COMPARISON OF NOMINAL AND MEASURED COMPRESSION RATIOS AND COMPRESSION THRESHOLDS, IN HEARING AIDS, USING ELECTROACOUSTIC MEASURES.

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This dissertation is submitted as part fulfilment for

the degree of Masters of Science (Audiology)

University of Mysore

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AUGUST 2022

CERTIFICATE

This is to certify that this Masters dissertation entitled **Comparison of nominal and measured compression ratios and compression thresholds, in hearing aids, using electroacoustic measures** is a bonafide work submitted as a part for the fulfilment for the degree of Master of Science (Audiology) of the student with Registration Number: 20AUD039. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this Masters dissertation entitled **Comparison of nominal and measured compression ratios and compression thresholds, in hearing aids, using electroacoustic measures** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this Masters dissertation entitled **Comparison of nominal and measured compression ratios and compression thresholds, in hearing aids, using electroacoustic measures** is the result of my own study under the guidance of Dr. P. Manjula, Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysuru. This has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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August, 2022

"It's the possibility of having a dream come true that makes life interesting."

– Paulo Coelho, The Alchemist

ACKNOWLEDGEMENT

I thank **God** almighty for all the blessings.
I express my sincere gratitude to my guide, **Dr. Manjula P**., Professor of Audiology for her patience, motivation, enthusiasm, and immense knowledge. Your guidance helped me in all the phases of research and writing of this dissertation. It is my faith in you that kept me grounded and determined.
I thank our esteemed Director, **Dr. M. Pushpavathi** for providing me the opportunity to carry out this research.
I extend my sincere gratitude to **Dr. Prawin Kumar**, HOD, Audiology, for providing all the facilities and permissions to carry out this research.
Sharath sir, Vikas sir, Ramadevi ma'am, thank you for your valuable inputs and help.
Vasanthlakshmi ma'am and Srinivas sir; sincere thanks for your valuable suggestions and guidance in statistical analysis.
Dhakshayini ma'am, Shraddha ma'am; I can't thank you enough for all the help done. Both of you have made this a lot easier.
I thank the **Dept. of Electronics**, especially Ravi Shankar sir for helping with the calibration and softwares.

Prof. T. Dattatreya, Swetha ma'am, Thejaswi Sir, Usha ma'am, Archana ma'am, Bennett ma'am; Thankful to you in the deepest sense for building the foundations of audiology in me and realizing my potential.
All the **teachers** who have imparted knowledge to me; I will always be indebted to you.

Ashiq & **Sahana;** we have been in this together; **Sahana**, I couldn't ask for a more dedicated partner. From pushing me to stick to the deadlines, to reminding me time and again to do my work… Thanks a lot.
Gurpreet, Nikhilesh, Malvika, Nethra; postings were much less stressful because of your madness.
Pooja, Aishwarya, Monisha, Malavika S; Much love to y'all.
Yoshita, Sonam; cheers to all the chai, maggi, gossip sessions, laughs, and memories made together.
Sanjay; your patience and kind self is much appreciated.
Rujman; I owe you for putting up with this big baby and her monkey business.

Amma, Acha; forever thankful for your love and care. You both are the biggest blessing that I possess. You keep your faith in me even when I doubt myself; this keeps me going. **Chinnu**; I am always trying to be the person that you think I am. And your high expectations make me a better person. **Achacha, Achamma, Nana, Nani;** Thank you for the blessings and prayers.

If I got rid of my demons, I'd lose my angels. – Tennessee Williams

Gratitude to everyone who has been instrumental in molding me into me.

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Abstract

Hearing aids incorporate compression in them and this will be useful for individuals having reduced dynamic range. In some hearing aids, the compression ratio (CR) and/ or compression threshold (CT) are programmable through the hearing aid programming software.

Various studies highlight the non-compliance of compression parameters when measured by electroacoustic measurements. The CR displayed on the programming screen, i.e., the nominal CR does not always represent the CR that is measured i.e., measured CR. Similarly, the CT that is displayed on the screen during programming, i.e., the nominal CT may not be equal to the CT measured through input-output function of electroacoustic measurement. The present study has two objectives. First, to compare the nominal CR with the measured CR. Second, to compare the nominal CT with the measured CT. Repeated measures research design was used to verify the objectives.

Method:

Hearing aids were programmed with the National Acoustical Laboratory Non-Linear 2 (NAL-NL2) fitting formula for flat hearing thresholds of 50 dB HL for low-powered and 70 dB HL for high-powered hearing aids, for naïve hearing aid users. The CRs and/or CTs were kept at low-, mid- and high- levels. The other hearing aid features were disabled. The input from the calibrated hearing aid test system was a 2 kHz tone that varied from 50 to 90 dB SPL, in 5 dB steps. The output of each programmed hearing aid (n= 13 in Group 1, low gain hearing aids, n=12 in Group 2, high power hearing aids) was measured in the form of input/output graph. From this, the measured CR and the measured CT were computed. The way in which the nominal CR and nominal CT was set in the two groups of hearing aids slightly differed depending on the programmability feature of CR and CT.

Results:

Descriptive statistics revealed that the nominal and measured compression parameters were not the same. Hence, Wilcoxon Signed Ranks test was administered since the data were not normally distributed. Measured CR was significantly different from the nominal CR in both the Groups 1 and 2.

In Group 1 hearing aids, there was a significant difference between the nominal and measured CR. In Group 2 hearing aids, at low nominal CR, the nominal CR was lower than the measured CR. At mid nominal CR, there was no significant difference between the nominal and measured CR. At high nominal CR, the nominal CR was significantly higher than the measured CR.

In Group 1 hearing aids, CT comparisons were not carried out as there was no provision for manipulating the CT, nor was the CT displayed in the programming software. In Group 2 hearing aids, at low nominal CT, the measured CT is significantly higher than the nominal CT. At mid nominal CT, no significant difference was noted between nominal CT and measured CT, except in the condition where the nominal CR was low, where the measured CT was significantly lower than the nominal CT. The measured CT was significantly lesser than the nominal CT at high nominal CT.

Conclusions:

In the present study, there was a significant difference between the nominal compression parameters and the measured compression. Similar findings were also reported by Verschuure et al. (1996). Hence, this has to be kept in mind while programming CR and CT in hearing aids, i.e., what is displayed on the programming screen is not the same as that measured through electroacoustic verification.

Keywords: Input-output function, Electroacoustic verification, Nominal compression ratio, Nominal compression threshold, Measured compression ratio, Measured compression threshold.

Chapter 1

INTRODUCTION

The primary rehabilitation option for individuals with sensorineural hearing loss is hearing aids (Walker & Dillon, 1981). The main function of a hearing aid is to amplify sounds in order to improve speech recognition by restoring audibility (Jenstad & Souza, 2007; Souza et al., 2007; Souza & Turner, 1999). Hearing aids when fitted according to the listening needs of the individual provide them with improved quality of life.

Earlier the hearing aids were mostly linear and therefore gave the same gain at all input levels. This was found to be detrimental for those individuals with hearing loss associated with cochlear damage. Hearing impairment with cochlear damage often manifests in softness imperception/ loudness recruitment, along with elevated thresholds. They have more or less the same uncomfortable levels leading to reduced dynamic range.

The earlier linear systems were not able to accommodate the wide range of sound intensities found in the environment into the reduced dynamic range of individuals with cochlear damage. This resulted in discomfort due to uncomfortably loud sounds through the linear hearing aids. The non-linear/ compression systems were, therefore, developed to provide variable gain at different input levels to relieve the discomfort of hearing aid wearers due to extreme loud sounds. Compression results in the dynamic range of the output of the hearing aid being less than that of the input (Walker & Dillon, 1981).

Compression systems have static and dynamic characteristics. Static characteristics are those that are constant over time, viz., the compression thresholds, and the compression ratio. Dynamic characteristics vary with time. These are the attack and release time constants (Stone & Moore, 1992).

The compression threshold (CT) is the level above which compression starts to operate. Below the CT, the hearing aid amplification is linear. In a study by Barker & Dillon (1999), a CT of 65 dB SPL was preferred by individuals with mild to moderate sensorineural hearing impairment over a CT of 45 dB SPL. The CT that is set while programming the hearing aid is the nominal CT, whereas that obtained from electroacoustic measurements is termed as the measured or effective CT.

Compression ratio (CR) is the difference in input level (in dB) that is required in order to produce a unit difference in output level (in dB). Greater the CR, greater is the amount of compression. Neuman et al. (1998) reported that increasing the CR led to decreased clarity and the overall speech quality. Speech recognition in noise was reported to be poor with higher compression ratios (Boike & Souza, 2000). The CR that is set while programming the hearing aid is the nominal CR, whereas that measured by electroacoustic measurements is termed as the measured or effective CR.

Input/Output (I/O) function is the graphical representation of the output from the hearing aid receiver at different input levels. It can be defined as the line plot of the sound pressure level (SPL) obtained in the coupler during electroacoustic measurements as a function of the input SPL for a individual frequencies (ANSI S3.22-1996 as cited in Banerjee, 2017).

The attack and release times are the times taken for the compression system to get in and out of action respectively. Attack time can be defined as the time taken by the compression to start after the spike in the input sound level, whereas the release time is the time required by the compressor to stop after a drop in the input sound level. These values depend on whether the main goal of compression is to control the maximum power, reduce the inter-syllabic intensity differences, or to reduce the long-term intensity differences of the output. Usually, small attack times are chosen to protect the hearing aid user from sudden increases in the sound (Moore et al., 2001). To reduce the inter-syllabic intensity differences, very small attack and release times are employed, and to maintain the long-term level of the output, long attack and release times are used (Dillon, 2008; Musa-Shufani et al., 2006). The compression systems with fast attack times may have negative effects on speech intelligibility (Plomp, 1988, 1994; van Dijkhuizen et al., 1991).

The level-dependent amplification is provided by wide dynamic range compression (WDRC). It is, hence, capable of increasing the audibility of soft speech components while avoiding over amplification of high-intensity input levels and the resulting loudness discomfort (Alexander & Rallapalli, 2017; Villchur, 1973). The compression systems in the modern hearing aid systems provide amplification within the user’s dynamic range. This enhances speech perception in quiet compared to linear hearing aids (Hickson, 1994).

The electroacoustic measurement is an objective measure meant to be used by audiologists to aid in hearing aid fitting to verify the performance of the hearing aids. It helps to check if the hearing aid conforms to the specifications given by the ANSI standards and the manufacturers claims. It serves as a quality control check, monitors the performance of the hearing aid at purchase and during use, and also, can be used to research the effects of different acoustic or electronic modifications to the hearing aid.

The extent to which the hearing aids comply with the manufacturer claims and standards is not clear. Studies have reported that more than 68% of the hearing aids do not comply with the ANSI standards (Callaway & Punch, 2008; Chial, 1977; Humes et al., 1997; Robinson & Sterling, 1980; Townsend & Olsen, 1982). In a study by Holder et al.

(2016), a large number of discrepancies have been observed between the specifications suggested by the manufacturer and the data obtained by quality control testing.

Verschuure et al. (1996) reported nominal or effective CRs of 2.0, 2.5, and 3.0 for the 2000 Hz octave range, for nominal CRs of 2, 4, and 8 respectively. Stelmachowicz et al. (1995) reported an effective CR of 1.3:1 for a nominal CR of 2:1. In another study by Geetha (2016), it was reported that the nominal CRs which were set during the programming of the hearing aids were not comparable to the CRs that were measured from the hearing aids.

Souza and Turner (1999) investigated CRs in low and high frequency channels. In the low frequency channel, they reported an effective CR of 1.2-1.3 for nominal ratio of 2:1, whereas in high frequency channel they measured an effective ratio of 1.7-2.0 for nominal ratio of 5:1.

In a study by Braida et al. (1982), it was found that the effective CR was similar to the nominal CR only when the stimulus had low modulation rate, and that the effective CR neared one at higher modulation rates. Stone and Moore (1992) have also reported similar findings. The rate and depth of modulation along with the level of the signal was found to affect the measured CR.

Henning and Bentler (2008) suggested that the number of channels will have an effect on the measured CR, further they reported this effect only when the nominal ratio was 4:1 rather than 2:1. In the same study, it was reported that the release time also had an effect on the measured CR. They suggested that compression was more effective when the release time reduced from 1024 ms to 32 ms.

Studies that have compared the nominal CT with the measured CT of compression hearing aids are scarce.

Aim

The aim of this study was to compare the nominal and measured compression parameters, i.e., CR and CT, of hearing aids using electroacoustic measures.

Objectives of the study

To fulfil the aim of the current study, the following objectives were taken;

1. To compare the compression characteristics of the hearing aid in terms of CR displayed while programming, i.e., nominal CR, and that measured through electroacoustic measurements, i.e., measured CR.
2. To compare the compression characteristics of the hearing aid in terms of CT displayed while programming, i.e., nominal CT, and that measured through electroacoustic measurements, i.e., measured CT.

Hypotheses

1. There is no significant difference between the nominal CR and the measured CR.
2. There is no significant difference between the nominal CT and the measured CT.

Chapter 2

REVIEW OF LITERATURE

In a linear hearing aid circuit, a constant gain is given to all input levels, until the hearing aid reaches its saturation. Since everyday speech or environmental sounds have an extensive range of intensities, from low energy consonants to high energy vowels, the value of a linear hearing aid is limited when the amplification required to make low energy sounds audible increases high energy sounds to the verge of distress. It is, thus, difficult to provide amplification to individuals with smaller dynamic range in everyday situations using a linear hearing aid.

To overcome this difficulty, hearing aids adjust gain based on the input intensity. When the input intensity is high, the gain given is less compared to the gain given to low-level input thereby compressing the dynamic range of the output of the hearing aid, or providing non-linear amplification. This is known as amplitude compression or just compression.

The relevant literature is discussed under the following headings:

I. Need for compression

- Discomfort, distortion, and damage reduction
- Reduction of inter-syllabic and inter-phonemic intensity differences
- Long-term dynamic range reduction
- Loudness normalization
- Increasing intelligibility
- Noise reduction

II. Different parameters of compression

III. Different compression strategies and technologies

Compression Limiting

Syllabic Compression

Automatic Volume Control (AVC)

I. Need for compression

Compression systems offer a range of benefits to the hearing aid wearer (Dillon, 2008). They include reduction of discomfort, distortion, damage, reduction of inter-syllabic intensity differences, loudness normalization, increasing intelligibility, reduction of long-term dynamic range and noise reduction.

Discomfort, distortion, and damage reduction

The level of a hearing aid's output cannot continue to rise as the level of the hearing aid's input rises, since it will cause discomfort due to the reduced dynamic range and may cause further damage to his/her residual hearing. Peak clipping at higher levels cause distortion. Thus, compression provides the audibility within the dynamic range with lesser distortion.

Reduction of inter-syllabic and inter-phonemic intensity differences

The vowels are more intense than consonants among speech sounds, and the difference between the vowel and the consonant ranges up to 30 dB (Freyman et al., 1991). The weaker phonemes will be masked out by the more intense ones for individuals with hearing loss. The weaker phonemes are boosted using compression amplification, while the powerful sounds, such as vowels, are compressed by providing less gain. As a result, the vowel-to-consonant level difference is maintained, avoiding the temporal masking phenomenon.

Long-term dynamic range reduction

The compression hearing aids reduce the long-term dynamic range while leaving the intensity relationships between syllables that are closer in time unchanged. This is accomplished by using attack and release times that are substantially longer than the average syllable duration.

Loudness normalization

Normalizing loudness is based on the equal-loudness contour, which indicates that all frequencies should be heard at the same loudness. This is a possible factor to consider for people who have sensorineural hearing loss and have great difficulty in loudness perception. The most common reason for utilizing compression is to normalize the perception of loudness. Separate compressors in each channel of a multichannel hearing aid are the most common approach to achieve loudness adjustment.

Increasing intelligibility

Multichannel compression can be used to achieve the level of audibility that maximizes intelligibility in each frequency band, subject to some constraints on overall loudness.

`Noise reduction

The compression can be used to reduce the interfering effects of noise by reducing low-frequency gains in loud environments, thereby improving intelligibility. In a study by Gatehouse et al. (2006a) he reported that lesser benefits are derived from linear hearing aids by individuals with more reduced dynamic ranges, sloping losses, and greater differences in dynamic range between higher and lower frequencies. Also, the non-linear hearing aids seem to provide better benefit to individuals with more varied auditory lifestyles and listening environments. But the researchers were not able to find a statistically significant difference in the self-reported Auditory Lifestyle and Demand Questionnaire in favour of either hearing aid. Gatehouse et al. (2006b) used APHAB, SADL, and GHABP and reported that non-linear fitting outpaced linear fitting in terms of listener satisfaction, listening comfort, speech intelligibility and, reported intelligibility.

II. Different parameters of compression

The static and dynamic characteristics of non-linear circuits dictate their function and application. Static characteristics are not influenced by time. The following are the properties of compression amplifiers (Hickson, 1994):

1. Compression knee-point & threshold: The smallest amount of input level required to initiate compression. This is the point on the input/output function where the circuit shifts from linear to compression, and it's also known as the compression knee-point. The compression threshold (CT) is defined as the input SPL that results in a gain decrease of 2 dB compared to the gain in the linear mode, (IEC 118-2, 1983 as cited in Banerjee, 2017) . Below the CT, usually linear gain is provided. Alternatively, some non-linear hearing aids provide expansion rather than linear amplification below CT. In expansion, low-level inputs are given lesser gain than the linear gain. This is mainly done to reduce the amplification given to low-level ambient noise or microphone noise (Kuk, 2002).

A compression system's CTs might be high or low depending on the application. A high CT, 60 dB SPL or more, is used to restrict a hearing aid's output so that it does not surpass the individual's loudness discomfort thresholds and to enhance listening comfort. A low CT, often set below 60 dB SPL, on the other hand, may be employed to increase the audibility of the softer components of speech and/or to restore loudness perception.

The CT that is set while programming is the nominal CT and that measured through electroacoustic measurements is the measured or effective CT.

2. Compression range: The input level range in which compression circuit comes into action.

3. Compression ratio (CR): The inverse of the input/output (I/O) curve's slope, i.e., the difference in input level divided by the difference in output level. CR of the aid is 2:1 if every 5-dB increase in the input results in a 2.5-dB rise in the output.
The CR controls how much the signal will be compressed when the input signal is loud enough to trigger compression (i.e., when the input level surpasses the CT). In other words, it signifies the magnitude of gain reduction (Souza, 2002). It is the ratio of the difference in input SPL to the difference in output SPL. (IEC 118-2, 1983 as cited in Banerjee, 2017). The CRs are commonly described in terms of the number of decibels (dB) that the input must change in order to produce a one-decibel change in the output. The CR that is set while programming is the nominal CR and that measured through electroacoustic measurements is the measured or effective CR.

This terminology can be used to describe a compression amplifier's input/output function. The static properties such as compression threshold and compression ratio reveal how the circuit behaves in response to steady-state input signals.

The dynamic parameters of compression are time-dependent and correspond to the system's temporal responsiveness to changes in input. They define the amount of time necessary for the circuit to respond to a changing input signal (Hickson, 1994). Based on the time constants of the feedback loop components, compression hearing aids require a certain time period to achieve a steady output level after variations in input. The time periods are known as compression amplifier dynamic characteristics, and they are described as follows (Australian Standard 1088.2, 1987 as cited in Banerjee, 2017):

1. Attack time: The period between a sharp rise in input intensity (typically 25–40 dB) and the instant when the hearing aid output SPL steadies at the new steady-state level (usually ±2 dB).
2. Release time: The time period between a sharp drop in the input SPL and the point when the SPL of the aid output steadies at the new steady-state level of ±2 dB. This is also identified as ‘recovery time’.

III. Different compression strategies and technologies

Various types/ strategies of compression are designed to satisfy the requirements of listeners with hearing impairment.

Compression Limiting

The compression limiting systems have brief attack times, high CT, and a high CR (usually greater than 5). For most input levels, the amplification is linear, and an average speech signal would not activate the compression circuit. This is also known as ‘high-level compression (HLC)’ (Walker & Dillon, 1981).

Compression is better than peak clipping. Peak clipping, an "instantaneous" regulator, that exacerbates harmonic and intermodulation distortion, is generally thought to be less beneficial. (Boothroyd et al., 1988; Braida et al., 1979; Dreschler et al., 1984; Preves, 1991; Walker & Dillon, 1981)

Syllabic Compression

Syllabic compression is characterized by the short attack and release times, a low CT, and a low CR (<5). They are termed so as this process compresses small syllable units of speech, reducing inter syllable level variations, and also inter phoneme level variations. Release times vary from less than 50 milliseconds to 150 milliseconds. The release time in this system must be lesser than the typical duration of a syllable in conversational speech, which is 200 to 300 milliseconds (King & Martin, 1984).

Automatic Volume Control (AVC)

The AVC is also known as automatic gain control (AGC) or long-term compression (King & Martin, 1984). The use of long time constants is a distinctive feature of such systems. The release time is longer than 150 milliseconds and can reach several seconds. The CT is often low, while the CR is high (more than 5) (Walker & Dillon, 1981). In theory, a hearing aid with AVC should benefit those with hearing impairment who don't have substantially limited dynamic range but does have a speech discrimination optimal level over which discrimination reduces. AVC helps to keep the output level close to this optimum level for maximum speech intelligibility, which correlates to the person's limited range (Braida et al., 1979; King & Martin, 1984; Walker & Dillon, 1981).

The compression parameters set as per the prescriptive formula for an individual may not always suit the individual with hearing loss. There can be instances where the audiologist will have to manipulate the compression parameters (CR and CT) during hearing aid programming. In such cases, the compression parameters have to be varied while programming, to match the individual's needs. However, some studies have reported a disparity between the CR that is set while programming (i.e., nominal CR) and that measured through electroacoustic measurements (i.e., measured CR or effective CR). Studies related to comparison measures of nominal and measured CTs were scarce.

Verification refers to the physical measurement of the output of a hearing aid. The purpose is to see if it meets certain predefined criteria. It may be as simple as testing the electroacoustic output of a hearing aid to see if it complies with the data on the specification sheet. Other verification techniques or indices include evaluating coupler output to see if it fits a prescribed output/gain objective, or measuring the real-ear output of a hearing aid to see if it matches a specified gain/output target (Kuk, 2002).

Examining a hearing aid's static I-O curve is one approach to learn more about how the compression operates. A steady-state sinusoid or a composite noise signal can be used to determine this curve (ANSI S3.22-1996 as cited in Kuk, 2002). Most studies use a 2000-Hz sinusoid as the stimulus to demonstrate the static and dynamic features of a compression hearing aid due to its simplicity (Kuk, 2002).

Braida et al. (1982) investigated the effect of a CR of 3 on the envelope of a sinusoidally amplitude modulated signal. They demonstrated that the effective compression ratio equaled the steady-state ratio only at low envelope modulation rates, and that at high modulation rates, the ratio approached one (i.e. no compression). Furthermore, when the modulation depth was raised for a given modulation rate, the effective CR dropped.

In 1992, Stone and Moore reported the following results in their study, which were recorded with a CR of 3. These results conform with that of Braida et al. (1982).

1. The effective CR of compression limiting circuits with exponential attack and release characteristics is significantly reliant on the level of the signal relative to the CT, the rate of modulation of the signal, and the depth of modulation of the signal.
2. The compressor's target CR is accomplished with modulation rates whose period is substantially higher than the sum of the attack and release durations, and for a signal completely above the CT.
3. While the input signal is only partially over the CT, as is frequently the case when wearing hearing aids, the effective CR is smaller than the nominal ratio.
4. Since the gain control signal cannot follow the modulation at high modulation speeds, the effective CR reduces. The effective CR approaches one when the modulation period falls below the sum of the attack and release durations. Other than a fixed, time-invariant gain adjustment, the short-term envelope shape can then be considered untouched by the compressor.
5. Because effective CR depends on signal level, as well as modulation rate and depth, an infinite compressor (compression limiter) with short time constants can behave similarly to a syllabic compressor for intermediate modulation rates, especially when only a portion of the signal is above the CT.

For nominal ratios of 2:1, 4:1, and 8:1, Verschuure et al. (1996) reported effective broadband CRs of 1.9, 3.8, and 5.2, respectively. They discovered effective CRs of 2.0, 2.5, and 3.0 for nominal CRs of 2, 4, and 8, respectively, for the 2000-Hz octave range.

Several studies have been conducted to determine effective CRs for various dynamic inputs. Stelmachowicz et al. (1995) used a K-Amp WDRC circuit with a release time of about 100 ms to study the acoustic effects of WDRC on eight vowel-consonant and consonant–vowel nonsense syllables. Although the nominal CR was 2:1, the effective or measured CR was just 1.3:1.

Souza and Turner (1999) assessed the efficiency of compression for vowel-consonant-vowel syllables in the low- and high- frequency bands. They used a two-channel WDRC system with 1500 Hz as channel boundary, a 45 dB SPL CT in each channel, a nominal CR of 2:1in the low-frequency channel, a nominal 5:1 CR in the high-frequency channel, and attack and release times of 8 ms and 15 ms, respectively. They discovered that the measured CR for speech in the low-frequency channel was 1.2–1.3 and 1.7–2.0 in the high-frequency channel.

Unlike the previous researchers who used syllables, Verschuure et al. (1996) tested the efficiency of phonemic WDRC (attack and release timings of 5 ms and 15 ms, respectively) on a 32-s sample of continuous Dutch speech. They discovered effective CRs of 1.9, 3.8, and 5.2 for nominal CRs of 2:1, 4:1, and 8:1, respectively.

A few researchers investigated the effect of release time on the efficiency of compression for dynamic signals. Verschuure et al. (1996) used a laboratory WDRC system with a nominal CR of 4:1 to investigate the impact of four release timings (15, 30, 60, and 120 ms) on the measured CR of amplitude-modulated pure tones. The WDRC became progressively effective as the release time decreased. The effective CR was around 3.8, 3.7, 3.5, and 2.3 for release time of 15, 30, 60, and 120 ms, respectively, for a modulation frequency of 5 Hz, which is similar to the modulation rate of speech syllables. With a quick release time, a WDRC system is more likely to be able to track the quick intensity fluctuations of dynamic signals and modify the amplification given correspondingly, resulting in more efficient compression for the short-term dynamic range of speech.

Stone and Moore (1992) reported similar results when they employed a low-frequency sine wave to signify the temporal envelope of the speech signal and discovered that this sine wave was more successfully compressed when release times were shorter.

According to Henning and Bentler (2008) when the nominal ratio was 4:1, the number of channels had a greater influence than when the nominal ratio was 2:1. The effectiveness of compression was measured in terms of the short-term dynamic range. It was noted that there was no significant difference in the short-term dynamic range with one channel versus four channels with the nominal ratio of 2:1, whereas, with nominal ratio of 4:1, there was a reduction in the short-term dynamic range when the number of channels was increased from one to four, especially for the higher frequencies. In the same study, they reported that for both the nominal ratios, compression was more effective when the release time was reduced from 1,024 milliseconds to 128 milliseconds. For a nominal ratio of 4:1, the efficiency of compression was reported to improve further when the release time was reduced to 32 milliseconds from 128 milliseconds. This trend was not observed in 2:1 nominal ratio.

Chapter 3

METHOD

The aim of the study was to compare the nominal and measured compression ratio (CR) and compression thresholds (CT) in behind the ear (BTE) hearing aids. The specific objectives were (a) to compare the CR displayed while programming (i.e., nominal) and that measured through electroacoustic measurements, and (b) to compare the CT displayed while programming (i.e., nominal) and that measured through electroacoustic measurements.

To realize the objectives of the study, repeated measures research design was framed (Dominowski, 1980). In this type of research design, multiple or repeated measurements are made on each experimental unit. In the present study, the 'experimental unit' is the 'hearing aid' which is set at different compression settings. The details of the method to achieve the objectives of the study are provided in the following sections.

Hearing aids

Twenty-five non-linear digital BTE hearing aids were used. These hearing aids had a feature to manipulate the CR and / or CT through the hearing aid programming software. The hearing aids were categorized into two groups: Group I contained BTE hearing aids with a fitting range from mild to moderate degree of hearing loss, and Group II contained BTE hearing aids with a fitting range from moderate to profound degree of hearing loss.

Inclusion Criteria

1. Hearing aids were digitally programmable BTE hearing aids.

2. The hearing aids had the option to vary the CR and/or CT settings from the programming software.
3. The hearing aids had a fitting range of mild to moderate degree of hearing loss (13 hearing aids) and moderate to profound degree of hearing loss (12 hearing aids).

Exclusion Criteria

1. Non-programmable, analog hearing aids were excluded from the study.
2. All other hearing aid styles other than BTE, namely, RITE, ITC, CIC, etc. were excluded.

Test Environment

Programming the hearing aids as well as carrying out the electroacoustic measurements were done in an air-conditioned sound treated room where the ambient noise levels were within permissible limits (Katz, 2015)

Tools/ Equipment

1. A computer with NOAH-2 and hearing aid programming software, and HiPro with programming cables or Noahlink Wireless were used to program the hearing aids.
2. Frye Electronics FONIX 8000 Hearing Aid Test System was used to carry out the electroacoustic measurement of the hearing aids.
3. Sound chamber 8120
4. HA-2 2-cc coupler with ear level adapter was used to couple the BTE hearing aid to the coupler microphone of the hearing aid test system.
5. Coupler microphone (M1958E) connected to the HA-2 coupler was used to pick up the output from the hearing aid.

Procedure

The procedure was carried out in two phases:

1. Programming the hearing aids
2. Performing electroacoustic measurements of the hearing aids

Phase 1: Programming the hearing aids

Twenty-five hearing aids of two categories were chosen (13 hearing aids with a fitting range from mild to moderate degree in Group 1 and 12 hearing aids with a fitting range from moderate to profound degree in Group 2). To program the hearing aids for the purpose of the study, the pure-tone threshold of 50 dB HL (air-conduction from 250 to 8000 Hz and bone-conduction from 250 to 4000 Hz, with a flat configuration) were used for first category hearing aids and 75 dB HL (air-conduction from 250 to 8000 Hz and bone-conduction from 250 to 4000 Hz, with a flat configuration) were used for the second category hearing aids. The hearing aids were from different companies and hence relevant programming software used were Rexton Connexx 9.6.6.188, Audio Service Connexx 9.6.6.118, Danafit 1.5, Resound Smartfit 1.11, Beltone Solus Max 1.12, XE Bemore 1.13.

The operational definitions of the measures used in this study are as follows:

a. Nominal CR: It is the CR that is set/displayed during programming of the hearing aids.
b. Measured CR: It is the CR that is measured from the I/O graph that is obtained from electroacoustic measurement. The computation of measured CR is explained in Figure 3.5.

c. Measured CR_h: It is the CR that is obtained for higher input levels in the hearing aids that show two CRs, one for low and the other for high input levels. Measured CR_h is illustrated in Figure 3.4.

d. Nominal CT: It is the CT that is set during programming the hearing aids using the hearing aid programming software.

e. Measured CT: It is the CT that is computed from the I/O graph obtained using electroacoustic measurements. Computation of measured CT is illustrated in Figure 3.6.

Throughout the study, for nominal and measured CRs, for representing the compression ratio, only the numerator value is mentioned, and the denominator is omitted, as it is ‘1’. For eg., CR of 1.1:1 is mentioned as 1.1, 2.51:1 is mentioned as 2.51, and 4:1 is mentioned as 4.

Programming the hearing aid from Group 1. Thirteen BTE hearing aids with the fitting range for mild to moderate degrees of hearing loss were chosen for Group 1. These hearing aids were programmed for a flat sensorineural hearing loss of 50 dB HL from 250-8000 Hz. The National Acoustical Laboratory Non-Linear 2 (NAL-NL2) prescriptive fitting approach was used to program the hearing aids. Group 1 hearing aids were programmed in one condition, i.e., compression was set as prescribed by the prescriptive formula as mentioned in Table 3.1. This was done as there was no provision to manipulate the nominal CR. The compression threshold could not be manipulated for these hearing aids. All the other features, namely, the noise reduction, directionality, bluetooth streaming, wind noise reduction, occlusion reduction and feedback management were disabled.

Table 3.1

Different settings of hearing aids from Group I

Nominal CR	Nominal CT	Hearing aid programming with
As prescribed by the prescriptive formula and displayed on the programming screen	Could not be manipulated	50 dB HL, NAL-NL2, naïve user

Note. CR=Compression ratio; CT= Compression threshold

Programming the hearing aids from Group 2. Twelve BTE hearing aids with a fitting range for moderate to profound degrees of hearing loss were selected. These hearing aids were programmed for a flat sensorineural hearing loss of 70 dB HL, using the NAL-NL2 prescriptive formula. The hearing aids were programmed for measurement in nine different conditions. This was done without explicitly manipulating the gain and MPO of the first/initial fit prescribed for a naïve user by the NAL-NL2 fitting formula. The CRs and CTs were kept at the low-, mid- and high- settings at the values mentioned in Table 3.2. All the other features, namely, the noise reduction, directionality, bluetooth streaming, wind noise reduction, occlusion reduction and feedback management were disabled.

Table 3.2

Different settings of hearing aids from Group 2

SN	Nominal CR	Nominal CT (in dB SPL)	Hearing aid programming with
1	1.1	55	70 dB HL thresholds, NAL-NL2, naïve user
2		70	70 dB HL thresholds, NAL-NL2, naïve user
3		86	70 dB HL thresholds, NAL-NL2, naïve user
4	2.51	55	70 dB HL thresholds, NAL-NL2, naïve user
5		70	70 dB HL thresholds, NAL-NL2, naïve user
6		86	70 dB HL thresholds, NAL-NL2, naïve user
7	4	55	70 dB HL thresholds, NAL-NL2, naïve user
8		70	70 dB HL thresholds, NAL-NL2, naïve user
9		86	70 dB HL thresholds, NAL-NL2, naïve user

Note. CR=Compression ratio; CT= Compression threshold

Phase 2: Performing electroacoustic measurements for the hearing aids

The instructions given in the instruction manual of the FONIX 8000 system were followed to perform the measurements. The calibration of the coupler microphone and levelling of the FONIX 8000 hearing aid test system were done to achieve a stored sound field equalization. Leveling was done which is a process in which the sound chamber response is measured and corrections are added in order to achieve a flat sound field. The correction factors were saved into the test system’s memory so that there was no need to level the test system every time the system was turned on.

To level the test system, the coupler microphone of the hearing aid test system was placed on the microphone grill at the reference point, facing the loud speaker, in the sound chamber of the test system. The lid of the sound chamber was closed and latched. The 'LEVEL' button of the test system was pressed to start the levelling process. The test system presented a complex composite signal consisting of tones from 100 to 8000 Hz. The coupler microphone measured the signal and saved the correction factors so that the sound field was flat for future measurements. The monitor/ screen displayed the message 'Leveled' under the Curve Characteristics box. The 'Leveled' condition of the sound field was ensured for electroacoustic measurement of all the hearing aids for the study.

Figure 3.1

Setup for levelling of the sound chamber

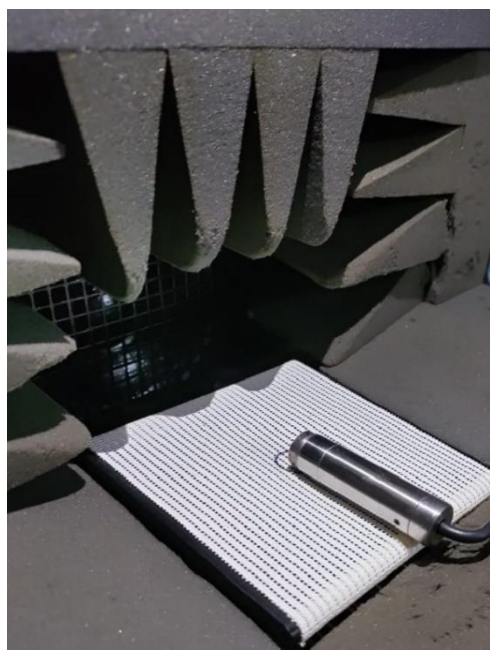


Figure 3.2

The message 'leveled' displayed on the screen

The programmed hearing aid was connected to the BTE adapter, HA-2 coupler and then to the coupler microphone which was placed in the sound chamber. The microphone of the BTE was located on the grill in such a way that it was at the reference point and facing the loud speaker.

Figure 3.3

Setup of hearing aid in the FONIX 8000 sound chamber

The electroacoustic measurements were carried out. The coupler input-output measurement screen was selected from the ‘Advanced Coupler’ option. The stimulus chosen was 2 kHz pure-tone and the intensity was varied, in 5 dB steps, from 50 to 90 dB SPL. In the menu of the hearing aid test system, the ‘AGC Aid Type’ was set at ‘AGC’. The ‘SPL (Output) display of the test results was chosen. The other settings in the menu were retained at default settings. That is, I/O pre-delay of 100 ms was given and an I/O measurement delay of 20 ms was given. The I/O pre delay is the time between the presentation of the first tone in the I/O sweep and obtaining the first measurement. The I/O measurement delay is the time duration between the different intensity levels in the I/O sweep.

Each measurement was carried out twice to ensure test-retest reliability. As there was not more than 2 dB difference between the two measurements, the first measure was considered for analysis. Out of the 25 hearing aids, eight (four from Groups 1 and 2 each) were randomly selected and all the conditions were programmed and measured following the same procedure mentioned earlier. This was done to check for test-retest reliability.

Data

The I/O characteristics, at different compression settings of the hearing aids, as mentioned in Tables 3.1 and 3.2, were measured.

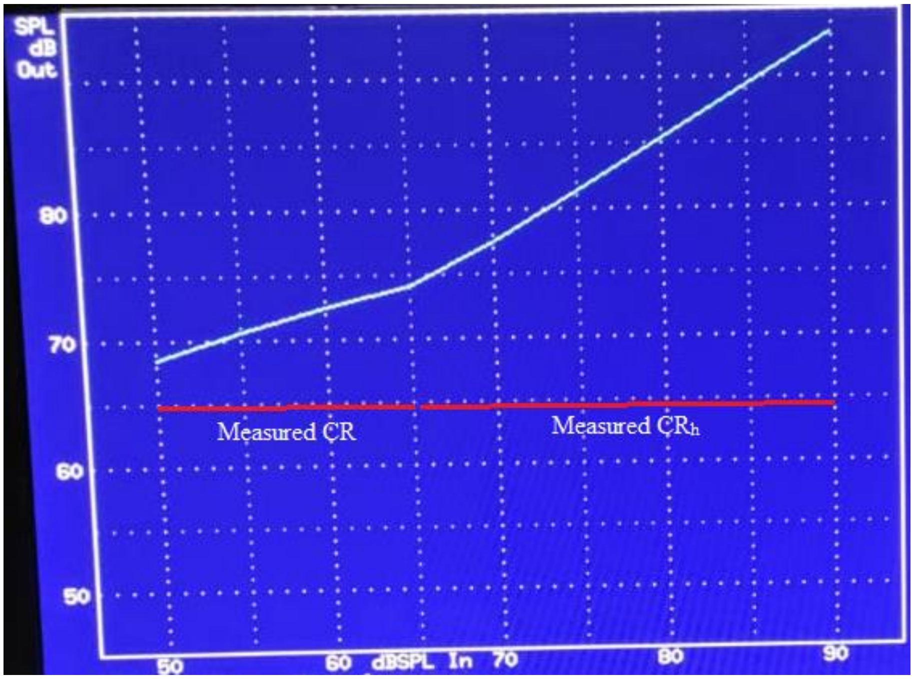
Computation of CR and CT

The nominal CRs and nominal CTs are those that were shown in the software at the time of programming the hearing aid. The measured CRs and/or CTs were computed from the I/O curves obtained by the electroacoustic measurements of hearing aids from Groups 1 and 2.

For Group 1 hearing aids, the nominal CRs were taken as that prescribed by the prescriptive formula, which was displayed in the programming software screen. This nominal CR was compared with the measured CR that was obtained from the I/O graph. The I/O graph obtained for some of the hearing aids depicted two measured CRs, i.e., the compression ratios were different for low and high input levels. The compression ratio varied with different input levels. Therefore, for such hearing aids, the first measured CR was taken as measured CR and the second measured CR is indicated as measured CR_h. This is illustrated in Figure 3.4.

Figure 3.4

Illustration of measured CR and measured CR_h



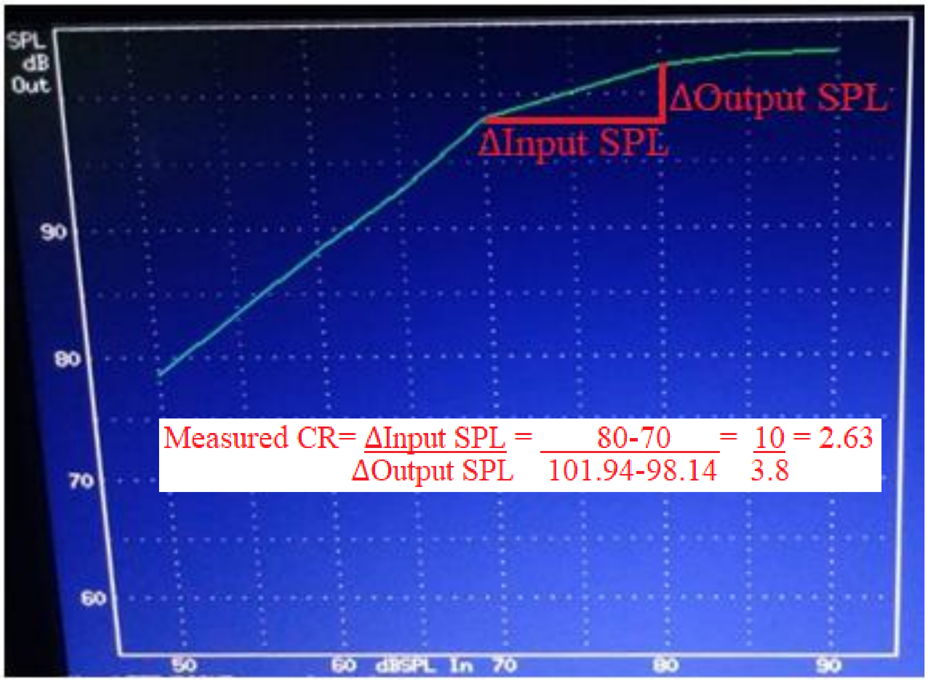
Note. Measured CR = measured CR or first measured CR; measured CR_h = second measured CR at higher input levels

The nominal CT for Group 1 were not taken into account as it was not displayed in the programming software. For Group 2 hearing aids, the nominal CR and nominal CT values were set during programming and taken from the programming screen as mentioned in Table 3.2.

The measured CRs, for Group 1 and Group 2, were computed by dividing the change in input by the change in output. The Figure 3.5 gives an example of how the measured CR is computed from the I/O graph.

Figure 3.5

Illustration of computation of measured CR from the I/O graph



Note. CR = compression ratio

Computation of the measured CT was not carried out for Group 1 hearing aids since nominal CT was not displayed during programming. The measured CT for Group 2 was measured as the input level (in dBSPL) at which there was a reduction in the gain by 2 dB compared to the gain in linear mode. The computation of measured CT is shown in Figure 3.6. For the purpose of the study, threshold kneepoint (TK) was taken as the measured CT.

Figure 3.6

Illustration of computation of measured CT from the I/O graph

Note. CT = compression threshold; TK = threshold kneepoint.

Statistical Analyses

Descriptive statistics and inferential statistics were done. Descriptive statistics included computing the mean, median, standard deviation (SD) and the inter quartile range (IQR). The Shapiro-Wilks test for normality was carried out. Since the *p* value was less than 0.05 for most of the data, non-parametric inferential test, namely, Wilcoxon signed ranks test was carried out.

Chapter 4

RESULTS

This study aimed at comparing the nominal compression ratio (CR) and/or nominal compression threshold (CT) with the respective measured or effective CR and/or CT computed from the input-output (I/O) curve obtained by electroacoustic measurements. The specific objectives of the study were to compare the compression characteristics of the hearing aid in terms of CR displayed while programming (i.e., nominal CR) with that measured through electroacoustic measurements (i.e., measured CR). The study also compared the compression characteristics of the hearing aid in terms of CT displayed while programming (i.e., nominal CT) with that measured (i.e., measured CT) through electroacoustic measurements.

In order to assess the objectives, electroacoustic measurements were carried out on two groups of hearing aids. Group 1 comprised of hearing aids with a fitting range for mild to moderate degree of hearing loss, and Group 2 hearing aids had a fitting range for moderate to severe degree of hearing loss. From the I/O graphs that were obtained, measured CRs and CTs were calculated. Statistical analysis was carried out using Statistical Package for Social Sciences software (SPSS version 20).

The results for the objectives are given under the following headings.

I. Comparison of nominal and measured CR

   a. Comparison of nominal and measured CR for hearing aids from Group 1

   b. Comparison of nominal and measured CR for hearing aids from Group 2

II. Comparison of nominal and measured CT

a. Comparison of nominal and measured CT for hearing aids from Group 1

b. Comparison of nominal and measured CT for hearing aids from Group 2

I. Comparison of nominal and measured CR

Descriptive analysis of the data was carried out to compute the mean, median, standard deviation (SD), interquartile range (IQR), and range of the measured CR provided by the hearing aids. Shapiro-Wilks test was carried out to test for normality of the data. It showed that the data were not normally distributed ($p<0.05$). Hence, non-parametric tests were carried out for comparison of the nominal and measured CRs as well as nominal and measured CTs.

I a. Comparison of nominal and measured CR for hearing aids from Group 1

Hearing aids from Group 1 did not have the provision for manipulating the nominal CR. Hence, the nominal CR was taken as the CR that was prescribed by the prescriptive formula. The descriptive analyses were carried out on the nominal CR and the measured CRs obtained from the Group 1 hearing aids. The mean, median, SD, IQR, and the minimum and maximum of the same are given in Table 4.1.

Table 4.1

Mean, median, standard deviation (SD), range, and interquartile range (IQR) of measured CR in Group 1 hearing aids (n=13)

CR	Mean	Median	SD	Range		IQR
				Minimum	Maximum	
Nominal CR (n=13)	1.88	1.80	0.31	1.60	2.10	0.40
Measured CR (n=13)	2.13	2.21	0.20	1.71	2.63	0.66
Measured CR_h (n=9)	1.19	1.25	0.09	1.05	1.30	0.19

Note. CR = compression threshold; Measured CR = measured CR or first measured CR; measured CR_h = second measured CR at higher input levels.

To test for normality of data, Shapiro Wilks test was carried out and the results showed that the data were not normally distributed ($p<0.05$). Hence non-parametric test, Wilcoxon signed rank test, was carried out.

Since some hearing aids from Group 1 had two values of measured CR (one for low input levels and one for high input levels), a comparison was made between them to see if they varied significantly, using Wilcoxon signed rank test. The results showed that the two data sets varied significantly ($|Z|=2.675$; $p<0.01$). Therefore, a comparison was done separately between each of the two measured CR data and the nominal CR. In order to know whether the nominal and measured CR were same or different, two samples Wilcoxon signed rank test was administered. The results revealed that both the measured

CR groups differed significantly from the nominal data ($p<0.05$), as shown in Figures 4.1 and 4.2. The standardized test statistic (Z) values and *p* values are indicated in Table 4.2. Further, it was found that the effect size was large (0.58 for CR; 0.62 for CR_h).

As seen in Figure 4.1, median of measured CR is significantly greater than the median value of the nominal CR. Figure 4.2 indicates that the median of measured CR_h is significantly lesser than the median of the nominal CR. It must be noted here that there were two measured CR values for some hearing aids. That is, the measured CR for low input levels were there for the entire group of 13 hearing aids, and the measured CR_h for high input levels were there only for 9 hearing aids. Thus, the nominal CR for high level inputs differed from the nominal CR for low level input.

Table 4.2

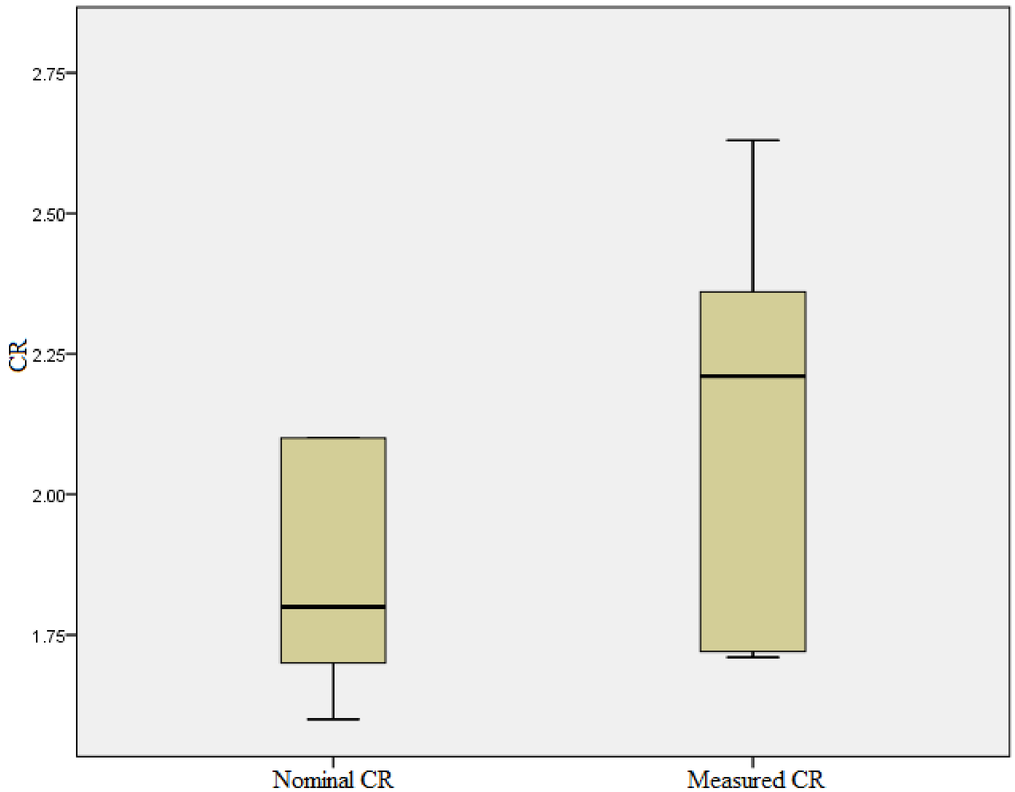
Standardized test statistic (Z) and p value of measured CR and measured CR_h of hearing aids in Group 1 (n=13)

Nominal CR & Measured CR		Nominal CR & Measured CR_h	
Z	*p* value	Z	*p* value
-2.972	0.003**	-2.668	0.008**

Note. Measured CR = measured CR or first measured CR; measured CR_h = second measured CR at higher input levels; ** = *p* at 0.01 level of significance; Z= Standardized test statistic.

Figure 4.1

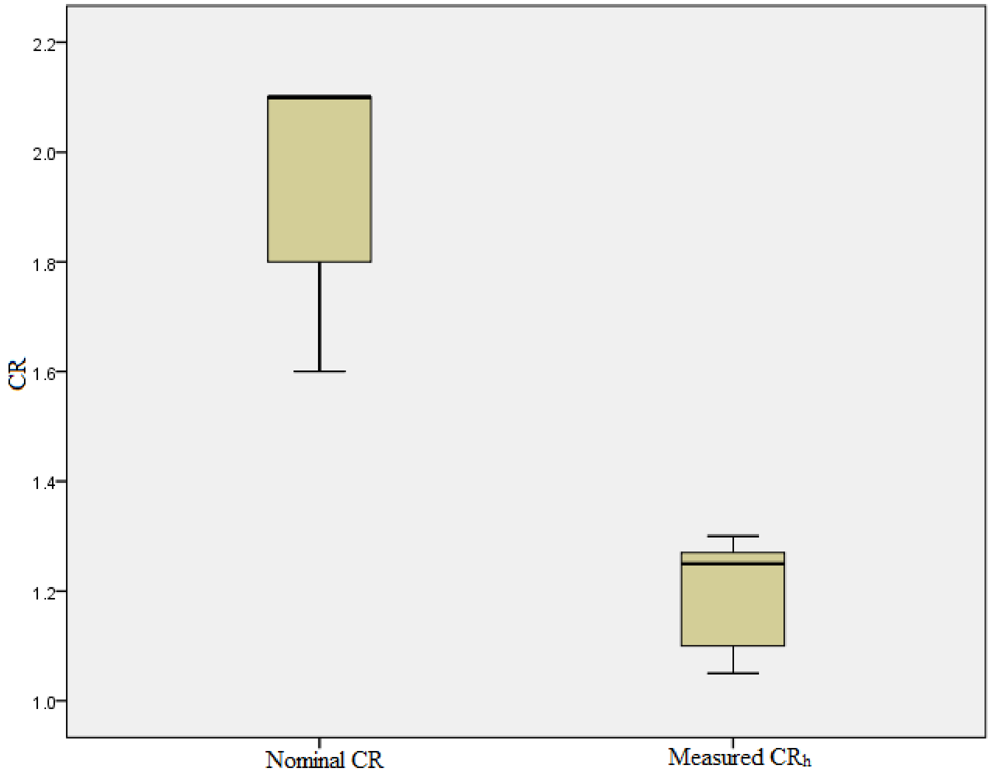
Comparison of measured CR and the nominal CR in hearing aids from Group 1



Note. CR = compression threshold; Measured CR = measured CR at the lower input level.

Figure 4.2

Comparison of measured CR_h and the nominal CR in hearing aids from Group 1



Note. CR = compression threshold; Measured CR_h = measured CR at the higher input level.

I b. Comparison of nominal and measured CR for hearing aids from Group 2

Descriptive statistics was carried out on the measured CR data and the mean, median, SD, range, and IQR were obtained. Table 4.3 shows the mean, median, SD, range, and the IQR of the measured CR for the different conditions in which measurement was carried out in Group 2 hearing aids (n=12).

Table 4.3

Descriptive statistics of the measured CR for different nominal CRs and CTs in hearing aids (n=12) from Group 2

Nominal CR	Nominal CT (dB SPL)	Measured CR					
		Mean	Median	SD	Range		IQR
					Minimum	Maximum	
Low CR (1.1)	Low	2.78	2.18	1.36	1.59	5.78	1.90
	Mid	2.34	1.97	0.84	1.62	4.58	0.91
	High	2.30	2.02	0.80	1.63	4.34	0.97
Mid CR (2.51)	Low	2.49	2.03	1.07	1.51	4.76	1.54
	Mid	2.41	1.89	1.10	1.36	5.00	1.44
	High	2.40	1.98	1.08	1.62	5.31	1.08
High CR (4)	Low	2.37	2.06	0.97	1.31	4.48	1.44
	Mid	2.37	2.02	1.05	1.49	4.76	0.82
	High	2.30	1.95	0.97	1.65	5.29	0.51

Note. CR=Compression ratio; CT= Compression threshold; SD = Standard Deviation; IQR = Inter Quartile Range; Low nominal CT = 55 dB SPL, mid nominal CT = 70 dB SPL, and high nominal CT = 86 dB SPL.

The measured CRs obtained for the various conditions were tested for normality using the Shapiro Wilk test. The test result showed that the data were not normally distributed ($p<0.05$). Hence, non-parametric test was carried out to check if there was a significant difference between the nominal and the measured CRs. One-sample Wilcoxon signed ranks test was applied to the data for this purpose. The *p* values and the standardized test statistic (Z) values are indicated in Table 4.4. The measured CR was significantly greater than the nominal CR at low nominal CR setting, i.e., 1.1 (The effect size was 0.88 for all the three CT settings), as shown in Figure 4.3. For the mid nominal CR, i.e., 2.51, no significant difference was seen between the nominal and the measured CR ($p>0.05$), as indicated in Figure 4.4. For the high nominal CR, i.e., 4, the measured CR was significantly lower than the nominal CR set value, i.e., 4, (The effect size was 0.86 for low- CT setting, 0.81 for mid- CT setting, and 0.86 for high-CT setting) as indicated in Figure 4.5.

Table 4.4

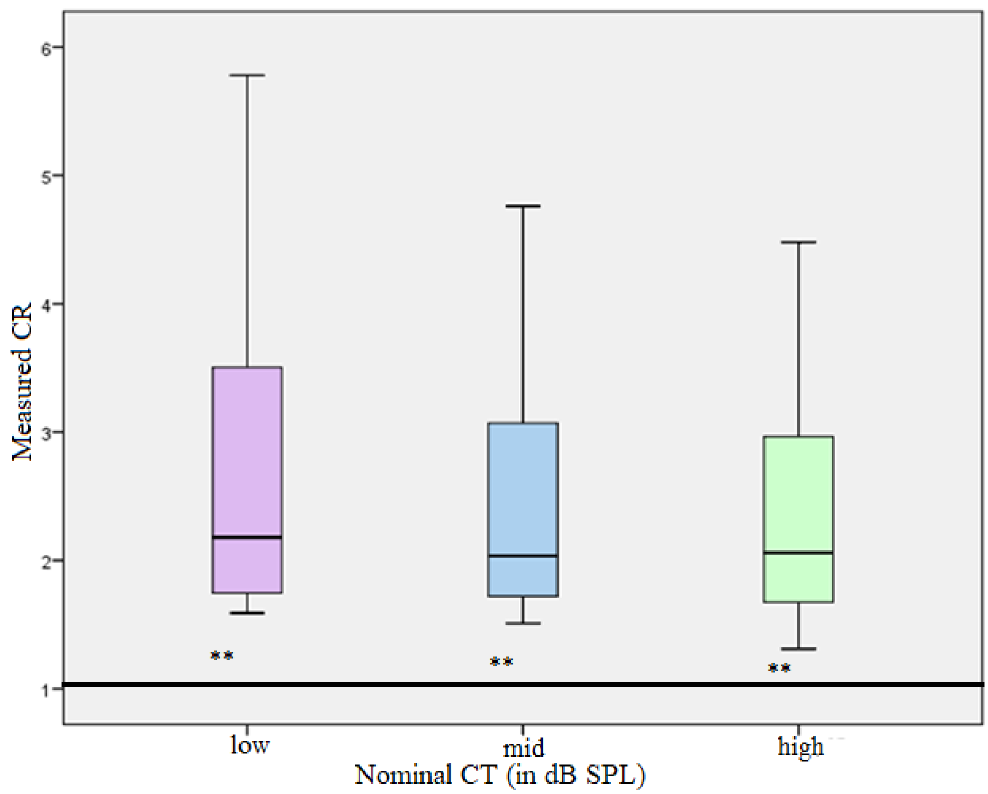
Z and p values of measured CR for different nominal CTs in hearing aids (n=12) from Group 2

Nominal CR	Nominal CT	Measured CR	
		Z	*p* value
Low CR (1.1)	Low	3.059	0.002**
	mid	3.059	0.002**
	high	3.061	0.002**
Mid CR (2.51)	low	-1.255	0.209
	mid	-0.785	0.433
	high	-1.255	0.209
High CR (4)	low	-2.982	0.003**
	mid	-2.825	0.005**
	high	-2.983	0.003**

Note. CR=Compression ratio; CT= Compression threshold; Low nominal CT = 55 dB SPL, mid nominal CT = 70 dB SPL, and high nominal CT = 86 dB SPL; ** = *p* at 0.01 level of significance; Z= Standardized test statistic.

Figure 4.3

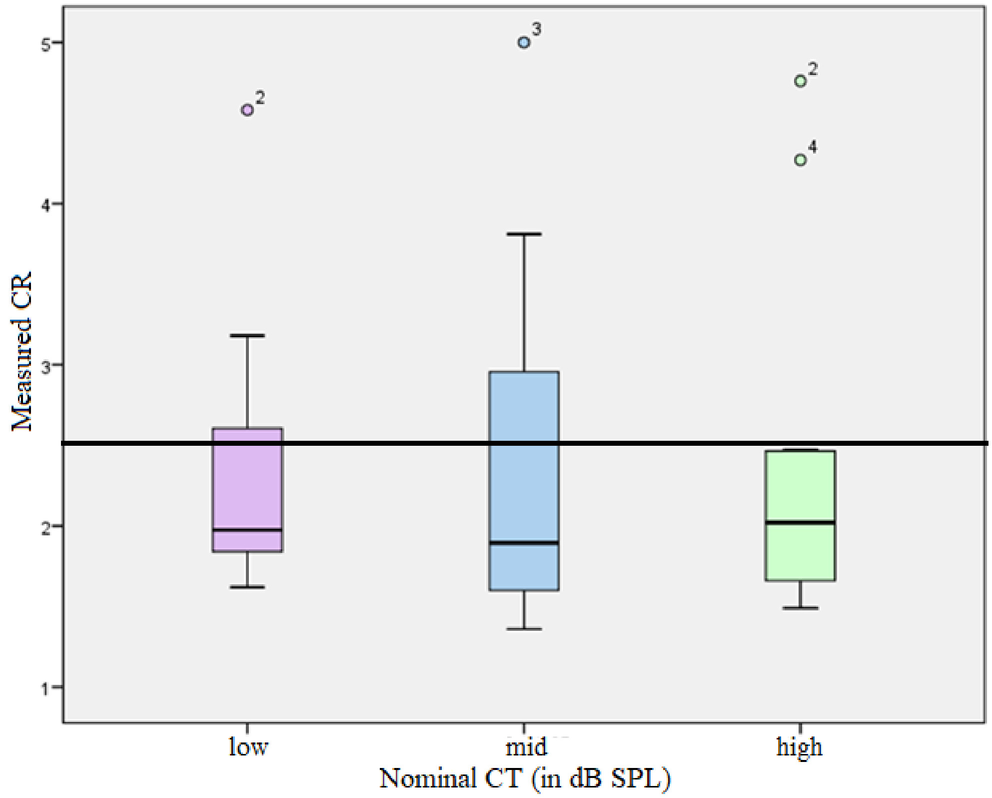
Box plots of measured CR at nominal CR of 1.1 at low-, mid-, and high- nominal CT



Note. Black horizontal line at 1.1 CR indicates nominal CR; Low nominal CT= 55 dBSPL, mid nominal CT= 70 dBSPL, high nominal CT= 86 dBSPL.

Figure 4.4

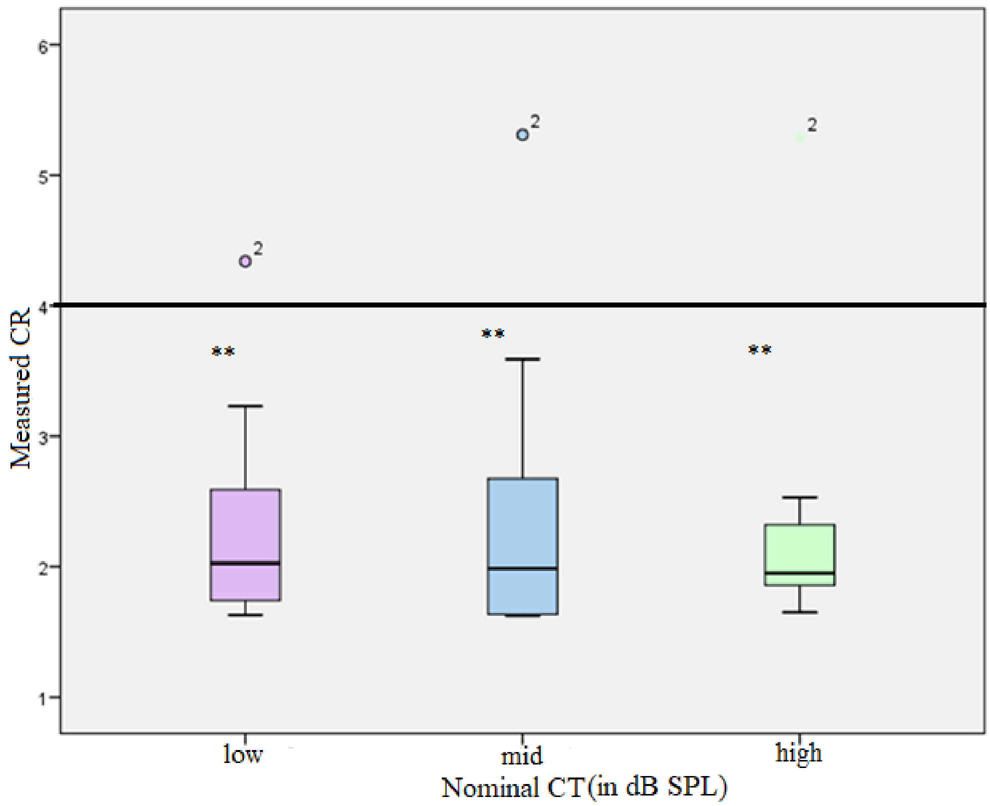
Box plots of measured CR at nominal CR of 2.51 at low-, mid-, and high- nominal CT



Note. Black horizontal line at 2.51 CR indicates the nominal CR; Low nominal CT= 55 dB SPL, mid nominal CT= 70 dB SPL, high nominal CT= 86 dB SPL. Sample 2 for Low nominal CT, sample 3 for mid nominal CT, and samples 2 & 4 for high nominal CTs are outliers.

Figure 4.5

Box plots of measured CR at nominal CR of 4 at low-, mid-, and high- nominal CT



Note. Black horizontal line at 4 CR indicates the nominal CR; Low nominal CT= 55 dB SPL, mid nominal CT= 70 dB SPL, high nominal CT= 86 dB SPL; sample 2 is an outlier for low-, mid-, and high- nominal CTs.

II. Comparison of nominal and measured CTs

The measured CTs obtained from the electroacoustic measurement were subjected to statistical analyses. Descriptive statistics showed that the measured CTs and the nominal CTs were not same. Test of normality was done to check for distribution of the data. Test for significance was administered to check if the measured and nominal data varied significantly. The results of the descriptive statistics, normality test and the tests for significance are given below.

II a. Comparison of nominal and measured CT for hearing aids from Group 1

In Group 1 hearing aids, there was no provision for manipulating the CT. The nominal CT was not indicated in the programming software screen as well. Therefore, comparison of nominal CT with measured CT could not be done.

II b. Comparison of nominal and measured CT for hearing aids from Group 2

The mean, median, SD, IQR, and the range of the measured CTs from Group 2 hearing aids were derived. These values are mentioned in Table 4.5 summarizes the values of the mean, median, SD, range, and IQR of the measured CT values for different conditions.

Table 4.5

Descriptive statistics of the measured CT for different nominal CRs and CTs in hearing aids (n=12) from Group 2

Nominal CT (dB SPL)	Nominal CR	Measured CT (dB SPL)					
		Mean	Median	SD	Range		IQR
					Minimum	Maximum	
Low CT (55)	low	67.50	67.5	2.61	65	70	5.00
	mid	67.08	67.5	3.34	60	70	5.00
	high	68.33	70.0	4.92	60	80	5.00
Mid CT (70)	low	67.08	67.5	3.34	60	70	5.00
	mid	67.91	70.0	3.96	60	75	5.00
	high	70.00	70.0	7.07	60	85	8.75
High CT (86)	low	66.66	67.5	3.89	60	70	5.00
	mid	68.75	70.0	4.33	60	75	5.00
	high	70.83	70.0	7.33	60	85	12.50

Note. CR=compression ratio; CT= compression threshold; SD = standard deviation; IQR = inter Quartile range; Low nominal CR = 1.1, mid nominal CR = 2.51, and high nominal CR = 4.

The Shapiro Wilk test for normality was carried out to test the data for normal distribution. The result showed that the data were not normally distributed (p<0.05). Therefore, non-parametric test was carried out to check for significance of the data. One sample Wilcoxon signed ranks test was administered, which resulted in the following findings. The p values and the standardized test statistic (Z) values are indicated in Table 4.6. At low nominal CT (55 dB SPL), the measured CT was significantly higher than the nominal CT ($p<0.05$), at all nominal CRs. This can be seen in Figure 4.6. The effect size was 0.9 for the low and mid CR setting, and 0.89 for the high CR. At mid nominal CT (70 dB SPL), no significant difference was noted between nominal CT and measured CT ($p>0.05$), except in the condition where the nominal CR was low, where the measured CT was significantly lower than the nominal CT ($p<0.05$). This result can be seen in Figure 4.7. The effect size for this was 0.67. At high nominal CT (86 dB SPL), there was a significant difference that was noted between the nominal and the measured CT ($p<0.05$), at all nominal CRs. The measured CT was significantly lower than the nominal CT, as shown in Figure 4.8. The effect size was large (0.89) for all the low-, mid- and high- CR setting.

Table 4.6

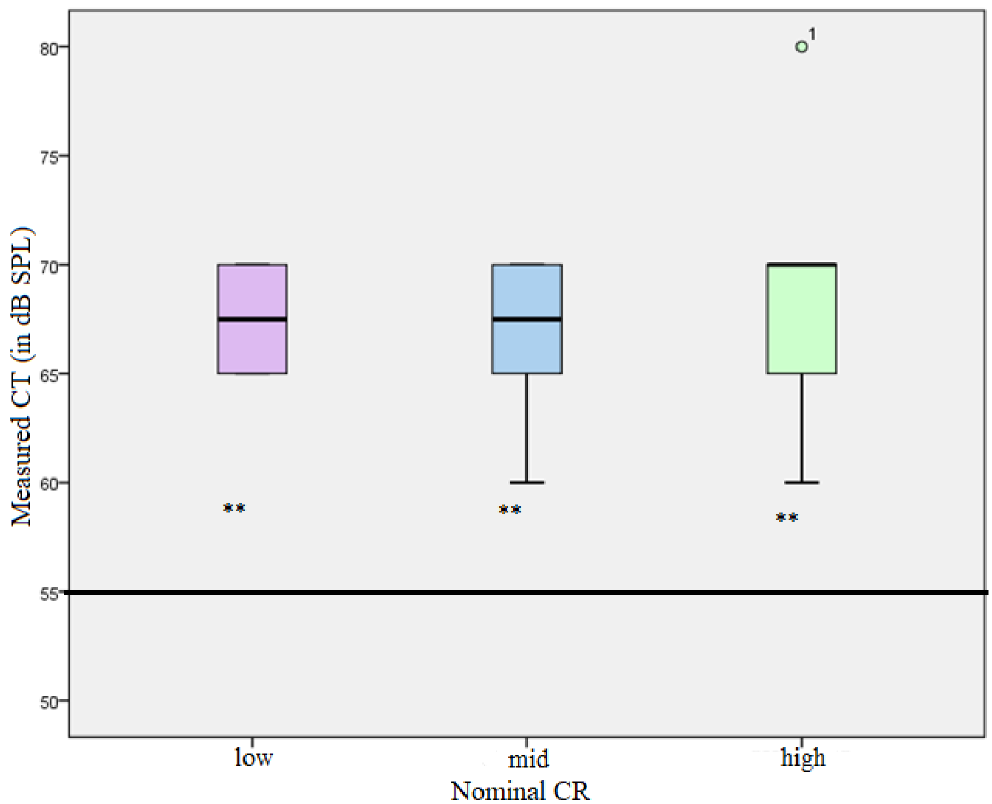
Z and p values of the measured CT (in dB SPL) for different nominal CTs and nominal CR, in Group 2 hearing aids (n=12)

Nominal CT (dB SPL)	Nominal CR	Measured CT (dB SPL)	
		Z	*p* value
Low CT (55)	low	3.145	0.002**
	mid	3.126	0.002**
	high	3.114	0.002**
Mid CT (70)	low	-2.333	0.020*
	mid	-1.667	0.096
	high	-0.072	0.943
High CT (86)	low	-3.115	0.002**
	mid	-3.108	0.002**
	high	-3.089	0.002**

Note. CR=compression ratio; CT=compression threshold; Low nominal CR = 1.1, mid nominal CR = 2.51, and high nominal CR = 4; ** = *p* at 0.01 level of significance; * = *p* at 0.05 level of significance; Z= Standardized test statistic.

Figure 4.6

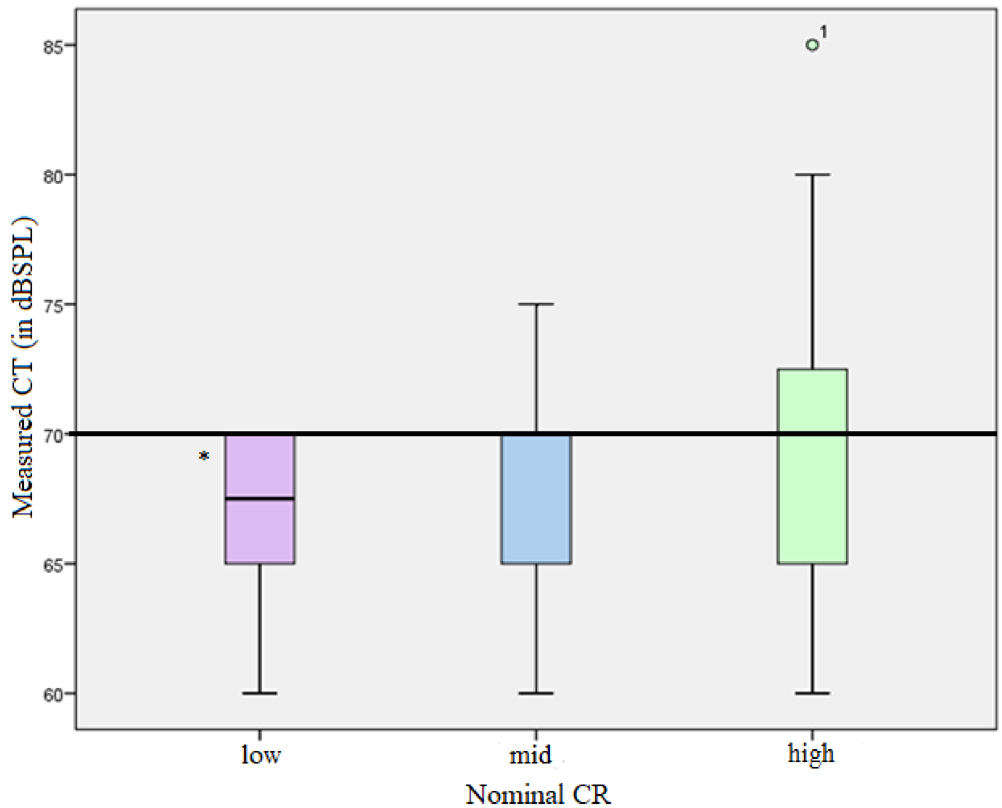
Box plots of measured CT (in dB SPL) at nominal CT of 55 dB SPL at low-, mid-, and high-nominal CR



Note. Black horizontal line at 55 dB SPL CT indicates the nominal CT; Low nominal CR= 1.1, mid nominal CR= 2.51, high nominal CR= 4. Sample 1 is an outlier for high nominal CR.

Figure 4.7

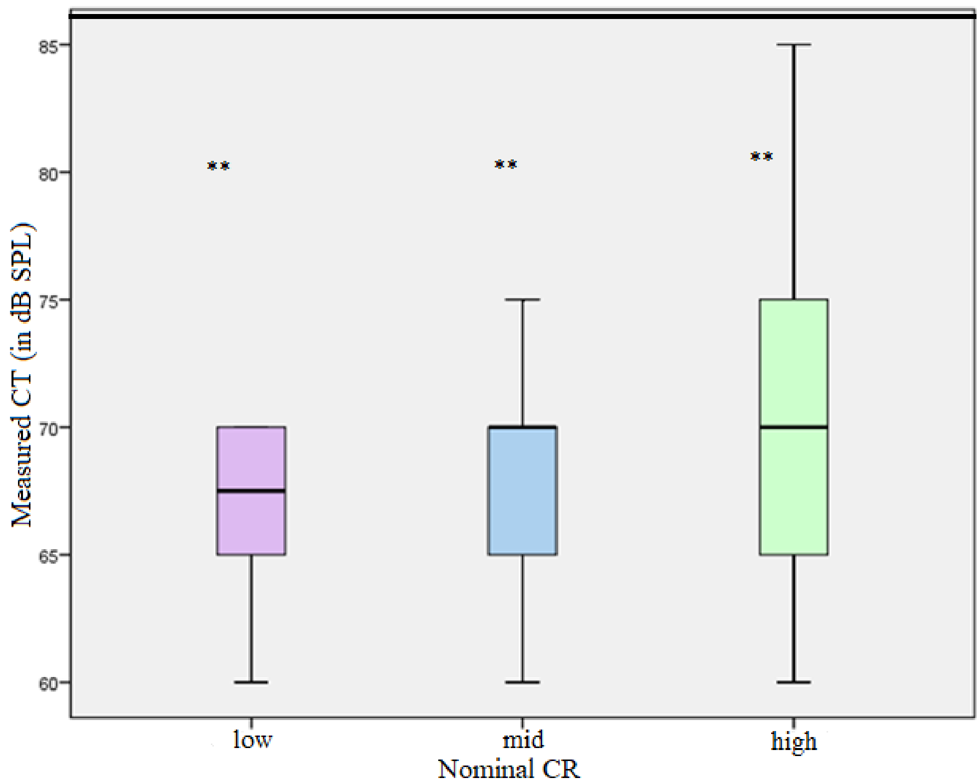
Box plots of measured CT (in dB SPL) at nominal CT of 70 dB SPL at low-, mid-, and high-nominal CR



Note. Black horizontal line at 70 dB SPL indicates the nominal CT; Low nominal CR= 1.1, mid nominal CR= 2.51, high nominal CR= 4. Sample 1 is an outlier for high nominal CR.

Figure 4.8

Box plots of measured CT (in dB SPL) at nominal CT of 86 dB SPL at low-, mid-, and high-nominal CR



Note. Black horizontal line at 86 dB SPL CT indicates the nominal CT; Low nominal CR= 1.1, mid nominal CR= 2.51, high nominal CR= 4.

To summarize the results, for hearing aids from Group 1, the nominal CR was significantly lesser from the measured CR for low input levels. Further, the nominal CR was significantly more from the measured CR_h for the high input levels. Table 4.7 shows the summary of significant differences between nominal and measured CRs at different CTs, in Group 2 hearing aids. It can be seen that there was a significant difference between nominal and measured CR, at low-, mid-, and high- CTs for low and high nominal CR. For the low nominal CR, measured CR was significantly greater than the nominal CR, whereas for the high nominal CR, measured CR was significantly lesser than nominal CR. For mid CR, there was no significant difference between the nominal and measured CR at low-, mid-, and high- CTs.

Table 4.7

Summary of significant difference between nominal and measured CRs at different CTs.

Nominal CR	Nominal CT (dB SPL)	Measured CR
Low CR (1.1)	low	Nominal CR < Measured CR (**)
	mid	Nominal CR < Measured CR (**)
	high	Nominal CR < Measured CR (**)
Mid CR (2.51)	low	-
	mid	-
	high	-
High CR (4)	low	Nominal CR > Measured CR (**)
	mid	Nominal CR > Measured CR (**)
	high	Nominal CR > Measured CR (**)

Note. CR= Compression ratio; CT= Compression threshold; Low nominal CT = 55 dB SPL, mid nominal CT = 70 dB SPL, and high nominal CT = 86 dB SPL; ** = p at 0.01 level of significance; - = no significant difference.

As shown in Table 4.8, the results for the comparison of nominal and measured CTs can be summarized. There was a significant difference between the nominal and measured CTs at low-, mid-, and high- CRs for both low and high nominal CTs. In low nominal CT, measured CT was significantly greater than the nominal CT, further for the high nominal CT, measured CT was significantly lesser than the nominal CT. In mid nominal CT, a significance difference was noted between the nominal and measured CT, only in the low nominal CR setting, where the nominal CT was greater than the measured CT. In mid and high nominal CR setting, there was no significant different difference that was observed between the nominal and measured CT.

Table 4.8

Summary of significant difference between nominal and measured CTs at different CRs.

Nominal CT (dB SPL)	Nominal CR	Measured CT
Low CT (55)	low	Nominal CT < Measured CT (**)
	mid	Nominal CT < Measured CT (**)
	high	Nominal CT < Measured CT (**)
Mid CT (70)	low	Nominal CT > Measured CT (*)
	mid	-
	high	-
High CT (86)	low	Nominal CT > Measured CT (**)
	mid	Nominal CT > Measured CT (**)
	high	Nominal CT > Measured CT (**)

Note. CR=compression ratio; CT=compression threshold; Low nominal CR = 1.1, mid nominal CR = 2.51, and high nominal CR = 4; ** = *p* at 0.01 level of significance; * = *p* at 0.05 level of significance; - = no significant difference.

Out of the 25 hearing aids (13 in Group 1 and 12 in Group 2), eight hearing aids (four from each group) were selected randomly and were subjected to all the measurements as given in method chapter. The test-retest reliability was assessed using the Alpha model for the measured CR and CT at all conditions. The Cronbach's Alpha was greater than 0.9, showing good reliability between the measures.

From the results, it can be construed that the measured CR and CT are not the same as nominal CR and CT. The results are discussed in the next section.

Chapter 5

DISCUSSION

The present study aimed to compare the nominal compression parameters, i.e., compression ratio (CR) and compression threshold (CT) with the corresponding measured values. As revealed from the results, in most comparisons a significant difference can be seen between the nominal and their corresponding measured values.

In a study by Holder et al. (2016), most hearing aids were reported not to comply with the ANSI specifications for quality control. In several studies, investigators have reported that not greater than 68% comply with the ANSI standards (Callaway & Punch, 2008; Chial, 1977; Humes et al., 1997; Robinson & Sterling, 1980; Townsend & Olsen, 1982)

The relevant discussion of the results is provided under the following headings:

I. Comparison of nominal and measured CR

II. Comparison of nominal and measured CT

I. Comparison of nominal and measured CR

For the low power hearing aids, the measured CR at low input levels is significantly greater than the nominal CR, whereas, the measured CR_h, i.e., the measured CR at high input levels is significantly lesser than the nominal CR. Therefore, for low power hearing aids, the null hypothesis, which states that there is no significant difference between the nominal and the measured CR, is rejected.

High power hearing aids also showed a similar result where the measured CR was significantly different from the nominal CRs.

a. The measured CR was significantly greater than the nominal CR at low nominal CR setting i.e., 1.1. Therefore, the null hypothesis, which states that there is no significant difference between the nominal and measured CR, is rejected.

b. For the mid nominal CR, i.e., 2.51, no significant difference was seen between the nominal and the measured CR. Since, there is no significant difference between the nominal and measured CR, the null hypothesis, which states that there is no significant difference between the nominal and measured CR, is accepted.

c. For the high nominal CR, the measured CR is significantly lower than the nominal CR set value, i.e., 4. Hence, the null hypothesis, which states that there is no significant difference between the nominal and measured CR, is rejected.

Therefore, the measured CR values were significantly different from the nominal CR and this is seen to be true for both low- and high- power hearing aids. It can be observed that irrespective of the low- or high- value of the nominal CR, the measured CRs tended to be closer to the mid value. This could be due to the manufacturers not implementing the compression features into the hearing aids effectively. Two reasons for this were put forth by Townsend and Olsen (1982). The financial requirements to manufacture hearing aids that meet the specifications may be high. Further, the testing techniques used by the audiologists may be different.

There are ample studies that report findings similar to the findings of this study. Verschuure et al. (1996) reported that the effective CR was significantly lesser than the nominal CR. They reported that the effective CR was 2, 2.5, and 3 for nominal ratios of 2, 4, and 8 respectively, for the 2000 Hz octave range. Using speech input, Stelmachowicz et al. (1995), reported a measured CR of 1.3, for a nominal CR of 2. Similar findings were reported by Braida et al. (1982), Henning and Bentler (2008), Souza and Turner (1999) and, Stone and Moore (1992).

The effective or measured CR may be affected by various factors. These factors can be stimulus related such as the type of stimulus used, the overall input level or hearing aid related such as the CT, the number of channels of the hearing aids, the attack and release time of the compression systems (Stone & Moore, 1992).

Dynamic signals or speech stimuli may interact with the dynamic properties of the compressor to further reduce the measured CR compared to the nominal CR. It has been reported that the measured or effective CR is lower than the nominal CR for speech. The reason given for this is that the speech and other everyday environment sounds contain wide range of intensities with fluctuate at a fast rate (Kuk, 2002). In this study, since we have used 2 kHz tone presented at increasing intensities, the variables present in the stimulus such as the peak to valley difference in the input signal, the frequency composition of the signal have been avoided. Also, this stimulus was chosen for the study as most of the speech spectrum energy is concentrated around the 2 kHz region and the standards specify the use of a 2 kHz tone for measurements related to compression.

The time constants of the compression circuits also have a significant effect on the measured CR. Kuk (2002) reported that larger release times causes the measured CR to move towards one, i.e., linear compression. Henning and Bentler (2008) also reported similar findings, where he mentioned that faster release times resulted in measured CR that was more similar to the nominal CR. The effects of the compression time constants on measured CR were not investigated in this study.

The number of channels of a hearing aid also has an effect on the measured CR. The effective CR matches the nominal CR for hearing aids that have a greater number of channels. This has also been reported in literature, that is, the measured CR is more closer to the nominal CR when the signal processing in the hearing aids are divided across the frequency range (Henning & Bentler, 2008). In the present study, the effect of number of channels were not investigated. The number of channels in different hearing aids varied.

II. Comparison of nominal and measured CT

Low power hearing aids did not have the provision to change the nominal CT. Hence, comparison of the nominal CT with the measured CT was not carried out.

Comparison of nominal and measured CTs in high power hearing aids also revealed that the nominal and the measured CT were not the same.

a. At low nominal CT (55 dB SPL), the measured CT was significantly higher from the nominal CT. Therefore, the null hypothesis, which states that there is no significant difference between the nominal and measured CT, is rejected.
b. At mid CT (70 dB SPL), no significant difference was noted between nominal CT and measured CT, except in the condition where the nominal CR was low, where the measured CT was significantly lower than the nominal CT. Therefore, the null hypothesis, which states that there is no

significant difference between the nominal and measured CT, is partially accepted.

c. At high nominal CT (86 dB SPL), the measured CT was significantly lower than the nominal CT. Hence, the null hypothesis, which states that there is no significant difference between the nominal and measured CT, is rejected.

Literature to support or disagree with the findings of this study was scarce. Therefore, this study will add to the information in this area.

Chapter 6

SUMMARY AND CONCLUSIONS

This study aimed to compare the compression parameters i.e., compression ratio (CR) and compression threshold (CT), displayed on the programming screen and that measured using electroacoustic measurements. The study looked into two objectives, which were:

1. To compare the CR displayed while programming, i.e., nominal CR, and that measured through electroacoustic measurements, i.e., measured CR.
2. To compare the CT displayed while programming, i.e., nominal CT, and that measured through electroacoustic measurements, i.e., measured CT.

The study was done on a total of 25 hearing aids (n=13 in Group 1 comprising of lower power hearing aids; n=12 in Group 2 comprising of high power hearing aids). The hearing aid from Group 1 were programmed for a flat sensorineural hearing loss of 50 dB HL. The hearing aids from Group 2 were programmed for a flat sensorineural hearing loss of 70 dB HL. The NAL-NL2 prescriptive formula was used to program the hearing aids.

The nominal CR was taken as that prescribed by the prescriptive formula for Group 1. The nominal CR was varied at low-, mid-, and high- levels for the Group 2 hearing aids. For Group 1 hearing aids, the CT comparison was not done as there was no provision to vary the nominal CT and also the nominal CT was not displayed in the hearing aid programming screen. The hearing aids from Group 2 were programmed by varying the CT at low-, mid-, and high- levels. The electroacoustic measurements were carried out for each setting in terms of the input-output function. From the input-output function curves, measured CRs and measured CTs were computed.

The data obtained were analysed using Statistical Package for Social Science (SPSS) software (version 20). Descriptive statistics were done. Shapiro Wilks test for normality was carried out to check for normality of the data. Since the data were not normally distributed, non-parametric test was done. One sample Wilcoxon signed ranks test was administered to compare the nominal CR and CT with the corresponding measured values. The following results were obtained:

1. Comparison of nominal and measured CR revealed that for both the low-power and high-power hearing aids, measured CR was not same as the nominal CR.
   a. For low power hearing aids, the measured CR at low input levels is significantly greater than the nominal CR, whereas, the measured CR_h, i.e., the measured CR at high input levels is significantly lesser than the nominal CR.
   b. The high power hearing aids also showed a similar trend where the measured CR was significantly different from the nominal CRs. The measured CR was significantly higher than the nominal CR at low nominal CR setting i.e., 1.1. For the mid nominal CR, i.e., 2.51, no significant difference was seen between the nominal and the measured CR. For the high nominal CR, the measured CR is significantly lower than the nominal CR set value, i.e., 4.

      Irrespective of the low- or high- nominal CRs, the measured CRs tended to be closer to mid CR values.
2. Comparison of nominal and measured CT revealed that the measured CT is significantly different for the low- and high- nominal CT conditions. In the low

nominal CT setting, the measured CT is greater than the nominal CT. In the high nominal CT setting, the measured CT is lesser than the nominal CT. In the mid nominal CT setting, the low nominal CR condition showed measured CT that was significantly lesser than the nominal CT. In the other two conditions, there was no significant difference between the nominal and the measured CT.

Clinical Implications of the Study

In this study, significant difference was observed between the nominal and the measured CR and CT. This requires that the audiologist to be more vigilant while programming the compression features in the hearing aid. It has to be understood that whatever is set during programming may not always be the same as what the hearing aid delivers.

Recommendations for Future Research:

1. Other dynamic and complex stimuli such as speech can be used to see the effective compression that is achieved by hearing aids, as such stimuli are more often encountered in everyday listening situations.
2. The study can be extended to include subjective responses to the different compression parameters that are set, and the subjective responses can be compared with the electroacoustic measures. This can throw some light onto the perceptual advantages and disadvantages of varying the CR and/or CT.

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