Case Study

Impact of Various Frequency Allocation Tables on Pitch Perception in Post-Lingual Cochlear Implant Recipients: A Case Series Study

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Short running title: Impact of Various Frequency Allocation…

Highlights:

- Study explores FATs impact on pitch perception in post-lingual CI users
- First-order carryover effect leads to better scores with logarithmic FAT
- Customized CI programming improves pitch perception in cochlear implant users

ABSTRACT

Background and Aim: Cochlear implants in post-lingually deaf patients often result in reduced hearing naturality compared to their previous acoustic hearing, making adaptation and speech perception challenging. This study aimed to evaluate participants' perceptual ratings using Speech, Spatial Qualities (SSQ) 12 and the sound quality rating scale, alongside speech and pitch perception, across four different Frequency Allocation Tables (FAT).

The Cases: Four post-lingual Cochlear Implant (CI) users completed subjective ratings using the Speech, Spatial, and Qualities of Hearing Scale (SSQ 12) and the speech quality rating scale, while objective tests, including speech perception scores in quiet and noise, and psychophysical assessments like pitch perception tasks, were conducted across the four FATs.

Results: Performance using logarithmic FAT was better across all the domains of SSQ 12 and speech quality rating scale and in Signal to Noise Ratio (SNR) at both 0 and +10 dB. Pitch perception across four FATs reveals

a statistically significant difference noted in the apical electrode score when compared with medial and basal electrodes across all the FATs.
Conclusion: The default FAT provided by the manufacturer may not be suitable for all users due to several factors such as length of the electrode array, shallow insertion of electrodes. Thus, all the FAT options must be utilized and tested for subjective, objective, and psychophysical performance and the best suitable FAT should be set for the specific patient.
Keywords: Cochlear implants; speech perception; pitch perception; frequency allocation table; hearing loss; post-lingual

Introduction

Cochlear Implants (CI) in patients with post-lingual deafness show compromised naturality of hearing compared with their previous acoustic hearing experience. Hence the individuals might have difficulty in adapting to the device and have poor speech perception and satisfaction. Considering their difficulties post-lingual CI patients pose several factors affecting speech perception are 1) auditory deprivation [1], 2) pre-implant residual hearing [2], 3) cortical plasticity/cross-modal plasticity occurred during the period of deafness [3], 4) age at implantation/duration of deafness, 5) cause of deafness, 6) results of promontory stimulation, 7) number of electrodes in use, and 8) depth of electrode insertion [1, 2]. Further research on this area claimed the following factors: CI electrode array design, CI speech processing strategies, residual hearing, and cognitive status influences speech perception [2]. The use of a standard frequency table for all individuals with CI is premised on the assumption that the brain can adapt to any frequency mismatch imposed by the frequency table and electrode insertion depth. However, it is possible that some patients would not be able to completely adapt to a frequency mismatch that increases the chance of impaired speech perception [4]. Thus, exploring other frequency tables becomes necessary.

Clinically, we come across CI implant users with good audiometry hearing thresholds, yet faces difficulty in speech recognition [5]. This proves the gaps between the electrophysiology parameters, hearing perception, and speech recognition, and a solution for these difficulties does not exist currently. Yet, the methods to measure speech perception traditionally incorporated two basic approaches first is a method where the target signal (e.g., speech) and a competing signal (e.g., noise) are presented at a fixed Signal-to-Noise Ratio (SNR) so that better performance means greater percent items correct at that SNR. Psychophysical and neurophysiological methods have been used to investigate the influence of the ability to detect frequency changes or temporal gaps on speech perception in post-lingual CI users. The ability to detect frequency changes may not have a significant influence on speech perception, while the ability to detect temporal gaps may have a considerable impact. Apart from the conventional test methods to assess speech perception, music perception can also be used. Previous studies on music perception on CI using melody recognition tasks without rhythm cues show trouble extracting melodic pitch, especially when a piece's timbre complexity is increased [6-11]. A significant correlation between melodic contour identification and vowel recognition performance, highlighted the significance of frequency allocation and harmonic relationships in the perception of melodic contours [12].

By using Frequency Allocation Tables (FAT), electrodes are assigned to stimulate particular frequency in the cochlea i.e. basal electrodes to higher frequencies and apical electrodes to lower frequency sounds [13]. This enables to overcome the frequency-to-place mismatch in cochlear implantees by mimicking the normal cochlear tonotopicity. This simulates the tonotopicity of a normal cochlea. Speech quality and recognition depend on the proper distribution of acoustic frequency to each electrode in a CI as well as the location of stimulation. MED-EL brand of CIs also allows the audiologist to select from a set of four FAT that control how the input sound frequencies are allocated across the active channels. They are logarithmic Fine Structure (FS), tonotopic, lin log, and linear increasing [14].

Logarithmic FS FAT is a default and the recommended allocation for most of the CI users, in which the input frequencies are allotted logarithmically spaced bands. Linlog FAT divides the lower frequencies into linear bands and the higher frequencies into logarithmic bands. This band provides improved spectral resolution in the low frequencies which in turn helps discriminate common speech and environmental sounds. Tonotopic FAT mimic the tonotopic organization observed within the normal cochlea. This approach is theoretically supposed to produce the most normal frequency percept. Linear increasing divides the input frequencies into linear bands with increased bandwidth from the apical to the basal direction [15].

Studies show that participants preferred logarithmic FS (default FAT) for speech perception in both quiet and noise and during the conversation. This could have led to a first-order carryover effect thus making participants prefer the first program which they tried immediately post CI. The increased neural plasticity during the initial period of implant use could have easily biased the documentation of subjective preference [14, 15].
The default FAT provided by the manufacturer may not be suitable for all users due to several factors such as length of the electrode array, shallow insertion of electrodes [14]. The main aim of the study was to assess the effect of the four FAT offered by MED-EL cochlear implant on pitch perception in post-lingual users. The objectives of the study are 1) to assess the perceptual rating of participants using speech spatial quality 12 inquiries about aspects of ability and experience of hearing and listening in different situations and sound quality rating a 5-point scale, non-standardized rating scale with 4 questions was developed to assess speech naturality, understandability, voice identification, and music perception across four FATs (logarithmic, tonotopic, lin log and linear increasing), 2) to assess the speech perception across four FATs and 3) to assess pitch perception across four FATs.

Case presentation

Participants

This study includes four post-lingual C recipients, all native Tamil speakers and graduates, implanted at the Madras ENT Research Foundation, Chennai. Each participant presented unique profiles based on age, cause, and duration of hearing loss, as well as implant details.

Case 1 (S1)

A 59-year-old male with bilateral cochlear implants experienced sudden hearing loss at age 50. With no prior hearing aid use and a 5-year duration of hearing loss, S1 adapted to the MED-EL Mi 1000 Concerto Standard implant with Rondo processor for over four years.

Case 2 (S2)

A 23-year-old female with bilateral implants lost hearing at 15 years due to ototoxicity. She has hearing loss for over 7 years duration and has no hearing aid experience. S2 is currently a user of MED-EL Sonata Standard implant with a Rondo II processor for one year.

Case 3 (S3)

A 20-year-old male experienced sudden hearing loss at 15 years. With prior hearing aid experience and unilateral (right ear) implantation using the MED-EL Sonata Flex Soft and Rondo II processor, he is in the early stages of rehabilitation with 7 months of implant use.

Case 4 (S4)

A 52-year-old female with left ear implantation suffered hearing loss at age 45 due to ototoxicity. She was implanted with a MED-EL Synchrony Mi-200 Flex 28 and Rondo II processor after 6 years of hearing loss.
All participants met inclusion criteria, including normal cochlear anatomy, post-lingual hearing loss, and fluent language skills. Table 1, highlights the cases individual variability in cochlear implant outcomes and adaptation.

Procedure

The procedure began by setting the map at a comfortable level for the participants. The procedure was explained to the participants before the study and written consent was obtained from the participants to take part in the study. It is a case series study where the patient has no detail about the FAT that has been set to them. The FATs are changed without disturbing the conventional map (FAT-1). A personal computer with MAESTRO software (version 7.0) along with the MAX programming interface was used for mapping cochlear processors.
Phase 1 baseline measurement was done on the conventional map (logarithmic, FAT-1) for all the participants. Measurements like aided score and speech in noise test was done. A well calibrated double channel diagnostic audiometer (Piano Inventis) was used for separate streaming of pure tone and speech stimuli for aided audiometry. Stimuli were delivered through a loudspeaker that was oriented at 0-degree azimuth with respect to the subjects. Testing was carried out in a well-lit, air-conditioned, and sound-treated room. Noise levels were maintained within permissible limits of ANSI S3.1-1999. Speech in noise test was done using Tamil PB word list (Dayalan

1972) and spondee words (Boominathan P 1999) were used for testing. Speech perception in both quiet and in noise using PB words at –10, 0, and +10 SNR were measured. Live speech stimuli were delivered in the same free field setup. Meludia is an online music training application for kids and adults with varied levels of musical experience that leads users through structured exercises and levels. It was given in FAT-1 for 2 weeks in order to train them to perform psychophysical test.

Phase 2 after 2 weeks SSQ 12 ratings of experience in hearing in different listening situations using the FAT-1 were measured. SSQ 12 [16] inquiries about aspects of ability and experience of hearing and listening in different situations (see Appendix 1 for more details on SSQ 12). Sound quality rating of the speech in FAT-1 was done using the rating scale (see Appendix 2 for the questionnaire). sound quality rating of the speech in different FATs was done using a questionnaire. sound quality rating scale was developed for the purpose of the study; it is not a standardized scale. It contains 4 questions related to the naturality of speech, understandability of speech, ability to identify voices, and ability to perceive music. It is a 5-point rating scale where 1 represents difficult and 5 represents easy.

Pitch perception was measured using electrical stimulation in their implant. Each electrode was stimulated and the participants were made to understand the difference between the loudness and pitch. The participants were first trained to differentiate pitch using a visual analogue scale (Bell and Drum). The participants were given 2 forced choices of electrical stimulation. The participants were asked to report if the two sounds heard were of same or different pitch. Analysis of the data was done based on the electrode array position in the cochlea. The electrodes were classified based on the electrode position inside the cochlea (i.e., basal 5 electrodes, medial 4 electrodes, and apical 3 electrodes) [13]. After which next FAT-2 (tonotopic) was set and the procedure was followed.

Phase 3 In week 4 subjective tests, perceptual rating, and the psychophysical test were performed after which the next FAT-3 (linlog) was set up.

Phase 4 at week 6 subjective tests, perceptual rating, and the psychophysical test was performed after which the next FAT-4 (linear increasing) was set.

Phase 5 in week 8 the final set of test procedures was done. It took about five sessions with each client. The data were gathered on time, and the test procedures were carried out a week after the target but not earlier if the time limit did not match the client's schedule.

Documentation of all the data was done.

Statistical analysis

Speech perception scores, sound quality rating scale, and Meludia scores across four FATs were analysed using the mean values. SSQ 12 scores across all the domains (speech, spatial and quality of hearing) and across four FATs were statistically analysed using Kruskal-Wallis test. Pitch perception scores in apical, medial and basal electrodes across four FATs were compared statistically using Kruskal-Wallis test.

Results

1. Our first goal is to assess the perceptual rating of participants using SSQ 12 and sound quality rating scale across FATs.

Comparison of speech spatial quality 12 scores across four frequency allocation tables

Table 2 shows no statistical significance found across the 3 domains in four FATs. Results reveal that the quality of hearing domain in the SSQ 12 has a better mean value which denotes lesser disability with a greater standard deviation when compared to speech and spatial across four FATs. Participants rating was higher in directional hearing, naturalness and clarity of sounds which require less attentional capacity when compared to auditory processing such as estimation of distance and perception of movement in directional hearing which demands higher cognitive processing. Results show that there are difficulties in listening to the conversation in the presence of competing signals. Even the bilaterally implantees faced difficulty in the speech hearing domain. Results show lack of ability to detect and discriminate signals coming from independent sources even in the bilateral CI participants. The quality of hearing domain in SSQ 12 has a better mean when compared to speech and spatial hearing across four FATs.

The Kruskal-Wallis test reveals no statistical significance found across four FATs in SSQ 12. However, on examining the mean values logarithmic FAT has a better mean score with a greater standard deviation when compared to the tonotopic, linlog, and linear increasing (Figure 1).

Comparison of sound quality rating scale scores across four frequency allocation tables

The results show that the naturality of speech is better in both logarithmic and tonotopic FATs. The speech understandability and recognizing different voices is better in logarithmic FAT. The ability to perceive music is better in logarithmic, linlog, and linear increasing FATs. the logarithmic FAT has a greater score in all the domains. Post-lingual cochlear implantees show compromised naturality of hearing compared with their acoustic hearing experience. Hence subjects have difficulty adapting to the device and have poor speech perception and satisfaction. Despite advances in CI technology, however, perceptual limitations remain in speech in noise, voice emotion, and music. One major limiting construct is sound quality but is not well-studied perceptually. Sound quality is different from sound appraisal, often referred to as subjective pleasantness or likeability of a sound.

2. Our second goal was to assess speech perception across FATs by comparing the scores of Speech Recognition Threshold (SRT), speech in quiet, questions, and SNR at –10, 0 and +10 dB.

Speech perception

Table 3 shows speech in quiet score is better in tonotopic FAT. Mean score of questions answered correctly is better in linlog FAT. Overall, all the participants had difficulty performing at –10 dB SNR. All the participants had obtained a score 0 for 25 words presented, hence these results were eliminated from statistical analysis. SNR at both 0 and +10 dB have greater scores in logarithmic. linlog FAT divides the lower frequencies into linear bands and the higher frequencies into logarithmic bands. This band provides improved spectral resolution in the low frequencies which in turn helps discriminate common speech and environmental sounds. Which explains the better SRT threshold in the linlog FAT. Tonotopic FAT attempts to mimic the tonotopic organization observed within the normal cochlea. This approach is theoretically supposed to produce the most normal frequency percept. Speech in quiet score is better in this FAT. Whereas in logarithmic FAT the input frequencies are allotted in logarithmically spaced bands. It is the default FAT that is set for all the patients with CI. Speech in noise ratio at both 0 and +10 dB have greater scores in logarithmic due to adaptation effect to the FAT.

3. Our third goal was to assess pitch perception across FATs.

Pitch perception

The result on Table 4 reveals statistically significant difference noted in the apical electrode score when compared with medial and basal electrodes. The apical electrodes are better discriminated when compared to medial and basal electrodes. Similar findings were found in the study indicating that the apical-member electrode of each electrode pair plays a much more important role in speech recognition than the basal-member electrode for most subjects [10].

Meludia performance

Meludia scores were recorded in 5 domains, density, melody, rhythm, spatialization, and tone stability. The participant's correct responses were noted out of 10 presentations. The mean score is greater in the density task at logarithmic FAT when compared to tonotopic, linlog and linear increasing. Performance in the melody task was better in tonotopic FAT. Rhythm task was performed better across all the FATs with a greater mean value. Spatialization task was better performed in logarithmic FAT when compared to tonotopic, linlog and linear increasing. Tone stability was a difficult task. Tonotopic FATs had a greater mean value when compared to logarithmic, linlog, and linear increasing. Poor performance of the participants in stable/unstable task is supported by a study done in CI users, pleasantness ratings in them did not decrease with increasingly dissonant chords, which differed to the normal hearing ratings.

Discussion

Post-lingual cochlear implant users experience reduced hearing naturality compared to their acoustic hearing, leading to challenges in adaptation, speech perception, and satisfaction. Despite advancements in CI technology, perceptual limitations persist, particularly in areas like speech in noise, voice emotion, music, and sound quality, which remains understudied. Sound quality is significantly impaired in CI users [8]. Studies show that the conventional logarithmic FAT, as it was the first program during trial sessions. And they tend to have a first-order carryover effect. They suggest that the increased neural plasticity during this period could have easily biased the documentation of subjective preference.

Speech perception

Tonotopic FAT yields the best speech in quiet scores, while the linlog FAT, which enhances spectral resolution in lower frequencies, improves SRTs and question response accuracy. Although the logarithmic FAT, typically the default setting, produced better SNR scores at both 0 and +10 dB, all participants struggled at –10 dB SNR, with those results excluded from analysis. Post-lingual CI users' speech recognition scores in the quiet might be higher; however, their speech recognition scores in noisy conditions are still not quite as competent [17]. There is lack of research on the speech recognition in different FATs.

Pitch perception

The apical electrodes are better discriminated when compared to medial and basal electrodes. Similar findings were found in the study indicating that the apical-member electrode of each electrode pair plays a much more important role in speech recognition than the basal-member electrode for most subjects [18]. Normally, temporal representation of sound is superior at the more apical regions of the organ of Corti, at least in the lower intensity range where filter functions of afferent fibers (tuning curve tips) are tuned to phase-locking frequencies. Thus, the central nervous system of normal-hearing subjects would be expected to derive the temporal code to a greater extent from more apical portions of the cochlea [8]. Similar study shows that performance on the basal electrode pair tended to be poorer than that on the apical and medial electrode pairs [9]. Similar finding with greater apical electrode response state greater number of neuronal cell stimulation is seen in the apical region. The predominant population of nerve cells in the apical region is the afferent peripheral axons. Studies indicate that more apical contacts elicit a greater Electrically evoked Compound Action Potential (ECAP) response. This leads to the assumption that apex of the cochlea has greater neural survival. The basilar membrane of the inner ear has mechanical properties which vary with position in such a way that high frequency vibrations cause maximal motion at the window end and low frequencies causes maximal motion at the apical end. It is therefore difficult to separate the effects of rate and position of stimulation on the perception of pitch in the normal ear because these parameters are inevitably correlated [8, 9, 13].

Meludia performance

Perception of music represents one of the greatest challenges for implant-mediated listening, and high-level perception of music is rarely attained through conventional CI technology. Numerous factors contribute to the difficulty in music perception in CI users. Technological, biological, and acoustical constraints that limit music perception in CI users [10]. Poor perception of dissonance of sound was seen in CI users. The association of pleasantness ratings to consonance-dissonance perception is a subjective evaluation and related to musical experience and cultural background [11]. All the participants scored good in the rhythm task. Similar findings reveal [19] ceiling effects were observed for the Rhythm exercise with perfect performance. The temporal regularity of the environment sounds is perceived with a privileged psychological status over the perception of irregular sequences. Sequences composed of regular beat are easier to perceive than sequences without such an organization [20].

Conclusion

Thus, default Frequency Allocation Tables (FAT) provided by the manufacturer may not be suitable for all users due to several factors such as length of the electrode array, shallow insertion of electrodes etc. All the FAT options must be utilized and tested for subjective, objective, and psychophysical performance and the best suitable FAT should be set for the patient. Studies can be done with a greater sample size to generalize the findings. Studies focusing on the different types of electrode array by cochlear implant manufacturers for post-lingual implants could be done.

Ethical Considerations

Compliance with ethical guidelines

The study was approved by the Ethical Committee of Madras ENT Research Foundation (Reg. No. 430320506018, Dated: 18/12/21). The procedure was explained to the participants before the study and written consent was obtained from the participants to take part in the study.

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Authors' contributions

SSV: Study design, acquisition of data, statistical analysis, interpretation of the results, drafting the manuscript; DKS: Study design and supervision, interpretation of the results, and critical revision of the manuscript; RR: Interpretation of the results, and validation the final revision of the manuscript.

Conflict of interest

There are no competing financial interests.

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Table 1. Demographic information of post lingual cochlear implant patients

Details	S1	S2	S3	S4
Age	59 years	23 years	20 years	52 years
Age of onset of hearing loss	50 years	15 years	15 years	45 years
Cause of HL	Sudden HL	Ototoxicity	Sudden HL	Ototoxicity
Ear implanted	Bilateral	Bilateral	Right ear	Left ear
Duration of HL	5 years	7 years	7 years	6 years
Hearing aid experience	No	No	Yes	No
Implant used	MED-EL Mi 1000 concerto standard	MED-EL Sonata standard	MED-EL Sonata Flex soft	MEDEL Synchrony Mi-200 Flex 28
Processor used	Rondo	Rondo II	Rondo II	Rondo II
Implant age	4 years	1 year	7 months	1 year
Educational Qualification	Graduate	Graduate	Graduate	Graduate

S; subject, HL; hearing loss

Table 2. Mean, standard deviation, and probability value of speech spatial quality 12 scores across domains in four frequency allocation tables

SSQ	Mean	SD	p
Speech	7.81	5.04	0.887
Spatial	7.44	6.24	0.35
Quality	10.38	7.46	0.909

SSQ; speech, spatial qualities

Table 3. Mean, standard deviation, and probability value of speech spatial quality 12 score, speech audiometry and meludia across 4 frequency allocation tables

		Logarithmic	Tonotopic	Ling log	Linear increasing
SSQ	**Mean**	11.17	8.42	7.25	7.33
	SD	8.13	6.60	5.26	4.75
	p	0.639	0.505	0.690	0.581
Speech audiometry	**SRT (in dB)**	52.50	50.80	43.30	45.80
	Quiet	6.33	6.67	6.00	5.33
	Questions	2.67	3.17	3.50	3.17
	–10 dB SNR	0.00	0.00	0.00	0.00
	0 dB SNR	1.33	0.83	0.50	1.00
	+10 dB SNR	3.17	2.33	2.33	2.83
Meludia	**Density**	8.10	6.80	6.00	6.40
	Melody	4.40	7.60	6.30	7.10
	Rhythm	10.00	10.00	10.00	10.00
	Spatialization	8.00	7.90	7.90	7.50
	Tone stability	3.40	5.90	4.10	4.40

SSQ; speech, spatial qualities, SRT; speech recognition threshold, SNR; signal to noise ratio

Table 4. Mean, standard deviation, and probability value of pitch perception score in apical, medial and basal electrodes

Variables	Mean	SD	P
OVERALL	28.46	10.33	0.259
APICAL	4.04	2.07	0.007*
MEDIAL	15.62	5.44	0.433
BASAL	8.79	5.96	0.774

* Kruskal-Wallis test, statistically significant (p<0.05)

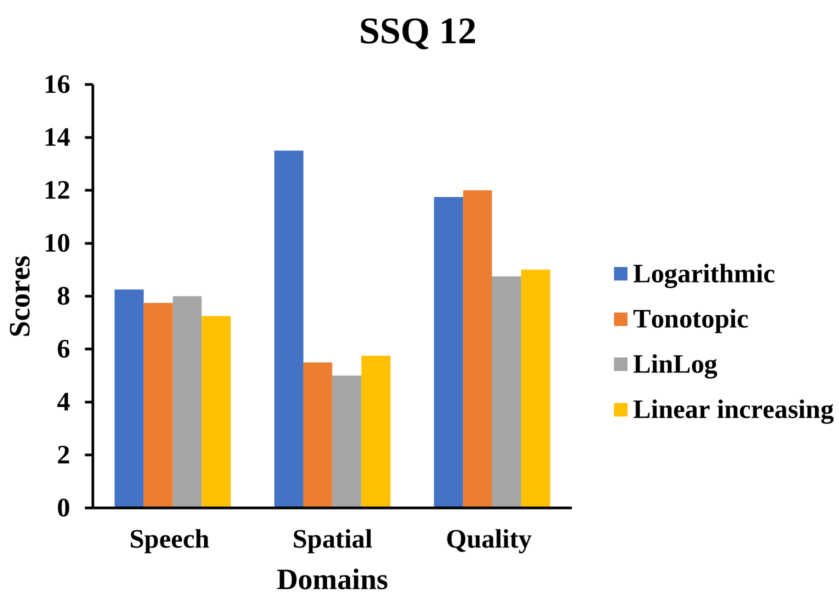

Figure 1. Speech spatial quality 12 scores in three domains across four frequency allocation. SSQ; speech, spatial qualities

Appendix 1. Speech spatial quality 12

The Speech Spatial Quality 12 questionnaire consists of 12 items, each with a possible score of 0 to 10 points. [9]

The item scores can be grouped into four subscales:

a. Speech scale (items 1, 2, 3, 4, 5) Total Score: 50

b. Spatial scale (items 6, 7, 8) Total Score: 30

c. Qualities-of-hearing scale (items 9, 10, 11, 12) Total Score: 40

d. Overall average score (items 1-12) Total Score: 120

Appendix 2. Sound quality rating scale

Sound Quality rating scale

Quality rating	Difficult 1	2	3	4	Easy 5
1. Do other people's voices sound clear and natural?					
2. Do you feel the speech of the person talking to you is understandable?					
3. Do you find it easy to recognise different people you know by the sound of each one's voice?					
4. Can you appreciate music?					