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ORIGINAL ARTICLE

Effects of Multi-Channel Compression on Speech Intelligibility at the Patients with Loudness-Recruitment

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Objective: In this study, the effects of different limiting methods on speech discrimination at the patients with recruitment had been investigated. For this purpose, audiologic, impedansmetric and speech discrimination tests were carried out on 43 ears with cochlear pathology.

Materials and Methods: The patients aged between 30 and 70 years (average 53.43±13.41). The sound pressure level at which the maximum speech discrimination score obtained was determined for each patient. A digital behind-the-ear four-channel hearing aid in which compression settings can be programmed independently in each channel was used for all listeners. The hearing aid was fitted to the test ear of the subjects and programmed according to WDRC, PC, CL, BILL and TILL limiting methods. Then speech discrimination scores with hearing aid were examined. This examination was done for the situations the speech noise is absent and S/N ratios of 0dB and +5dB.

Results: Although for noiseless situations there was no significant difference between CL and TILL, it has been found that with TILL method statistically better speech discrimination scores were obtained for both 0dB and +5dB S/N ratios. No any significant differences have been marked among the scores obtained with WDRC, PC and BILL methods both in noise and noiseless situations. Any statistically significant correlation was not found between the determined speech discrimination scores and the sound pressure level that rollover occurred.

Conclusion: Examination of the results statistically shows that, the highest speech recognition performance obtained with TILL limiting method. The results obtained with CL method were worse than TILL but better than WDRC, BILL and PC. It can be stated that, it is better to adjust the hearing aids used for the patients with recruitment phenomenon for TILL type operation. The CL limiting method could be second choice for limiting but PC, WDRC and BILL methods may not be good candidates for these patients.

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Introduction

Sensorineural (S/N) hearing loss is a result of a pathology in the cochlea or 8th nerve that could cause problems in hearing and speech production. Loudness recruitment is a phenomenon observed in patients with inner ear hearing loss who exhibit an abnormally rapid rise in loudness sensation with a small increase in sound stimulus intensity. Many such patients feel more uncomfortable than normal hearing subjects when they hear loud sounds. These patients have poorer word recognition performance than normal subjects, even when hearing threshold differences are compensated. As the presentation level increased to the higher levels the word recognition performance of some patients with S/N hearing loss shows a decline. This performance reduction is called as roll over.

When selecting any hearing aid, some factors such as, the age of patients, the configuration and severity of hearing loss should be considered. The selected hearing aid should be appropriate for patient requirements in order to achieve better speech intelligibility performance. In order to prevent patients

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from loudness recruitment, hearing aid should limit output level below Uncomfortable Level (UCL) while preserving a reasonable sound quality. There are several types of compression methods in the literature that have been used to control output level of the hearing aids.

In this study the effects of Peak Clipping (PC), Wide-Dynamic Range Compression (WDRC), Compression Limiting (CL), Bas Increase at Low Level (BILL) and Treble Increase at Low Level (TILL) limiting methods on speech discrimination were investigated in the patients with loudness recruitment.

Materials and Methods

Thirty patients (17 males and 13 females), who ranged in age from 30 to 70 years (mean age 53.43⊕13.41), participated this study. All patients had loudness recruitment and mild to severe sensorineural hearing loss (13 bilateral and 17 unilateral, total 43 ears). Each listener had a minimum of one year of experience as a hearing-aid user.

The patients participated this study selected according to a procedure. For this purpose, for all tested ears standard ENT examination, pure tone audiological, impedancemetric and speech reception tests were carried out and word-recognition psychometric functions determined. The ears showing a rollover characteristic selected as a participant. Figure 1 shows the mean pure-tone thresholds and their ranges for the 43 tested ears.

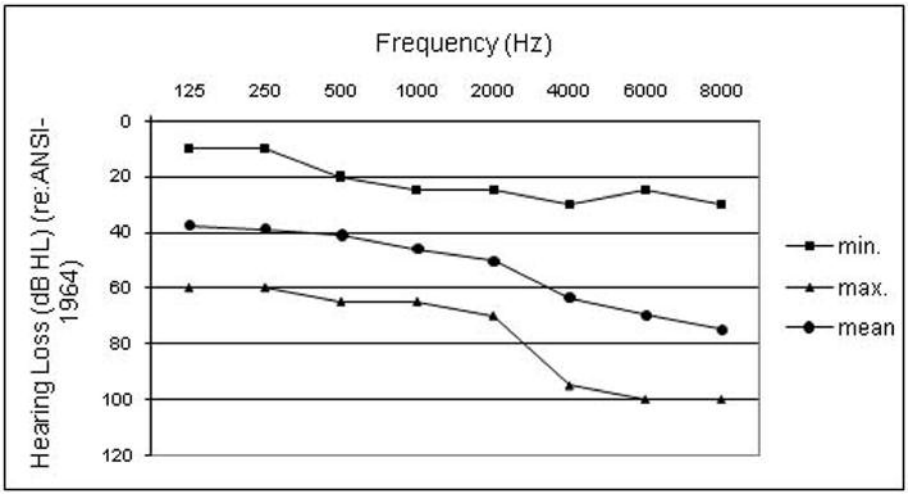

Figure 1. The mean audiogram of 43 ears (circles connected with solid lines). Curves above and below the mean audiogram denote ranges.

Speech materials consisted of compact disk recording of monosyllabic words prepared and standardized for Turkish language. The Speech-Noise of the audiometer (Interacoustics AC-40) is used as a noise material. The speech stimuli were presented to the listeners by means of a Technics SLP-6390 CD player. The left channel of the CD player was routed to the left channel of an Interacoustics AC-40 audiometer, the outputs of which were led to a pair of Dali 2B-BL loudspeakers. Playback level for each channel was set to 1000 Hz calibration tones, which preceded the speech on CD. Listeners were seated in a double-walled sound chamber, satisfying IAC (Industrial Acoustics Company) standards, with the two loudspeakers positioned 30 inches from the test ear at azimuths of 90 and 270 degrees (Figure 2).

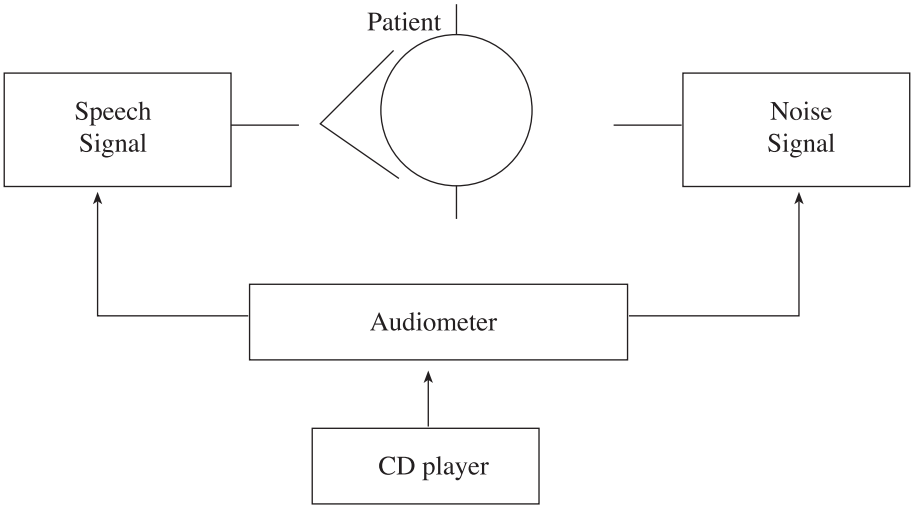

Figure 2. Test setup

The unaided ear was not occluded. The speech stimuli were presented through the front loudspeaker at patient's comfortable hearing level. The noise stimuli was presented through the rear loudspeaker, and its overall level was measured in the sound chamber by means of the Larson-Davis 812 sound level meter set to A-weighting and slow response. The microphone of the sound level meter was positioned in the area that would be occupied by a listener's head (listener absent).

A digital behind-the-ear four-channel hearing aid in which compression settings can be programmed independently in each channel was used for all listeners. The hearing aid was programmed with a computer equipped with Hi-Pro interface and the manufacturer's software (Connexx, Version-3.0). Advance feature of the aid was disabled for this study. Crossover frequencies between the adjacent frequency channels were 565Hz, 1130Hz, and 3200Hz. The gain in each channel of the hearing aid was adjusted to best fitting values using DSL I/O method. The programmed hearing aid was then coupled to the listener's ear by means of a foam insert earmold, and the gain was verified by conducting real-ear measurements performed with Madsen Aurical Fitting instrument.

All limiting methods were fitted consecutively for each patient and, the speech discrimination performance values were measured with each limiting method in noiseless and S/N ratio of 0 dB and +5dB situations. The following paragraphs describe how the hearing aid was programmed for different compression conditions.

Peak Clipping:

For this condition, the compression characteristic in the Connex software was set to "Linear gain" for all channels. The hearing aid has an adjustable output limiting. "Hard limiting" was selected as an output limiting method. The compression threshold of limiting was set such that the Maximum Peak Output (MPO) level of the hearing aid could not exceed the sound level at which the maximum of word-recognition psychometric function occurred. Measured gain of the hearing aid adjusted to PC method with 2cc coupler is shown in Figure 3.

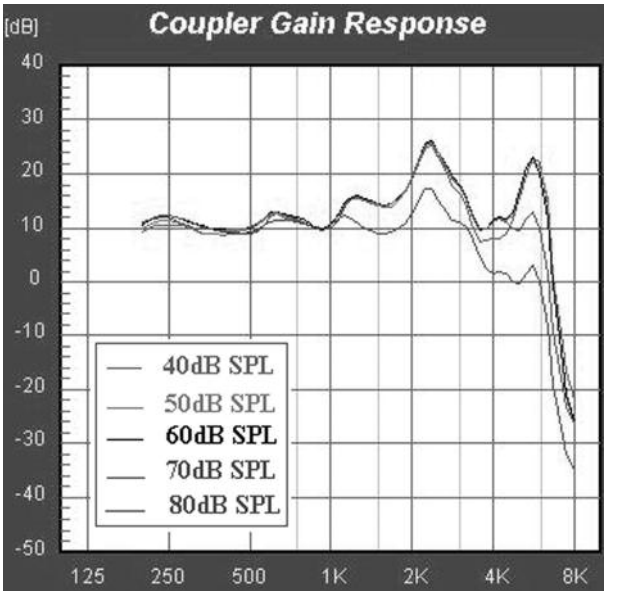

Figure 3. Gain of the hearing aid in dB as a function of the frequency in Hz with the hearing aid programmed to Peak Clipping.

Compression Limiting:

For this condition, the compression characteristic in the Connex software was set to "Linear gain" for all channels. "Broadband-AGC-O" was selected as an output limiting method and the compression threshold of limiting was set to the sound level of which the maximum of word-recognition psychometric function occurred. Measured gain of the hearing aid adjusted to CL method with 2cc coupler is shown in Figure 4.

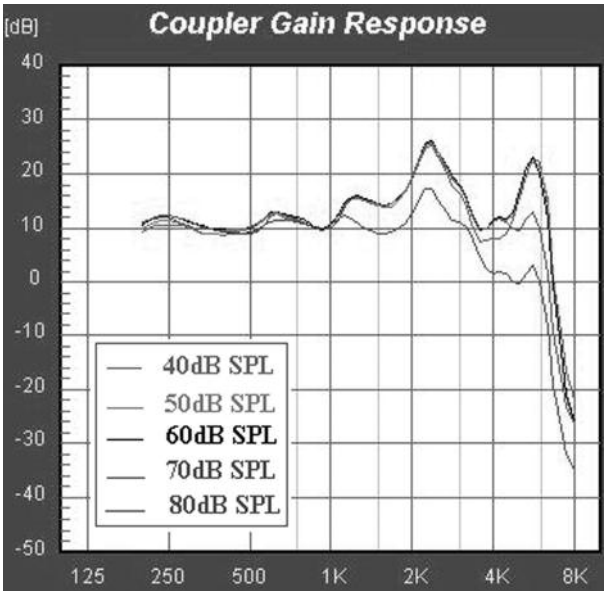

Figure 4. Gain of the hearing aid in dB as a function of the frequency in Hz with the hearing aid programmed to Compression Limiting.

Wide Dynamic Range Compression:

In this condition, compression ratio of 3:1 was selected and the compression threshold was set to 36dB SPL for all channels. "Hard limiting" was selected as an output limiting method and the compression threshold of limiting was set to the sound level of which the maximum of word-recognition psychometric function occurred. Measured gain of the hearing aid adjusted to WDRC method with 2cc coupler is shown in Figure 5.

Bass Increase at Low Level:

In this condition, the compression characteristics of second, third and fourth channels in the Connex software were set to "Linear gain". For the first channel, compression ratio of 3:1 was selected and the compression threshold was set to 36dB SPL. "Hard limiting" was selected as an output limiting method and the compression threshold of limiting was set to the sound level of which the maximum of word-recognition psychometric function occurred. Measured gain of the hearing aid adjusted to BILL method with 2cc coupler is shown in Figure 6.

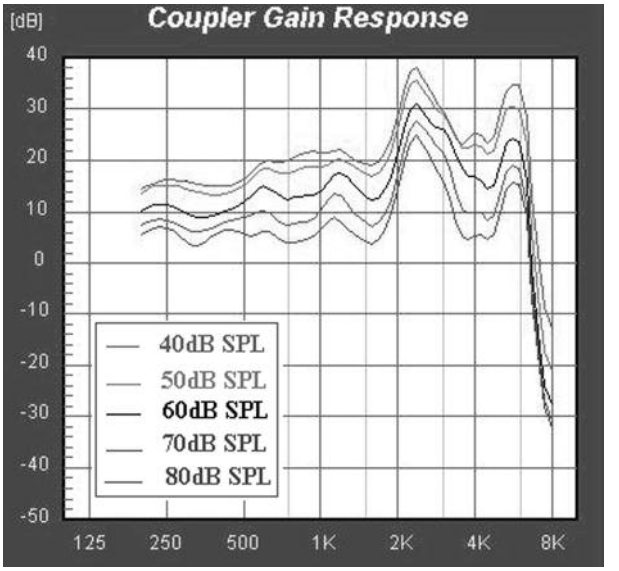

Figure 5. Gain of the hearing aid in dB as a function of the frequency in Hz with the hearing aid programmed to WDRC.

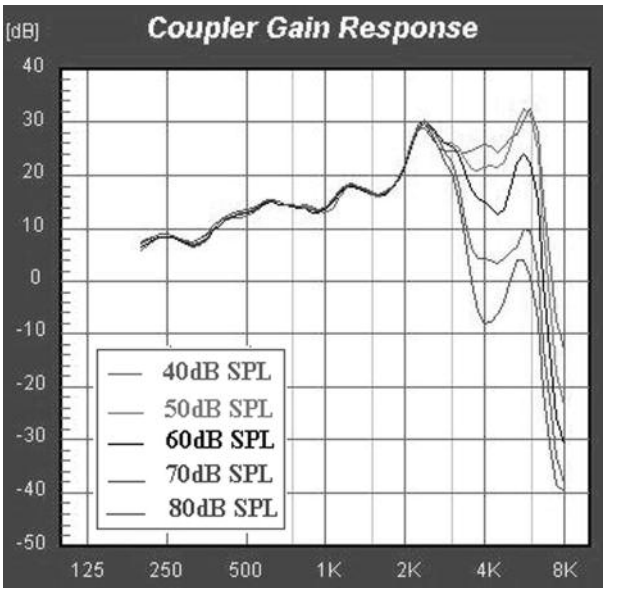

Figure 6. Gain of the hearing aid in dB as a function of the frequency in Hz with the hearing aid programmed to BILL.

Treble Increase at Low Level:

In this condition, the compression characteristics of first, second and third channels in the Connex software were set to "Linear gain". For the fourth channel, compression ratio of 3:1 was selected and the compression threshold was set to 36dB SPL. "Hard limiting" was selected as an output limiting method and the compression threshold of limiting was set to the sound level of which the maximum of word-recognition psychometric function occurred. Measured gain of the hearing aid adjusted to TILL method with 2cc coupler is shown in Figure 7.

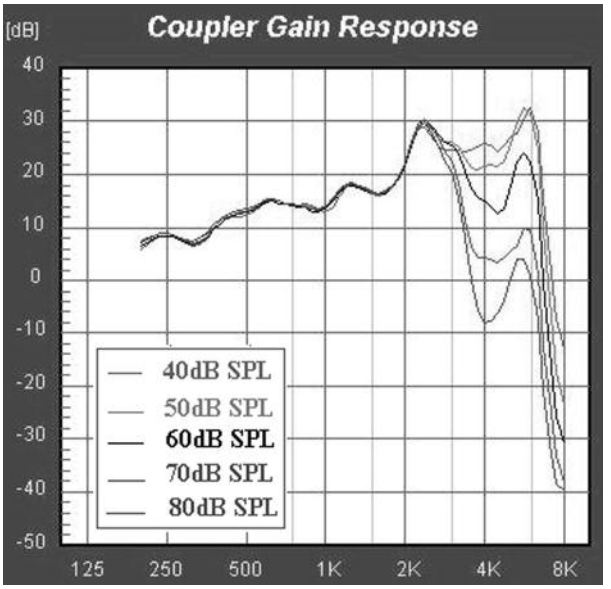

Figure 7. Gain of the hearing aid in dB as a function of the frequency in Hz with the hearing aid programmed to TILL.

Results

Table 1 shows rollover peak level and speech discrimination performance without hearing aid. A hearing aid programmed according to WDRC, PC, CL, BILL and TILL limiting methods, fitted to the test ear and the speech discrimination scores with hearing aid were examined for the situations the speech noise is absent and S/N ratios of 0dB and +5dB (Table 2).

The bar graph in Figure 8 gives the mean percentage of monosyllabic words correctly recognized by listeners in each condition. As would be expected, the highest scores were obtained in the absence of background noise. When the noise was mixed with the speech, the mean scores dropped in each condition.

A one-way repeated-measures analysis of variance revealed a significant main effect ($p< 0.05$). Performance Differences between different pairs of limiting methods are shown in Table 3.

Discussion

In this study, the effects of five different limiting methods (PC, WDRC, BILL, CL, TILL) on speech discrimination at the patients with recruitment had been investigated. According to the results obtained in this study, no statistically significant differences were found between PC, WDRC and BILL limiting methods regarding the speech discrimination performances of patients ($p>0.05$). These results are similar with the results in the literature [1,2,3,4].

If we remember the characteristics of the S/N hearing loss, we will see that these results are inevitable. The hearing aids used for the patients with S/N hearing loss should solve dynamic range reduction and abnormal loudness sensation growth problems shown at these patients. Villchur studied the average response of hearing of six hearing-impaired subjects[5,6] and showed that, although the speech has been amplified to the subject's preferred level, most of the high frequency

Table 1. Rollover peak level and speech discrimination performance without hearing aid

	Minimum	Maximum	Mean ⌖ Standard Deviation
Speech Discrimination	%64	%96	%82.23 ± 8.74
Rollover peak level	90 dB HL	115 dB HL	102.21 ± 7.18 dB HL

Table 2. Mean percentage of monosyllabic words correctly recognized by listeners in each condition

	Noiseless	S/N= 5 dB	S/N= 0 dB
WDRC	76.88+/-12.09	66.74+/-12.09	59.53+/-11.15
PC	76.84+/-8.60	68.47+/-9.57	62.00+/-9.75
CL	82.74+/-7.93	74.65+/-9.57	69.21+/-10.19
BILL	78.47+/-10.23	68.37+/-12.68	61.81+/-13.59
TILL	83.95+/-8.89	77.58+/-10.82	72.37+/-11.86

Table 3. Performance Difference between different pairs of limiting methods.

Performance Difference between different pairs of limiting methods	Statistical		
	Noiseless	S/G=+5dB	S/G=0dB
WDRC and PC	p>0.05	p>0.05	p>0.05
WDRC and BILL	p>0.05	p>0.05	p>0.05
PC and BILL	p>0.05	p>0.05	p>0.05
WDRC and CL	p<0.05	p<0.05	p<0.05
WDRC and TILL	p<0.05	p<0.05	p<0.05
PC and CL	p<0.05	p<0.05	p<0.05
PC and TILL	p<0.05	p<0.05	p<0.05
CL and BILL	p<0.05	p<0.05	p<0.05
BILL and TILL	p<0.05	p<0.05	p<0.05
CL and TILL	p>0.05	p<0.05	p<0.05

consonants remain below hearing threshold. In order to fit comfortably the speech signal into the dynamic range of the hearing, high frequency portion of the speech spectrum needs to be amplified further. In that case, speech signal level will be higher than rollover peak level and cause loudness recruitment. In order to find solution for both of these problems, a compression method not causing distortion in the sound should be applied together with high frequency emphasizing[5,6,7,8].

Due to clipping of signal peaks, PC limiting method cause higher distortion than compression. In the literature there are several studies claiming the negative effects of distortion on speech perception [9-,10,11]. In this study it has also been found that the worst speech perception performance is obtained with PC limiting method. Because of this disadvantage, PC limiting method is rarely used in the modern hearing aids and different limiting methods have been supplied to users.

Another limiting method BILL (Bass Increase at Low Level), has a broad frequency response in quiet surroundings. A high-pass filter or similar device is activated when the input level reaches certain intensity, providing a high-frequency emphasis for high-level signals (Figure 8). This is intended to help listening in background noise by filtering out low-frequency signals. Since BILL limiting method does not apply compression to the high frequency signals, it can not be a solution to the patients with loudness recruitment who have reduced dynamic range of hearing at high frequencies. Although the patients participating this study showed better speech perception performance when they used BILL limiting method, the difference was not significantly better than the performance when they used PC and WDRC.

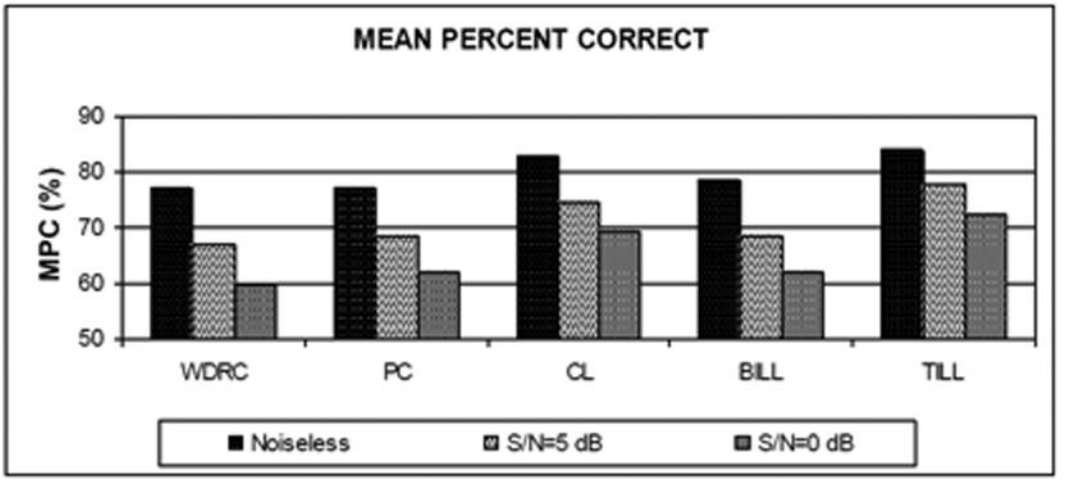

Figure 8. Mean percentage of monosyllabic words correctly recognized by listeners in each condition

WDRC compressors attempt to deliver sound within a patient's dynamic range. This is accomplished by using a low knee point with a low compression ratio (<3). Figure 9 shows the Input/Output functions of WDRC (dashed) and CL (solid) that have similar electroacoustic characteristics. Both amplify soft levels with the same amount of gain and limit the output at the same point. The difference between the two is the amount of gain applied for moderate level sounds. Due to less gain applied moderate level sounds, the output sound level was perceived by the patients participating this study as being softer for the WDRC circuits than for CL. The speech perception performance obtained with WDRC had also been found comparable and not significantly better than the performance with PC.

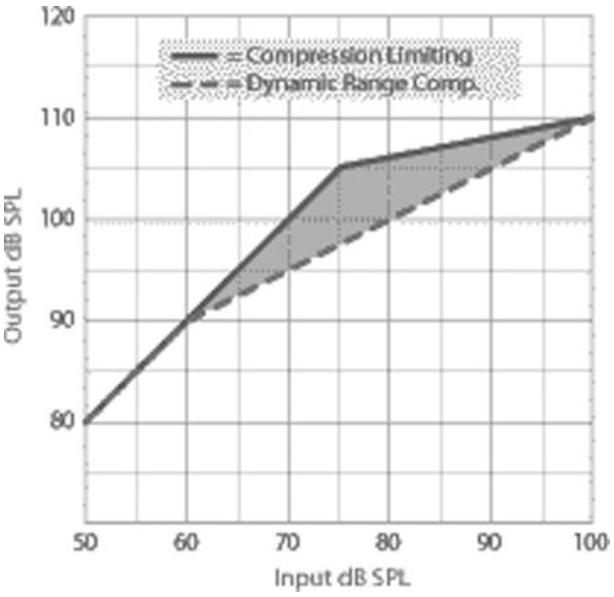

Figure 9. Input/Output functions of wide-dynamic range compression (dashed) and compression limiting (solid) which have similar electroacoustic characteristics.

The subjects with recruitment require a reduction in amplitude contrasts between sounds. In the literature, Dillon called this as "loudness normalization" and its positive effects on speech perception were emphasized[5]. Since the amount of gain applied for moderate level sounds is higher for CL circuits, loudness normalization could be more precisely established with CL limiting method. If properly applied compression combined with frequency-response shaping, the high frequency portion of the speech spectrum could be fit more precisely in to the residual dynamic range of hearing. In the multi channel compression circuits the gain, compression knee point and compression ratio could be independently adjusted for each channel. With the use of this facility, hearing aids could be easily fitted according to dynamic range and frequency characteristics of hearing of the patients with recruitment. In this study, speech perception performance with CL method has been found statistically better than the performance with PC, BILL and WDRC ($p<0.001$). These results are also consistent with the literature[12,13,14].

In this study the highest speech reception performance scores were obtained with TILL method. The speech perception performance with TILL method has been found significantly better than with PC, BILL and WDRC ($p<0.001$). Although the performance with TILL method has not been found significantly different from CL method in the noiseless environment ($p>0.05$), it has been found significantly better than CL in noisy environments (for the SNR values of 0dB and +5dB).

The difference between the performance of CL and TILL in noisy environments could be due to different compression ratios used for CL and TILL methods. In this study, compression ratio of 5:1 ore more was used for CL. On the contrary, a smaller compression ratio of 3:1 was used for TILL. In the study of Boike & Souza[13], it is stated that, although they did not see any difference in noiseless environment they found degradation in speech perception performance as compression ratio increased in noisy environments. Therefore the result of this study is also consistent with the results obtained in the literature[15,16,17,18].

The maximum sound level of the hearing aids used for the moderate to severe hearing losses could reach 130-150 db HL. Most of the patients such as the subjects participating our study have a roll over peak sound

level of 90-115db HL. The speech perception performance of the patients with S/N hearing loss would degrade due to sound level greater than roll over peak level. As a result; the loudness growth function and roll over peak level should be determined, in order to propose the most suitable hearing aid to the subject with S/N hearing loss.

As explained before the patients with S/N hearing loss are at more risk for loudness recruitment due to reduced dynamic range. Therefore the proposed hearing aids should have more than one channel each could be adjusted for different compression threshold and compress ratio.

Examination of the results statistically shows that, the highest speech recognition performance obtained with TILL limiting method. The results obtained with CL method were worse than TILL but better than WDRC, BILL and PC. It can be stated that, it is better to adjust the hearing aids used for the patients with recruitment phenomenon for TILL type operation. The CL limiting method could be second choice for limiting but PC, WDRC and BILL methods may not be good candidates for these patients.

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