Long-term Average Speech Spectra of Postlingual Cochlear Implant Users

Mustafa Yüksel and Bülent Gündüz, *İstanbul, Turkey*

Summary: Long term average speech spectra (LTASS) is a commonly used voice analysis method for different purposes. This method offers an acoustic representation of the language in daily conservations. Results of that method can be altered by the deteriorations in the auditory feedback loop. Hearing losses occurred in the post lingual stage of life have some serious negative effects on the auditory feedback loop. Cochlear implantation may help these patients with regards to auditory feedback loop. Therefore, we aimed to evaluate the LTASS of cochlear implant users whose have a post lingual hearing loss. We assessed the LTASS of 24 cochlear implant users and compared our findings with normal hearing subjects. Our findings revealed that cochlear implant users have similar LTASS findings with normal hearing subjects. We conclude that cochlear implantation helps to the recovery of auditory feedback loop in patients with post lingual hearing losses.

Key Words: Long-term average spectra–Post lingual–Cochlear implant–Voice analysis–Auditory feedback loop.

INTRODUCTION

There are many different language-specific frequency and amplitude analysis methods; among these, long-term average speech spectra (LTASS) are used and analyzed extensively in the literature. The LTASS technique includes the recording of a long speech sample and analysis of frequency and intensity distributions of that recorded speech sample. This method offers an acoustic representation of the language in daily conservations and helps to obtain additional information on spectral energy distribution of a speech signal in a longer speech sample. Acoustic properties of different languages have been studied with the LTASS method since the 1980s.[1–5] The LTASS method has been employed as an evaluation and research method for subjects with normal hearing, those with specific speech and voice properties,[1,6–8] and those with different hearing and language problems.[9–14] This method also served as a basis for hearing aid fitting procedures, articulation index, and speech recognition applications.[15–18]

Voice production involves respiratory, phonatory, and articulation systems. It also involves the peripheral and central auditory systems, which manifest as the auditory feedback loop.[19] Problems in the auditory system and auditory feedback loop at prelingual or postlingual stages in life might have different deteriorating effects on the frequency and amplitude properties of subjects' voices.[10,20–23] Different degrees, types, and configurations of hearing loss are likely to cause different types of voice and speech disorders.[24] Hence, past studies use different voice analysis methods with hearing impaired subjects and noted deteriorations in different voice parameters.[25–29] Similar analyses were conducted for cochlear implant users and documented improvements after the use of cochlear implants.[9,14,30–32] Improvements after amplification are considered signs of a restored and functional auditory feedback loop, thus supporting this view that different voice analysis methods are necessary. Studies in the literature present very valuable and important findings; however, most of these studies analyzed short-term voice samples and parameters. In a recent study, researchers investigated the acoustic characteristics of voice in children with cochlear implants and analyzed the formants and aerodynamic features of the vowel with 3-second duration.[33] Similar studies employed short-term analysis methods such as formant analysis and pitch, loudness, speech rate, and intonation properties.[34,35] Most of the studies in the literature agree on the positive effects of cochlear implantation on voice parameters; hence, we believe that supporting these findings with different acoustic analysis methods, such as long-term average of speech spectra, is required. To support these positive effects of cochlear implantation, we used the LTASS to analyze and reflect on the voice properties of cochlear implant users.

The mentioned studies were conducted with both prelingually and postlingually deafened subjects. Postlingually deafened adults have used speech as a primary means of communication at at least one point in their lives; in contrast, prelingually deafened adults are a heterogeneous group in terms of primary communication methods.[32] The advantage of postlingually deafened adults resides with a fully or limited functional capacity auditory feedback loop. It can be expected that with the help of cochlear implantation, the auditory feedback loops of these patients can get better with time. Therefore, our primary aim was to evaluate postlingually deafened adults who used cochlear implants, using the LTASS method, and to compare observed values with those obtained from normally hearing subjects without any speech or language problems.

MATERIALS AND METHODS

Subjects

We evaluated and compared the LTASS of postlingual cochlear implant users with normal-hearing subjects. Participants were evaluated in their fitting appointments in our clinic. Normal-hearing participants were matched with cochlear implant users by age, education, and male-to-female ratio. The normal-hearing subjects had similar ages and education levels compared with the cochlear implant users. We compared cochlear implant users and normal-hearing subjects both by gender and by general hearing status.

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From the Audiology, Marmara University, Fevzi Cakmak Mah., Pendik, Turkey.
Address correspondence and reprint requests to Mustafa Yüksel, Audiology, Marmara University, Fevzi Cakmak Mah., Pendik, Turkey. E-mail: mustafa.yuksel@marmara.edu.tr
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All subjects received informed consent before participation in any of the procedures, and all procedures and protocols received prior approval from the ethics committee. An expert otolaryngologist evaluated all subjects' voices, and an audiologist evaluated all subjects' hearing thresholds. All participants in the normal hearing group had pure tone hearing thresholds below 15 dB and had normal middle ear functions (type A tympanogram with acoustic reflexes present) as well as normal otoacoustic emission responses. Furthermore, participants were all at least 20 years old to ensure the maturity of voice characteristics and younger than 60 years old to eliminate the possibility of presbyphonia.

All participants were (1) literate, (2) without any voice or speech disorder, (3) without any upper respiratory tract infections over the preceding 2 weeks, and (4) native Turkish speakers. For cochlear implant users, we sought to evaluate patients whose hearing loss occurred in the postlingual stage and who had used cochlear implants for at least 6 months.

To ensure that any unwanted effects of language acquisition were precluded, we chose cochlear implant users whose hearing loss occurred after language acquisition. Therefore, we aimed to eliminate the problems that might be caused by language and speech disorders related to hearing loss, thereby evaluating the effects of cochlear implant use only. We excluded patients who did not attend the follow-up meetings regularly. Moreover, we asked patients to remove their hearing aids in the contralateral ear.

Recording procedure

We used methods and tools recommended in the literature for audio recording.[36–39] For the reading material, we chose the 400 words of text from Omer Seyfettin's novel "Diyet." Because there are not any phonetically balanced reading materials for Turkish speakers, we selected a Turkish literature classic that is used widely in Turkish voice studies. Furthermore, Kitzing[12] and Lofqvist[40] stated that voice samples with a duration of 20–40 seconds are adequate for eliminating differences that may be caused by the recorded content throughout the spectrum. Recordings were conducted in the Voice Analysis Laboratory, which is treated and isolated acoustically for voice recording purposes. Background noise for the recording room was measured as 22.1 dBA. For the recording format, 16-bit quantization and a 44,100-Hz sampling rate was employed, and the audio format was Waveform Audio File Format (wav). The equipment used at the recordings was specifically programmed to acquire the necessary frequency responses and analog-to-digital converters. For that purpose, a Focusrite Scarlett 2i2 audio unit and a Rode M5 omnidirectional condenser microphone with an almost flat frequency response (20 Hz–20 kHz ±2.5 dB; 125–8000 Hz <±1 dB) were used. Omnidirectional condenser microphone selection was designed to remove any possible proximity effect. The microphone was positioned 15 cm away from the participants' mouths in a microphone stand and the mouth-to-microphone distance was kept constant through the recordings.

LTASS analysis

Lofqvist and Mandersson[41] argue that "gaps" in speech voices can cause corruption on LTASS analysis. In our study, we automatically removed all silence periods with *Audacity* (Version 2.1.1. Audacity Team) voice recording and processing software, using the "truncate silence" command. Thus, the possible corruptive effects of gaps on sound, analyzed by Fast Fourier transform, were eliminated.

As for the second step, 40 seconds of speech samples from the middle of the full speech samples (average sample duration of 3 minutes, 12 seconds) was extracted by *Praat* v.5.4.08 (University of Amsterdam, Netherlands)[42] software and recorded as separate files. This was necessary to create consistency in the beginning and at the end of the speech samples and to prevent effects from factors such as breath, microphone distance, possible microphone anxiety, or body position.

The final intervention is the normalization process of the speech samples, which are detached from the gaps and converted to 40 seconds. Studies on long-term spectral energy distribution indicate that normalization of the voice samples with respect to a specific value is necessary to compare speakers.[43] Likewise, the literature indicates various comments and applications used for normalization parameters.[7,36,44] In our study, the highest dB sound pressure level (SPL) value obtained from all of the voice samples included in the analysis was calculated (72.4 dB SPL), and each peak value in the spectrum was equalized to 72.4 dB SPL.

Praat v.5.4.08 software was used for acoustic analysis of the speech samples. *Praat* enables analysis from the intended bandwidth using a "long-term average spectrum" command among spectral analysis options. We obtained 68 different parameters from each voice recording. The analysis was made within a band range of 62.5–8000 Hz, 125-Hz bandwidth ($N = 65$), and 50-ms window length. *Praat* automatically gives an evaluation of the half value of the first frequency (125 Hz because the bandwidth is 125); for that reason, our measurements started from 62.5 Hz. Various bandwidths and ranges were used by previous studies. One of the two main reasons for choosing 125 Hz for this study was to indicate the spectrum display in detail, and the second reason was to include frequencies widely used in audiological applications. Analysis of 65 different frequencies enabled us to attain a level of detail that is either equal to, or above, many past studies.

In addition to the frequency bands, three other parameters were analyzed. These were (1) fundamental frequency (because it is taken from the speech sample, speech fundamental frequency [SF0]); (2) standard deviation of SF0 obtained during the speech (standard deviation); and (3) alpha value that shows the difference (ratio) between average voice amplitude under 1 kHz—where speech voices are mostly found—and the average voice amplitude between 1 and 5 kHz range.

Statistical analysis

SPSS Statistics version 20 (SPSS Inc., Chicago, IL) was used for the statistical analysis of the collected data. Differences between the groups were tested with independent samples t tests. Because there were a total of 68 t tests conducted, we used Bonferroni correction to prevent type 1 errors. For all statistical analysis, the significance level was set as $P < 0.05$.

RESULTS

The study involved 24 cochlear implant users (12 men and 12 women) and 24 normal hearing subjects (12 men and 12 women). Average age was 37.6 years for the cochlear implant group and 36.5 for the normal hearing group. Detailed demographic features of the cochlear implant group can be seen in Table 1.

Average duration of hearing loss in the cochlear implant group was 13.13 years (range: 4–20), average onset age of hearing loss was 23.88 years (range: 12–40 years), and average duration of cochlear implant use was 28.46 months (range: 12–54 months). Etiologies of hearing losses were diverse (head trauma, ototoxic effects, idiopathic).

There were no statistically significant between-group differences in 65 frequency bands and in SF0, SF0 standard deviation, and alpha values ($P < 0.05$). There were no statistically significant differences in any variable between male cochlear implant users and male subjects with normal hearing and female cochlear implant users and female subjects with normal hearing (Tables 2–4).

Comparison of the average LTASS curve of cochlear implant users and normal hearing participants can be seen in Graphic 1. The same comparison can be seen in Graphic 2 for males and Graphic 3 for females.

DISCUSSION

The aim of current study was to reveal the LTASS of cochlear implant users and to compare these properties with normal-hearing subjects. We did not observe any statistically significant

TABLE 1.
Demographic Features of Cochlear Implant Users

	Age	Gender	Education	OAHL (y)	DOHL (y)	DOCI (mo)	CIB	UHA
	24	F	High school	12	12	19	Med-El	No
	25	M	High school	13	12	24	Med-El	Yes
	25	F	High school	10	15	38	Med-El	Yes
	27	F	High school	13	14	14	Nucleus	Yes
	27	M	High school	12	15	17	Nucleus	No
	27	F	Bachelor	17	10	36	AB	No
	28	M	High school	14	14	23	Nucleus	No
	30	F	High school	26	4	23	Nucleus	Yes
	31	F	Middle school	23	8	54	AB	Yes
	36	F	Bachelor	20	16	25	Med-El	No
	37	M	Middle school	27	10	23	Nucleus	Yes
	38	F	High school	23	15	48	Nucleus	No
	38	F	High school	30	8	37	Nucleus	No
	39	F	High school	25	14	40	AB	No
	40	M	Middle school	20	20	15	Nucleus	No
	40	M	High school	27	13	26	Nucleus	No
	40	F	Bachelor	21	19	23	Med-El	Yes
	46	M	Bachelor	26	20	16	Nucleus	No
	47	F	Bachelor	29	18	26	AB	No
	47	M	High school	33	14	35	Nucleus	Yes
	48	M	High school	38	10	30	Med-El	Yes
	48	M	Middle school	39	9	24	Med-El	No
	50	M	Middle school	35	15	40	Nucleus	No
	50	M	Bachelor	40	10	27	Nucleus	No
Average	**37**			**23.88**	**13.13**	**28.46**		

Abbreviations: CIB, cochlear implant brand; DOCI, duration of cochlear implant use; DOHL, duration of hearing loss; OAHL, onset age of hearing loss; UHA: use of hearing aid in the contralateral ear.

TABLE 2.
Findings and Statistical Values of Voice Assessments

	Normal Hearing		Cochlear Implant			
Parameters	Mean	SD	Mean	SD	*T*	*P*
SF0	178.44	45.70	186.77	44.55	1.812	0.079
SF0 SD	34.38	10.13	32.97	9.05	0.682	0.500
Alpha	–21.84	2.64	–22.08	3.98	0.115	0.909

Abbreviations: SD, standard deviation; SF0, speech fundamental frequency; SF0 SD, standard deviation of speech fundamental frequency.

TABLE 3.
Findings and Statistical Values of Voice Assessments of Female Participants

	Normal-hearing Females		Cochlear Implant Females		*t* Test	
Parameters	Mean	SD	Mean	SD	*T*	*P*
SF0	206.5	39.06	230.58	37.58	1.539	0.138
SF0 SD	36.91	8.64	36.18	9.89	0.193	0.849
Alpha	–22.03	1.84	–20.48	4.71	1.064	0.305

Abbreviations: SD, standard deviation; SF0, speech fundamental frequency; SF0 SD, standard deviation of speech fundamental frequency.

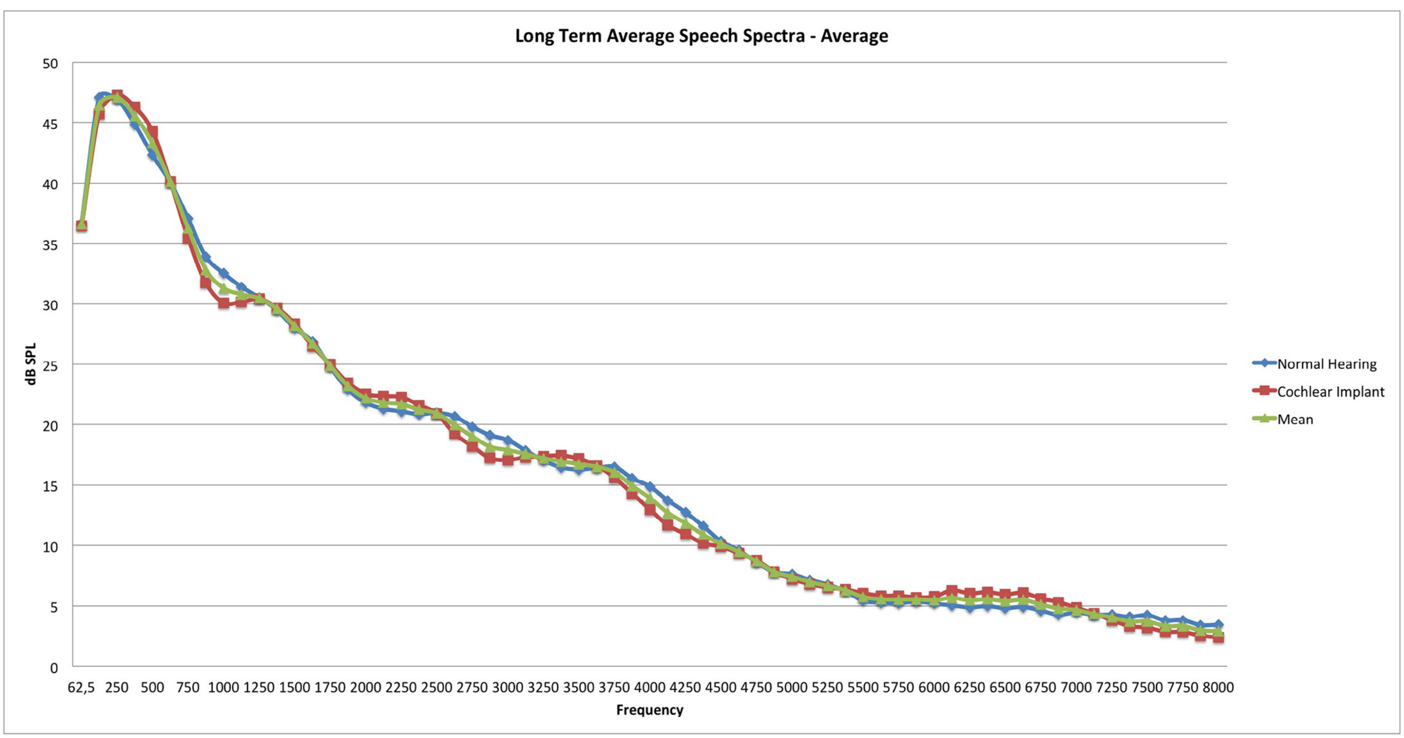
differences in 68 parameters between cochlear implant users and normal-hearing subjects.

Voice improvements in cochlear implant users—especially postlingual cochlear implant users—after the cochlear implantation, have been repeatedly demonstrated in the literature. Past studies have found lowering of voice intonation, improved control of voice intensity, reduction of nasal quality, lowering of fundamental frequency (F0),[45] increase in the ranges

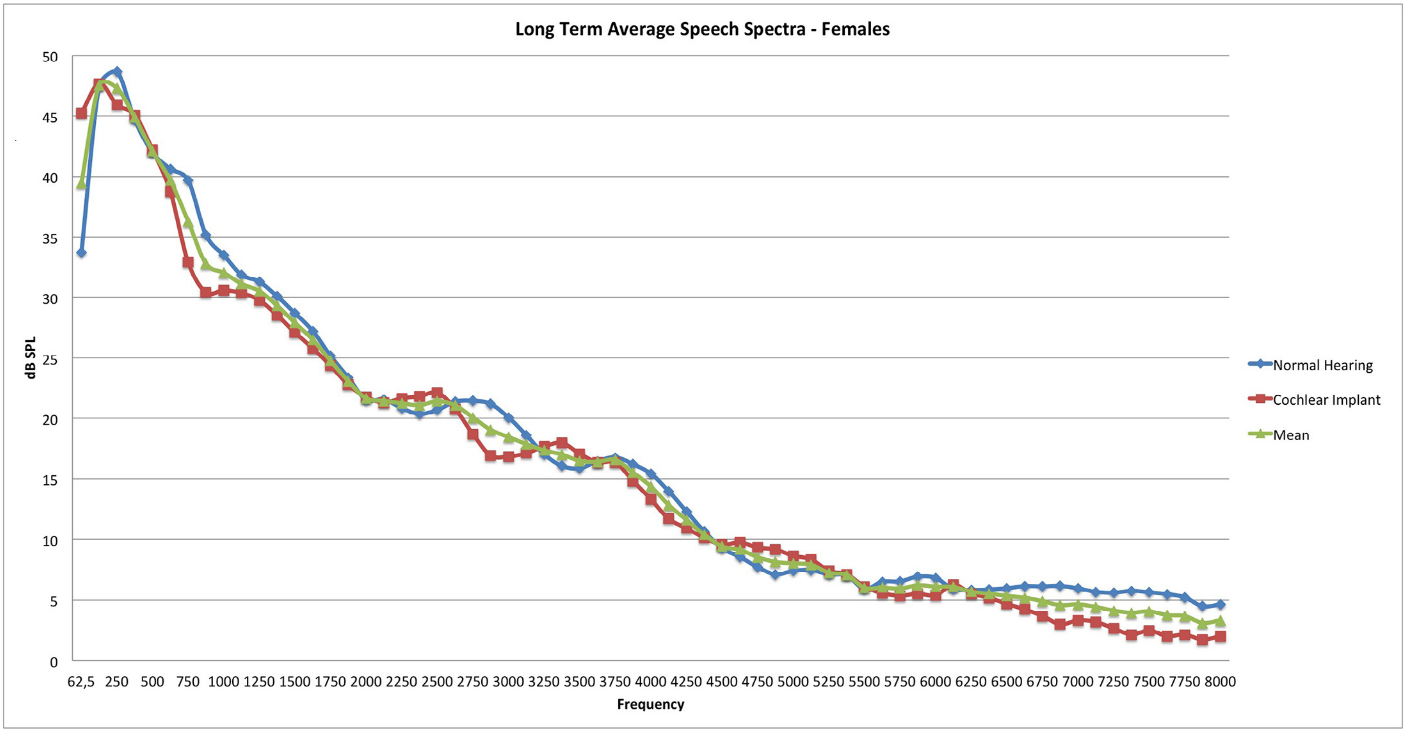
TABLE 4.
Findings and Statistical Values of Voice Assessments of Male Participants

	Normal-hearing Males		Cochlear Implant Males		*t* Test	
Parameters	Mean	SD	Mean	SD	*T*	*P*
SF0	134.01	24.98	159.74	31.51	2.218	0.037
SF0 SD	25.38	6.61	32.69	10.41	2.052	0.052
Alpha	–22.18	2.45	–22.52	5.52	0.280	0.782

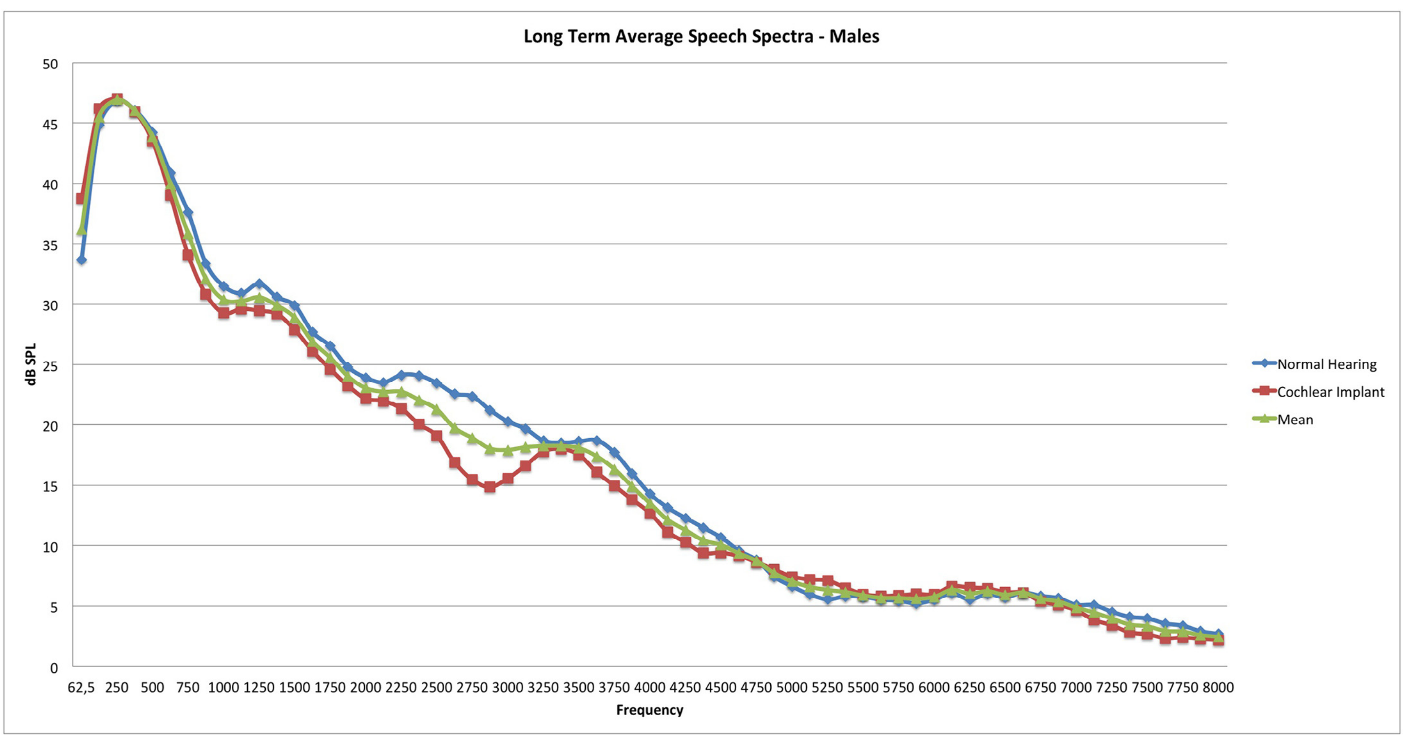
Abbreviations: SD, standard deviation; SF0, speech fundamental frequency; SF0 SD, standard deviation of speech fundamental frequency.



GRAPHIC 1. Comparison of LTASS (blue/diamond, normal hearing; red/square, cochlear implant; green/triangle, mean; vertical line dB SPL; horizontal line Hz). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



GRAPHIC 2. Comparison of LTASS for women (blue/diamond, normal hearing; red/square, cochlear implant; green/triangle, mean; vertical line dB SPL; horizontal line Hz). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



GRAPHIC 3. Comparison of LTASS for men (blue/diamond, normal hearing; red/square, cochlear implant; green/triangle, mean; vertical line dB SPL; horizontal line Hz). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of the first and second formant frequencies, and shift of the first and second formant frequencies toward the normative values at 12 months post implantation,[46] changes in overall severity, strain, loudness, and instability values, and reductions in F0 and its variability at 6–9 months after the implantation.[47] The likely reason for these improvements is the partial restoration of the auditory feedback loop after cochlear implantation. Thus, we would expect to observe changes in the voice properties of patients, toward normative values, after the cochlear implantation. Our findings are in agreement with that expectation. We can speculate that deteriorations that occur in the auditory feedback loop, caused by hearing loss in the postlingual stage, can be reversed with cochlear implantation—at least to some extent.

This conclusion is already supported by existing findings in the literature; however, supporting this conclusion with other voice analysis methods is necessary. There are two similar studies, which examined postlingual cochlear implant users. Ubrig et al[35] evaluated 40 cochlear implant users and analyzed the phoneme, both in isolation and extracted from longer sentences. They analyzed overall severity, strain, loudness, instability values, and controlled F0. In a similar study, Hassan et al[34] employed a similar method and analyzed *Multi-Dimensional Voice Program* parameters like F0, jitter, pitch perturbation, shimmer, and noise-to-harmonic ratio. These analysis methods are mostly used for dysphonia research and are indeed useful, but the LTASS method offers more general and inclusive information. Hence, we believe that the assessment of the auditory feedback loop after cochlear implantation with a method other than a short-term or dysphonia evaluation method will be a helpful addition to the literature.

The LTASS reflects a broader aspect of human voice with a longer analysis time; still, there are other available long-term analysis methods such as the cepstral peak prominence or spectral moment analysis. Both of these methods reported a high degree of within-speaker consistency[48] and the ability to distinguish dysphonic voices from normal voices.[49] To extend the LTASS findings to subjects with cochlear implants, hearing aids, and hearing loss, these analysis methods are possible next steps.

Other important issue is the effect of auditory rehabilitation. Researchers noted positive effects of auditory rehabilitation on postoperative measurements. These positive effects were in significant relationship with the duration of hearing loss (<6 years) and postoperative auditory rehabilitation. All cochlear implant users in our study received auditory rehabilitation, to some extent. Type and duration of auditory rehabilitation were mixed for our patients; therefore, we did no classify our patients by that variable. However, we can assume that rehabilitation had a positive effect on the voice properties of cochlear implant users.

For our subjects, the average duration of hearing loss was 13.3 years. This is a relatively long duration. The expected relationship was better voice parameters with shorter duration of hearing loss. Because we have too many variables to compare, we did not investigate the relationships between duration of hearing loss and LTASS variables. Still, normal values obtained from users with hearing losses of such long durations are remarkable.

Our study has several limitations. Because a limited number of patients attended fitting sessions regularly, we could not include preoperative measurements. Voice measurements performed before implantation can more confidently show the improvement in voice characteristics following implantation.

CONCLUSION

Cochlear implantation has some well-known positive effects on the auditory feedback loop. That loop system helps to maintain normal voice characteristics. Cochlear implant users in our research had normal voice characteristics in a long-term analysis of spectral properties. Although our outcomes were expected, they are unique to the literature. Thus, we suggest that cochlear implantation has positive effects on the long-term average spectra of voice.

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