Impact of Amplitude Compression Settings of Hearing Aid on Acceptable Noise Level

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Abstract: *Objective*: The aim of this study was to investigate the effects of various wide dynamic range compressions (WDRCs) on the acceptable noise level (ANL).

Design: The ANL under various conditions of amplitude compression times and compression ratios (CRs) was assessed. The CR numbers were 1, 2, 4, and 8. Both linear and nonlinear (syllabic and dual) amplifications were tested.

Study Sample: 32 male subjects (aged 51.5 ± 6.0 years) enrolled in this study had moderate sensorineural hearing loss.

Results: There were significant differences between the linear amplification and syllabic acting compression conditions as well as between syllabic and dual acting compression conditions. The ANL for syllabic acting compression was higher than that for both linear amplification and dual acting compression. The lowest and highest ANLs were observed for the linear amplification and 8-CRs syllabic WDRC, respectively. The ANL was increased when the number of different CRs in both syllabic and dual acting compressions was increased.

Conclusions: Aggressive WDRC increases ANL and this is probably because of the effects of smearing noise, which is in turn the result of the aggressive amplitude compression.

Keywords: Hearing Aid, Hearing Loss, Acceptable Noise Level (ANL), Amplitude Compression, Syllabic/Dual Acting Compression.

INTRODUCTION

One of the most important objectives of fitting hearing aids is compensation for the loss of cochlear compression, which is caused as a result of loss of outer hair cells. Cochlear compression is helpful in the detection and discrimination of important signals such as speech in noise. Wide dynamic range compression (WDRC) is commonly used in modern hearing aids. It is an advantageous option and intended to improve the patient's audibility of soft sounds and make the hearing aid comfortable to the user during exposure to loud sounds [1]. But comprehensive study using a method [2], the *Inversion Technique* to measure signal to noise ratio (SNR) in hearing aid output, showed that: 1) Fast-acting WDRC deteriorates SNR in hearing aid output; 2) With compression ratio (CR) = 1, the output SNR is the same as input SNR; 3) As CR is increased, the output SNR was deteriorated more; 4) As compression becomes less fast acting, the decrement of output SNR is decreased; 5) Even for the slowest compression (with attack and release time constants of 50 and 1550 ms, respectively), there is noticeable decrease in the hearing aid output SNR compared with that in the linear processing; and 6) As the number of compression channels increases, the output SNR decreases increasingly. Accordingly, it could be concluded that the more aggressive compression (fast-acting, high CRs, more channels) leads to more decrement of SNR in the hearing aid output compared with the original SNR in the hearing aid input. It introduces distortions into the spectral and temporal structures of signals and results in less speech intelligibility in noise and lower sound quality. Although the difference between the input SNR and the output SNR in a WDRC hearing aid depends on the modulation characteristics of signal and noise, the deviation between them increases when using more aggressive compression.

Nabalek *et al*. developed acceptable noise level (ANL), which quantifies the subjects' willingness to accept background noise while listening to a running speech [3]. In fact, it is the lowest subjective SNR that a listener can tolerate. ANL is not related to age,

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subject's gender, applied noise type when testing, and uncomfortable loudness level. It has been thought that ANL is strongly influenced by more central regions rather than the peripheral auditory system. It is highly reliable and predicts the degree of hearing aid usage by a subject in the real-world conditions with a high accuracy of about 85%. For example, it has been shown that a full-time user of hearing aid has lower ANL whereas a part-time user has higher ANL. However, all studies are not consistent with the strong relationship between ANL measurement and hearing aid outcome in the real world. Based on a hypothesis that if any technology increases the patient's noise acceptance, then it could result in more successful usage of hearing aid, the ANL has been applied to study the effects of different hearing aid technologies for patients with sensorineural hearing loss. For example, ANL measurement was used for the assessment of digital noise reduction (DNR) and directional microphone. The above studies showed that directionality when compared with the omnidirectional microphone and the DNR improves the ANL. Therefore, it has been claimed that the ANL has a strong capability to show benefits of various hearing aid technologies in the context of the reduction of noise.

Since the hearing aid processing technology or algorithm affects the ANL, it is acclaimed that ANL can be used as a test for evaluating various processing algorithms with regard to the SNR of the hearing aid output. In other words, any type of change in the hearing aid output as a result of hearing aid processing would be reflected in the ANL. In a recent study, with the assumption of the fact that ANL represents the lowest SNR that a subject can tolerate and that ANL is intrinsic to an individual, Wu and Stangle investigated the effect of various mixed processing algorithms and the location of noise on ANL under two unaided and seven aided conditions [4]. They also calculated the hearing aid output SNR using a phase-inversion technique. Their results revealed that DNR and directionality decreased (improved) ANL. Moreover, they found an interesting result that WDRC increased (worsened) the ANL by 1.5 dB, which is in contrast to the ANL improvement as a result of DNR and directionality. In addition, they found that there was a systematic pattern of ANL change across different aided conditions. This pattern of ANL change was correlated to the hearing aid output SNR. Finally, they concluded that WDRC, compared with linear processing, decreases SNR in hearing aid output and consequently provides a noisier sound image for the patient.

However, when they evaluated ANL in WDRC processing, they used only one condition of WDRC (syllabic acting compression). Hence two main questions remain, which are 1) what is the effect of various WDRC conditions on ANL and 2) what is the pattern of ANL change across the various WDRC conditions. Therefore, the purpose of the current study was to evaluate the effects of various types of WDRC constant times (syllabic vs. dual) as well as the different patterns of CRs across channels on moderate sensorineural hearing loss. It was hypothesized that WDRC worsens ANL in general, and the more aggressive WDRC (syllabic and different CR conditions) increases ANL; moreover, the pattern of ANL change across different CR conditions and across different types of WDRC time constants is consistent.

MATERIALS AND METHODS

Subjects

A total of 32 veterans who were provided audiology services at the Department of Audiology in Iran University of Medical Sciences (IUMS) were enrolled in the present study. All the subjects were males with inclusion criteria of being 30–60 years old, post-lingual sensorineural hearing loss for at least 5 years, experience of full-time usage of a hearing aid for at least 2 years (for more information, see the Supplemental), word recognition score greater than 72% in speech recognition testing in quiet (monosyllabic words, PB50), score of at least 21 in Mini-Mental State Examination (MMSE), not using medicines that suppress the central system, sensorineural hearing loss, no history of trauma in the head, and dominantly right-handed. Of the 32 subjects, 17 were using bilateral hearing aid and the others (15 subjects) had unilateral hearing aid. All the subjects had nonlinear hearing aids (For more information about their hearing aids, see the Supplemental). All of them were tested by audiometry and immittance tests, which were performed using the devices OB822 (MADSEN Co., Sweden) and AZ7 (Interacoustic Co., Denmark), respectively. All the subjects signed the written informed consent of the IUMS. All the used procedures, methods, and tests were approved by the ethical committee in the IUMS.

The subjects in the present study were aged between 40 and 59 years (mean age 51.5 ± 6.0 years). They were full-day users of hearing aid with the range of using experience from 2 to 30 years (8.7 ± 7.1). They had blast-induced hearing loss. Their mean audiograms showed hearing loss ranging from moderate in low frequencies to severe in high frequencies (Figure **1**).

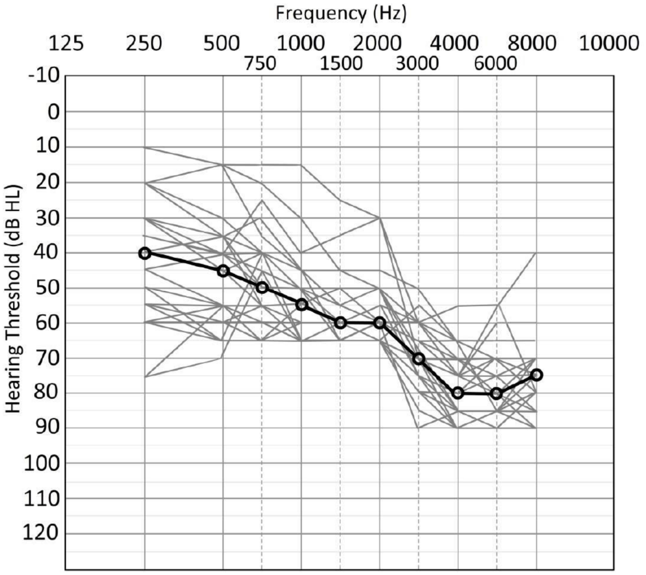

Figure 1: Hearing threshold levels of every participant in the current study. The mean of hearing thresholds is shown as a bold curve with circles (N = 32).

Hearing Aid

For all subjects, a Siemens Motion 700 P behind-the-ear (BTE) hearing aid was used as a test instrument. This instrument was used because of enough gain and output up to the severe hearing loss, and the possibility to change the amplitude compression settings (compression ratio and compression time constants). This hearing aid was fitted monaurally and the opposite ear was closed by an individual ear impression. Since there would be an interference of the vent-transmitted sound with the hearing aid WDRC function, to prevent the effects of the vent on compression function and consequently the probable effect on the results of ANL test, the earmolds of all the patients were without vent. The patient audiogram was given into Siemens fitting software (Connexx 6.4) and the hearing aid was fitted by "First Fit" option inside the software. Amplification targets were determined by the NAL-NL1 (National Acoustic Laboratories – Nonlinear, Version 1) for nonlinear conditions and NAL-RP (National Acoustic Laboratories – Revised for Profound) for the linear condition. The frequency response of amplification for soft sounds was shaped by gain adjustments in Connexx 6.4 according to the NAL-NL1 targets. One of the main aims in this study was to explore the effect(s) of CR difference or consistency across channels on ANL. For this reason, CR was calculated by assuming CRs of 1, 2, 4, and 8. In different CR conditions (1, 2, 4, and 8 CRs across the different channels), the calculation of CR was based on the corresponding hearing thresholds in different frequencies for a situation that there were more CRs (8 CRs) or frequency averages for conditions that there were less CRs (1, 2, and 4 CRs) (Table **1**). This is mentioned to point out that these applied conditions do not indicate the real channel effect. Because, in a real channel processing, the processing (such as gain and compression settings) is independently separated for every channel. This is why the CR settings are different across different channels in this study. Although it could not acclaimed that independent channels were used in the study because of channel coupling and compression action of neighbor channels on each other in the applied hearing aid, the effect(s) of CR consistency across channels was studied. The calculation of CR for each testing condition was based on the formula presented by Gathouse *et al.* [5]. This formula was chosen so that we could provide the best amplification condition and control the side effects of CR(s) on speech perception and sound quality. When setting the CR(s) in Connexx 6.4, the nearest one to the calculated CR(s) was selected if there was not the exact number in the list of CRs in Connexx 6.4. The real ear-aided responses for soft sounds in every condition of nonlinear amplification were measured for the input level of 50 dB SPL (Sound Pressure Level) according to NAL-NL1 targets (±3 dB). The real ear-aided responses for linear amplification were measured for the input level of 65 dB SPL according to NAL-RP targets (±3 dB). All real ear measurements were carried out by the FP35 (Frye Electronics Co, USA). To measure real ear aided responses, *Digital Speech* stimulus was used. Also, according to the possible effect(s) of compression constant times on real measurement, the average of several measurements was used. Before starting the test, the two programs were configured. The first program was for the linear amplification, and the second program was for the nonlinear amplification. For conditions of syllabic and dual acting, the *Syllabic* and *Dual* conditions were respectively chosen in Connexx 6.4. The *Syllabic* condition has 10 and 100 ms for the attack and release times, respectively. In *Dual* condition, there are two combined modes of compression. The fast level meter provides an immediate reduction in gain for higher-level impact sounds. The fast attack time is 5 ms. The second level meter with 900 ms attack time and 1400 ms release time provides gain adjustments based upon

Table 1: The WDRC characteristics of various conditions. Three general amplification conditions (linear, syllabic WDRC, and dual WDRC) were tested. Every syllabic and dual acting WDRC conditions had four subconditions that differ in terms of CR settings and type of time constants. Also, ANL (mean ± SD) is shown in the left column

Condition	Description	Frequencies of hearing thresholds for calculation of Compression Ratios (CRs)	ANL (Mean ± SD)
Linear Amplification	CR = 1	------	8.9 ± 4.3
Syllabic WDRC Amplification	One CR	average of all frequencies0.25, 0.5, 0.75, 1.5, 2.0, 3.0, 4.0, & 6.0 kHz	11.7 ± 4.8
	Two CRs	CR_1: average of 0.25, 0.5, 0.75, & 1.5 kHz, CR_2: average of 2.0, 3.0, 4.0, & 6.0 kHz	12.2 ± 6.0
	Four CRs	CR_1: 0.25 kHz, CR_2: 1.0 kHz, CR_3: 3.0 kHz, and CR_4: 6.0 kHz	12.4 ± 6.0
	Eight CRs	CR_1: 0.25 kHz, CR_2: 0.5 kHz, CR_3: 0.75 kHz, CR_4: 1.5 kHz, CR_5:2.0 kHz, CR_6: 3.0 kHz, CR_7: 4.0 kHz, and CR_8: 6.0 kHz	12.7 ± 5.9
Dual WDRC Amplification	One CR	average of all frequencies 0.25, 0.5, 0.75, 1.5, 2.0, 3.0, 4.0, & 6.0 kHz	9.6 ± 5.1
	Two CRs	CR_1: average of 0.25, 0.5, 0.75, & 1.5 kHz, CR_2: average of 2.0, 3.0, 4.0, & 6.0 kHz	9.1 ± 5.3
	Four CRs	CR_1: 0.25 kHz, CR_2: 1.0 kHz, CR_3: 3.0 kHz, and CR_4: 6.0 kHz	9.6 ± 5.9
	Eight CRs	CR_1: 0.25 kHz, CR_2: 0.5 kHz, CR_3: 0.75 kHz, CR_4: 1.5 kHz, CR_5:2.0 kHz, CR_6: 3.0 kHz, CR_7: 4.0 kHz, and CR_8: 6.0 kHz	10.0 ± 6.6

the average level of the incoming signal [6]. The compression thresholds in all channels were set in 51 dB SPL. In all programs, all the adaptive settings (automatic microphone, feedback canceling, speech and noise management, and *ewindscreen*) were switched off. The microphone was fixed in the omnidirectional mode.

ANL Measurement

Speech and noise stimuli were delivered via a compact disc player through a clinical audiometer to the same speaker that was located in front of and 1 m away from the patient (0 degree azimuth) in an audiometric test room. Speech stimulus was a recorded by running story with a female talker and the background noise was a 12-talker babble speech noise. The used ANL in this study was a Persian version [7] that as provided by the Tehran University of Medical Sciences (TUMS). Both levels of speech and noise were specified by dB HL (decibel Hearing Level). The audiometer and sound field were calibrated based on ANSI S3.6-2004 (American National Standard Institute). Before starting the test, every subject was given both verbal and written instructions, describing the way of experiment and his task in the experiment. As in the typical ANL test, the subject's MCL (Most Comfortable Level) was obtained first. At the start of the test, speech was presented in 30 dB HL and the patient was to signal with his thumb (up or down for increasing and decreasing the level, respectively) in steps of 5 dB. The subject was instructed to signal the level adjustment until his most comfortable loudness level. To construct the perceptual reference on the MCL, the patient was told that he will be presented with higher and lower level of speech and he would be able to compare the levels and select his most comfortable level. The written instructions were as follows:

> "A running female speech will be played for you. You have to adjust the loudness level of the speech to a level louder than what you prefer, then softer than you consider most comfortable, and finally adjust it to a level that is most comfortable for you. Say "okay" when you have reached that level."

After determining the primary level of his MCL, the level of running speech was increased or decreased in steps of 2 dB to find out the exact MCL of the patient. Once the subject determined the final level of the most comfortable level, the level was recorded as the subject's MCL. After the measurement of the MCL, the BNL (Background Noise Level) was measured. For this, the running female speech was played at the MCL and the secondary stimulus (12-babble speech noise) was added as a competing signal. Again, the secondary stimulus was introduced at 30 dB HL and adjusted in steps of 5 dB in the same way as for the MCL measurement. At first, the subject was to adjust the level of the babble noise to a level that the female speech could not be heard clearly, then to a level that the female speech could be heard clearly. Finally, the subject was instructed to determine the level of babble noise "backing up to the most noise that you would be willing to put up with and still follow the story for a long period of time without becoming tense or tired." During this final adjustment, the step size was changed to steps of 2 dB. Once the subject determined the final level, the level of babble noise was recorded as the BNL. The BNL was measured three times, and the average of the three values was considered as the final BNL. Then, the ANL was calculated using the MCL and the BNL (ANL = MCL − BNL).

The above measurements for ANL were accomplished for varying number of CRs and time constants (Table **1**).

All tests were accomplished in three sessions. The first session was to describe the purpose of the study, interview with the subject, and sign the consent. The audiometric and immittance tests were accomplished during the first session, and the ear impression was also taken from the patient's ear to provide his individual earmold. During the next two sessions, the MCL, BNL, and ANL were measured in nine different conditions (Table **1**). In every session, the measurements for the nine conditions were randomized. Between the measurements in every session, the subjects were given a few minutes to relax. Each one of the two last sessions took a time period of between 2 and 2.5 hours.

Statistical Method

To analyze the results, the SPSS software (version 22.0) was used. The statistical descriptive parameters such as the mean and standard deviation of the ANL were considered. To determine the statistically significant differences among the various conditions of ANL, at 0.05 level, a one-factor, repeated-measurement analysis of variance (ANOVA) test was performed. Also, while comparing the various conditions, the Bonferroni test was used.

RESULTS

The average of the ANLs under the various hearing aid conditions is shown separately in Table **1**.

Comparing ANL in Linear Condition with all-Syllabic and Dual WDRC Conditions

To compare the ANLs obtained in the linear and WDRC (syllabic and dual) conditions, a one-factor repeated measures ANOVA was conducted. The within-subjects independent variable was amplification type (linear, all syllabic WDRCs, and all dual WDRCs). Significant main effect was observed ($F_{(8, 24)} = 15.34$, $p < .001$). Post hoc analyses (Bonferroni test) suggested that all-syllabic acting conditions significantly increased the ANL (2.8, 3.3, 3.5, and 3.8 dB; 1, 2, 4, and 8 CRs syllabic WDRC versus linear) and that the increment of ANL was increased with increase of different CRs, whereas dual WDRC conditions did not significantly change the ANL (0.7, 0.2, 0.7, and 1.1 dB; 1, 2, 4, and 8 CRs dual WDRC versus linear).

Comparing ANL in all-Syllabic WDRC Conditions with all-Dual WDRC Conditions

To compare the ANLs obtained in the syllabic and dual WDRC conditions, the one-factor repeated measures ANOVA was conducted. The within-subjects independent variable was WDRC type (all-syllabic WDRCs and all-dual WDRCs). Significant main effect was observed ($F_{(7, 25)} = 9.84$, $p < .001$). Post hoc analyses (Bonferroni test) suggested that ANL in 1 CR-syllabic acting compression was higher than the ANL in 1- and 2-CR dual acting compressions (2 and 2.5 dB, 1-CR-syllabic WDRC versus 1 and 2 CRs dual WDRCs). In addition, the ANL in the condition of 2-CRs syllabic acting compression was significantly higher than the ANL in all-CR conditions of dual acting compression (2.6, 3.1, 2.6, and 2.2 dB, 2 CRs syllabic WDRC versus 1, 2, 4, and 8CRs dual WDRCs). This trend was also applicable when comparing the ANL in the condition of 4 CRs syllabic acting compression with all conditions of dual acting compression (2.8, 3.2, 2.7, and 2.3 dB, 4 CRs syllabic WDRC versus 1, 2, 4, and 8 CRs dual WDRCs), as well as for the comparison of ANL in the condition of 8CRs syllabic acting compression with all conditions of dual acting compression (3.1, 3.6, 3.1, and 2.7 dB, 8CRs-syllabic WDRC versus 1, 2, 4, and 8CRs-dual WDRCs).

Lowest and Highest ANL Conditions

Finally, the best condition of ANL, i.e., the lowest ANL, was observed for the linear amplification and the worst condition, i.e., the highest ANL, was observed for 8CRs-syllabic condition. The ANL for the dual acting compression was somewhere between the ANL for linear and ANL for syllabic acting compression conditions.

Generally, the ANL was increased with the increment of the number of different CRs in both syllabic and dual acting compressions (Figure **2**).

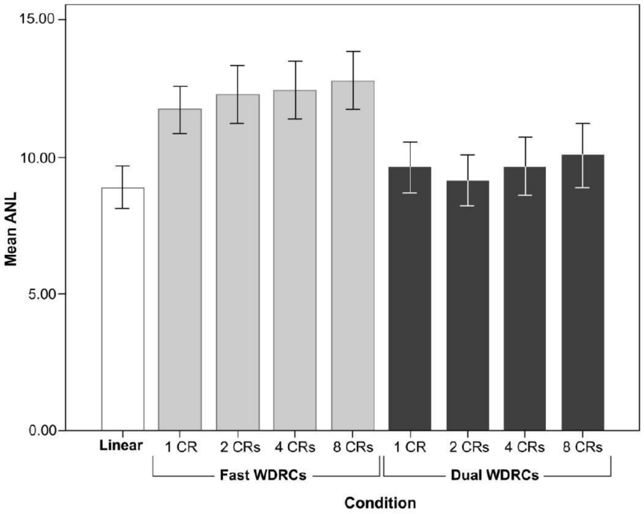

Figure 2: The average values of ANL in various conditions of amplification and its trend with increasing different CR numbers (N = 32). Error bars show the 95% confidence intervals. The white bar is for the linear condition. The four gray bars indicate the syllabic acting WDRCs. The four black bars indicate the dual acting WDRCs. Also, the number of applied different CRs for each condition is shown.

DISCUSSION

In the current study, we aimed to explore the effect of different WDRC settings of hearing aid on patients with moderate sensorineural hearing loss by using ANL test. Our results showed that the ANL in various conditions of amplification is variable and strongly depends on the compression patterns. Moreover, we investigated the effects of both the CR consistency across channels and type of compression action on ANL. We concluded that WDRC, either syllabic or dual acting, increases (worsens) ANL in comparison with the linear amplification. The syllabic acting amplitude compression significantly deteriorates this condition. The ANL was increased with the increment of the number of different CRs in both syllabic and dual acting compressions.

Because the ANLs in various conditions of amplifications (linear, syllabic acting, and dual acting) were significantly different, we concluded that ANL depends on the settings of amplitude compression (the time constants and CR consistency or differences in this study). Our results speculated that the linear amplification presents the best figure of signals (mainly speech) in noise and that the amplitude compression presents the noisy figure of signals for the patients. The faster the acting compression, the more noisy is the figure of signals. This result is in agreement with the last performed study, in which both subjective measurements (by ANL test) and objective measurements (by measuring the SNR in the hearing aid output using the procedure of Hagerman and Oloffsson [8] showed that WDRC has a detrimental effect on the ANL. The detrimental effect of syllabic acting compression, however, could be offset by the dual time constants, but not to as much as the condition of linear amplification.

Our results showed that by increasing the number of different CRs, in both syllabic and dual compressions, the ANL increases. But this difference was not statistically significant. However, when considering the interaction of different CRs with the constant time of compression, there were statistically significant differences among the amplification conditions. The lowest ANL score, i.e., the best condition of amplification, was observed for both linear and 2CRs-dual WDRC. The highest ANL score, i.e., the worst condition of amplification, was observed for 8CRs-syllabic WDRC. However, the 8CRs-dual acting was better than its syllabic acting counterpart. Among the conditions of syllabic acting compressions, 1-CR is the best, but among the dual acting compressions, 2-CRs condition was the best, even better than a 1-CR syllabic acting. This finding is completely consistent with the findings of a previous study. When using slow-acting component of compression, because of higher amplification of low frequencies resulting from the slow action of hearing aid in decreasing the gain for this range of frequency, the upward spread of masking might be possible. The upward spread of masking affects speech in noise discrimination. But when using two channels, this condition disappears. That is why 2-CRs dual acting compression has the lowest ANL in comparison with the 1-CR dual acting condition.

It has been thought that ANL is an inherent characteristic of the individual rather than an attribute of the hearing aid. Our findings suggest that ANL is not only inherent to individual characteristics, but also it depends on the type of WDRC applied in the worn hearing aid.

There is a fact that ANL is strongly dependent on the presentation level of speech. Since the level of speech or noise would be higher when using the dual acting compression as a result of the application of slow-acting component of compression, we have to predict that the ANL would be increased. But, the reverse condition was observed when using the dual WDRC. Thus, it can be explained that the significant ANL change across conditions (syllabic vs. dual and consistent CRs vs. different CRs) might be due to the consequent change of signal contrasts rather than change in the presentation levels of the stimuli as a result of syllabic or dual action of WDRC. This is a finding that needs more comprehensive and highly controlled research.

Finally, since there would be a possible relationship between the benefit of WDRC type, the patient's cognition, and degree and configuration of hearing loss, we controlled those factors by including the subjects with high level of cognition (MMSE scores higher than 21) and relatively similar audiogram configuration and degree. Furthermore, a new research showed that ANL is affected by personality type [9]. As mentioned before, we tried to study on full-day hearing aid users with relatively similar audiogram configuration and degree and did not consider the subjects' personality type and unsuccessful hearing aid users. Since ANL for a full-day hearing aid user is always lower than an unsuccessful user of hearing aid and our WDRC settings affect ANL in full-day users, it would be predicted that ANL will be affected similarly or even deteriorated severely in the later subjects.

CONCLUSION

To summarize, first, the settings of amplitude compression can affect the ANL. The application of more aggressive amplitude compression (syllabic acting and more different CRs) results in increased ANL in moderate sensorineural hearing loss. But the less aggressive amplitude compression (slow-acting and consistent CRs) improves the ANL results.

SUPPLEMENTAL MATERIALS

The supplemental materials can be downloaded from the journal website along with the article.

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