with sensitivity of 95% and specificity 95%. At 4000 Hz, DLI has a good diagnostic power for patients with CI (AUC = 0.999, P < 0.001), At cut off 1.5, with sensitivity of 100% and specificity 100% (Fig. 2).

Discussion

Speech perception requires frequency discrimination, particularly under difficult listening circumstances. Additionally, for the recognition and localisation of auditory impulses as well as for the enjoyment of music [15]. Additionally, it's important to perceive differences in intensity. According to reports, NH people use intensity variations to judge the relative distance of sounds in their surroundings [16].

The findings of the current work revealed that, FMDL in NH subjects was smaller than that of the study group as shown in Table 1. Comparing the results of both groups revealed a statistically significant difference at all frequencies tested. Results revealed that patients with CI required higher frequency modulation to discriminate (P value = 0.001).

The findings of the work research are supported by the results of Kopelovich et al. [17]. These researchers

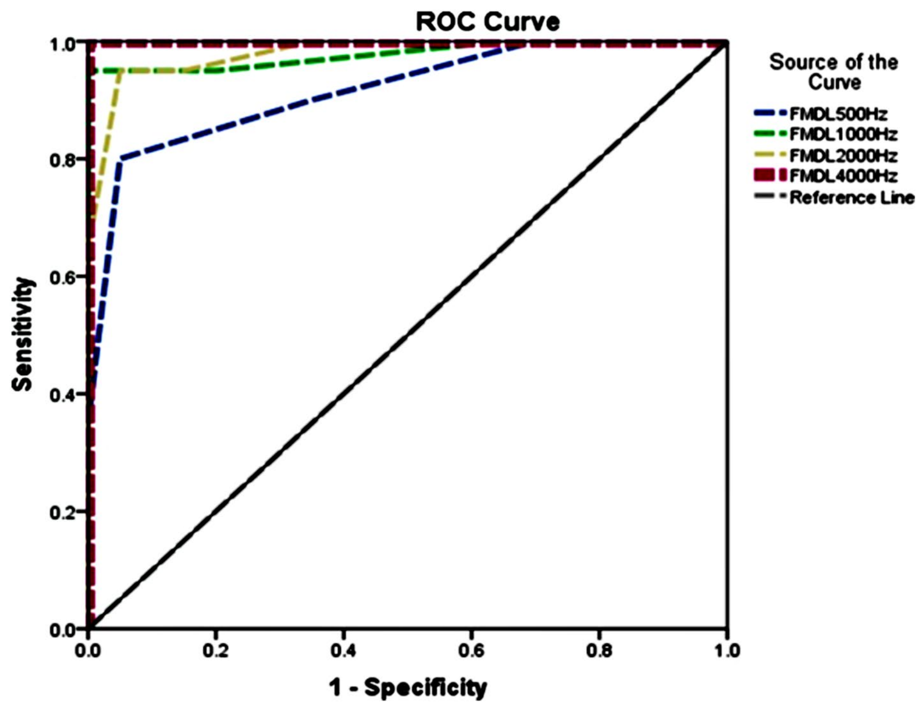

Fig. 1 ROC curve of sensitivity and specificity of FMDL (%) between children with CI and the control group

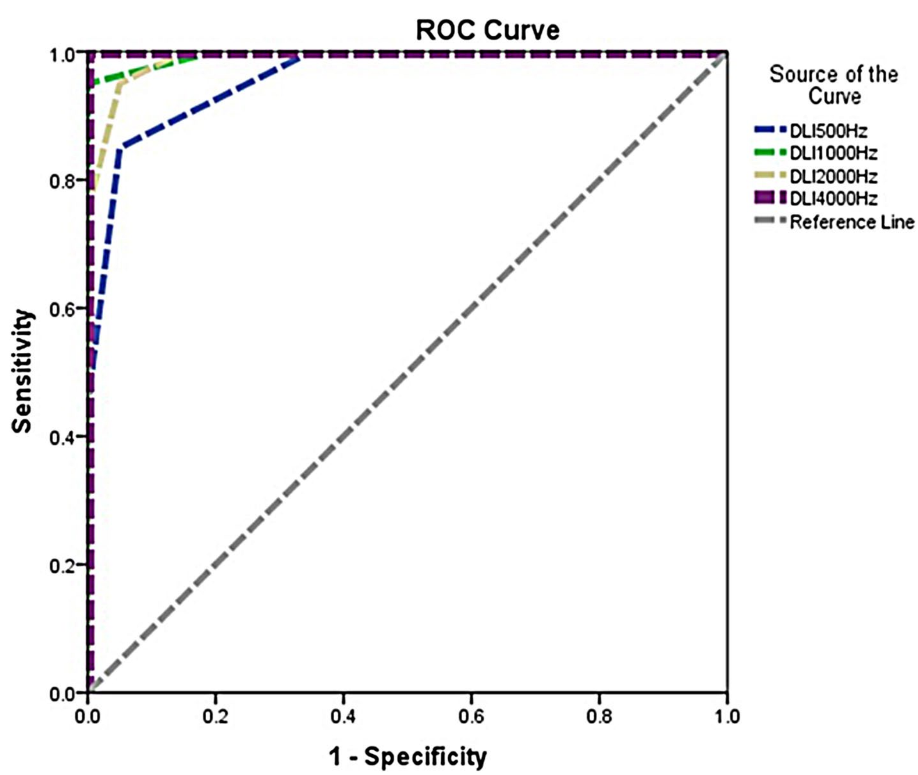

Fig. 2 ROC curve of sensitivity and specificity of DLI (%) between children with CI and the control group

reported that comparing results of NH to that of CI frequency discrimination, showed better results in NH ($p=0.0007$). Kopelovich et al., [17] also reported that CI children had larger frequency difference limen than normal-hearing children. This might be attributed to a signal's resolution when processed by a small number of electrodes as opposed to a significant number of sensory cells.

In the present study, DLI in NH subjects was smaller than that of the study group as shown in Table 2. Comparing the results of both groups revealed a statistically significant difference at all frequencies. CI as patients required higher intensity modulation to discriminate than NH children (P value = 0.001).

The findings of the current work agreed with the results of Tak and Yathiraj [18]. They reported that the significant difference between CI and NH children could only be observed for certain vowels and warble-tone frequencies. However, Tak and Yathiraj [18] reported that Particularly at the maximum measured frequency (4000 Hz) were children utilizing CI perform considerably worse than children receiving NH. At 500 Hz or 1000 Hz, this variation was not present. This finding showed that children utilizing CI require a bigger intensity variation at greater frequencies to sense a change in loudness than children who were normally developing.

The present study's implanted children were all hearing aid users for a minimum of 6 months prior to the CI. They would have been subjected to mid- to low-frequency sounds, which they could hear with hearing aids. It is likely that this prolonged exposure to mid- to low-frequency ranges improved the perception of intensity variations there compared to higher frequency ranges. Once they had used their CI, those involved would've just been subjected to greater frequencies. (Tak and Yathiraj et al. [18]). The authors may have employed a stronger pedestal tone than the one used in the current experiment, but they did not specify its intensity.

Up to the knowledge of the authors of the current study, no other researchers determined diagnostic power analysis of FMDL and DLI among children using CI at different frequencies. In the present study, sensitivity and specificity of FMDL was done at frequencies 500Hz- 4000 Hz as shown in Fig. 1. At 2000 and 4000 Hz: FMDL has the best diagnostic power for patients with CI (AUC = 0.980, 0.998 respectively, $P<0.001$), At cut off 1.5, FMDL has 100% sensitivity and 100% specificity.

In the present study, DLI has the best diagnostic power for patients with CI at 4000 Hz (AUC = 0.999, $P<0.001$), at cut off 1.5, with sensitivity of 100% and specificity 100%. In the same context Tak and Yathiraj [18] reported that 4000 Hz was the most sensitive and specific frequency at which children using CI performed significantly poorer than typically developing children.

Finally, results of this study showed that CI individuals needed more modulation difference than those with normal hearing for both frequencies and intensity discrimination. Accordingly, frequency and intensity discrimination are important in CI children for developing normal language. They also would help in prediction of language outcome in CI children.

Conclusions

Subjects with CI required greater modulation difference than NH subjects for both frequency discrimination and intensity discrimination. Consequently, both FMDL and DLI are larger in subjects with CI than NH subjects. Frequencies of 2000 and 4000 Hz have the best sensitivity and specificity of FMDL (AUC = 0.980, 0.998 respectively, $P<0.001$). Frequency 4000 Hz has the best sensitivity and specificity of DLI (AUC = 0.960, P value < 0.001).

Abbreviations

CI	Cochlear implants
FMDL	Frequency modulation difference limen
NH	Normal hearing
DLI	Difference limen for intensity
AUC	Area under the curve
PTA	Pure tone average
SRT	Speech recognition threshold
WRS	Word recognition score
ROC	Receiver operating characteristic

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None.

Authors' contributions
NMN analyzed and interpreted the patient data regarding the hematological disease and the transplant. THE, EAK and MAK performed the histological examination of the kidney and was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available as MS Excel files (.xlsx) from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This case control work was performed in the period between September 2020 to June 2022 at Audio-Vestibular Medicine Unit at E.N.T Department, Tanta University Hospitals with ethical approval code number: 34080/9/20. A written consent was taken from each subject or parent of each participant in this study after explaining the tests and the objectives of the study.

Consent for publication
Not applicable.

Competing interests
All authors have no conflict of interest.

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