An Evaluation of Acoustic and Perceptual Effects of Feedback Management in Hearing Aids

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Abstract

The present study aimed at evaluating the efficacy of the feedback reduction methods in the hearing aid, namely the phase cancellation algorithm and the use of acoustic modification (damper) in the ear mould using insertion gain measure and Speech Identification Scores (SIS). The data were collected from 60 ears of 30 children who had severe to profound hearing losses in both ears. The results indicated that there was an increase in the gain available as well as the output with the activation of feedback management and with the use of dampers. The behavioural measure, the speech identification scores, was higher with the activation of feedback management method and dampers compared to without them. The increase in gain can be attributed to the principle of working of phase cancellation method which reduces the feedback so that useful gain can be increased. As the dampers smoothen the frequency response at mid frequencies, a greater available gain is possible at mid- and high- frequencies. The increase in the available gain along with the efficient cancellation of feedback may be attributed to improved speech identification scores in the condition with feedback management activated and with the use of dampers. The findings of the study support the necessity of use of feedback management method like phase cancellation algorithm in digital hearing aids and dampers in analog hearing aids in children with severe to profound hearing loss.

Keywords: *Feedback Management, Phase Cancellation, Dampers, Insertion Gain, Speech Identification Scores.*

Introduction

Audible feedback is amongst the most prominent problems with hearing aids (Kochkin, 2002). In a hearing aid, the acoustic feedback or squeal occurs when the output of the hearing aid leaks out of the ear canal and enters the hearing aid microphone and is amplified again. The acoustic leakage is often attenuated by the ear mould coupled to the hearing aid. The conditions necessary for audible feedback oscillation are met when the degree of attenuation is small and/or when the gain of the hearing aid is high (Kuk, Ludvigsen & Kaulberg, 2002).

Generally, this feedback is associated with high gain hearing instruments. During such times, the annoyance, frustrations and embarrassment caused by the feedback may even outweigh an individual's otherwise perceived benefit from amplification. Acoustic feedback also can indirectly reduce the benefit from amplification. The hearing aid users may prefer to opt less-than-optimal gain to avoid the likelihood of feedback, or use the hearing aids for situations known to be 'feedback-free', or in extreme cases, simply stop using the hearing instruments (Chalupper, Powers & Steinbuss, 2011).

Thus, acoustic feedback is annoying and reduces the maximum usable gain of the hearing devices (Siqueira, Speece, Petsalis, Alwan, Soli & Gao, 1996). These peaks in the response of the hearing aid, which are often high-frequency in nature, may produce an uncomfortable sharpness in the hearing aid processed speech and affect speech recognition (Freed & Soli, 2006). Acoustic feedback phenomenon can thus deteriorate the performance of digital hearing aids working at high gains, causing instability and speech degradation (Leira, Bueno, Pita, & Zurera, 2008). This phenomenon even contributes to the 'hearing aid effect' , as potential users of amplification view acoustic feedback as a part of the negative stigma (Cox & Alexander, 2000).

The main challenges faced by the hearing aid users prone to feedback problems are mostly threefold. First, it can distort the sound signal across all the frequencies, causing a noticeable reduction in sound quality. Second, it can be so annoying to the user's environment that he/she is forced to turn the instrument down, thus loosing the crucial speech information when it is most needed. And finally, it can restrict the full use of the volume control, which in turn limits the person's ability to hear and understand speech.

Acoustic feedback is also associated, more often, with children having severe to profound degree of hearing loss. In young children the problem of feedback is exacerbated as the external ear is still growing (Westwood & Bamford, 1995). Consequently, after certain weeks or months, the initially good fitted ear mould can become loose and hence may increase the probability of occurrence of feedback (Flynn & Flynn, 2006). For the above reasons, consideration on feedback management in hearing aids is of extreme importance in paediatric population with severe to profound hearing impairment.

Feedback reduction algorithms in digital hearing aids may provide a solution for some of these problems. The acoustic feedback suppression in hearing aids can in-

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crease the maximum insertion gain of the aid. The ability to achieve target insertion gain leads to better utilization of the speech band-width. Thus, improved speech intelligibility for the hearing aid user can be expected as the most probable outcome (Siqueira et al., 1996).

Different approaches to feedback management have been introduced in hearing instrument technology (Dillon, 2001). With the advent of digital signal processing, audible feedback oscillation can be minimized without sacrificing gain, audibility, loudness, and speech intelligibility. A more promising solution for acoustic feedback would be the use of a feedback cancellation algorithm. The feedback canceller produces an estimate of the feedback signal and subtracts this estimate from the microphone signal, so that, ideally, only the desired signal is preserved at the input. Since the acoustic path between the loudspeaker and the microphone can vary significantly depending on the acoustical environment, the feedback management must be adaptive.

Among the feedback reduction methods, generally phase cancellation has been used. Phase cancellation systems are capable of suppressing feedback without degrading the audibility of speech, and therefore, this type of feedback reduction is preferable (Chalupper, et al., 2011).

Techniques for better ear mould design such as reducing the size of the conventional vents, coupling of hearing aids, and fitting methods have also been proposed to reduce feedback problems (Cox, 1982). Use of dampers in ear moulds can increase the usable gain of hearing aids. They increase the low frequency attenuation and provide greater high frequency output and a smoother frequency response by reducing the peakedness caused at high frequencies due to feedback (Valente, 1984). Therefore aim of the present study was to evaluate the feedback reduction methods in hearing aids, namely the feedback reduction algorithm and use of acoustic modification (damper). The specific objectives were, first, to evaluate the effect of the feedback reduction strategies in hearing aids, such as the phase cancellation method and use of damper in ear mould, on the insertion gain measures. Second, to evaluate the effect of the feedback reduction method and use of damper in the ear mould, on speech identification scores (SIS).

Method

The study aimed to evaluate the efficiency of phase cancellation method and use of dampers as the two feedback management methods using insertion gain measures and behavioural measures.

Participants

The data were collected from a total of 60 ears of 30 children, in the age range of six to eight years (Mean age of 6 years 5 months). The participants considered for the current study had Kannada as their mother tongue and had pre-lingually acquired bilateral severe to profound hearing loss, pure tone average ranging from 75 to 120 dB HL in the speech frequencies. All of them had flat or gradually sloping (with a slope of $<$15 dB per octave) hearing loss in both the ears. On immittance evaluation with GSI Tympstar middle ear analyzer (version 2), all the participants got 'A' type tympanogram with reflexes being absent. TEOAEs carried out through ILO 292 instrument, were absent in both the ears revealing outer hair cell dysfunction in both the ears. Auditory Brainstem Responses done with Intelligent Hearing System were absent in both ears for all the participants.

The thresholds for the frequencies at which the feedback occurred mostly from 1500 Hz to 6000 Hz (Martin, & Robert, 2006) was equal to or greater than 90 dBHL for all the participants, irrespective of minimal residual hearing at low frequencies till 1000 Hz. All the participants were using binaural digital Behind-The-Ear (BTE) hearing aids with a gain lesser than the target gain due to the occurrence of the feedback. With this gain setting, all the participants obtained an aided closed-set speech identification (through picture identification task) score of 50% or greater in the aided condition. The participants had no significant history of otologic, neurologic, cognitive or psychological problems. All the participants attended listening training and speech therapy for a period of at least of three months and they had the auditory skills at least for the identification of words.

All the testing was carried out in an air-conditioned sound treated double room situation. The study was carried out in three different phases. Phase I- Selection of participants, Phase II-Insertion Gain measurement and Phase III-Aided behavioural testing.

Phase I: Selection of Participants

Audiological evaluation: A detailed case history, routine audiological tests including pure tone audiometry, speech audiometry and immittance evaluation were carried out for all the participants for each test ear to confirm the inclusion criteria.

Speech Identification Scores (SIS) for selection of participants: A digitally programmable two channel Behind-The-Ear hearing aid with a fitting range for severe-to-profound sloping hearing loss, with custom made soft shell ear mould was used for the testing. The hearing aid used had 2 channels and 8 bands with 4 programmable memories. The hearing aid had a maximum output level of 135 dB SPL, maximum gain of 70 dB and a reference test gain of 52 dB. The basic frequency response was from 200 Hz to 6400 Hz. The hearing aid utilized 'Active Feedback Intercept' which worked on the principle of phase cancellation method for feedback management. (Engebreston & St. George, 1993).

The hearing aid was programmed to match the target gain curves obtained using the proprietary prescription formula. A personal computer with NOAH-3 and hearing aid specific softwares, and Hearing Instrument Programmer (Hi-Pro) interface were used to program the hearing aids and to activate or de-activate the feedback reduction algorithm. The aided closed-set speech identification scores were calculated as the number of words correctly identified, out of a total of the 25 words, when presented at 45 dBHL. The response mode was through the picture identification. A score of 50\% and above was considered as the criterion for the inclusion of participants in the current study.

Phase II: Insertion Gain Measurement Procedure

Fonix 7000 real ear measurement (computer controlled real-time analyzer version 1.70) with probe tube microphone option was used in order to measure the amount of gain/output delivered by the hearing aid in the ear canal of the participant through the insertion gain measurement procedure.

The loudspeaker of the real ear measurement system was placed at approximately 12 inches and at 450 Azimuth from the participant, at the level of participant's head. The integrated probe microphone was placed on the test ear of the participant. The reference microphone was secured on the ear hanger above the ear. After the probe tube was inserted, the probe microphone body was pivoted towards the ear to help hold the probe tube in place.

The ear mould was placed next to the probe tube, so that the tube rested along the bottom of the canal part of the ear mould, with the tube extending at least 5 mm from the tip of the ear canal opening, where a marking was done. For the aided testing, length of the canal portion of the custom ear mould, in addition to a length of 5 mm, was considered as the marking point on the probe tube which was made to coincide at the tragal notch of the participant's test ear.

Real Ear Measurement Procedure: The sound field was levelled by keeping the probe tube near the ear canal. A digi-speech signal was used at 65 dB SPL for the measurement of Real Ear Unaided Response (REUR). A hearing aid was fitted with custom ear moulds. The NAL-NL1 fitting formula was used to prescribe the hearing aid gain. The hearing aid was programmed to match the target gain. During this process, if there was occurrence of feedback, the volume control was reduced to a level at which there was no feedback with the programmed gain. Thus, the real ear measurements were obtained at the reduced volume control setting in the 'feedback reduction - off' condition. The Real Ear Aided Response (REAR) was measured at this setting of the hearing aid. Further, closed-set Speech Identification Score was also obtained with these settings on the hearing aid.

Likewise, the hearing aid was programmed to reach the target gain with the 'feedback reduction - on' condition. The volume control was set to the optimum setting i.e., to a point where there was feedback. The Real Ear Aided Response (REAR) was measured with this setting. It must be noted that the same volume control setting was used for measuring the SIS from the participant.

All the participants were tested with the 'Active Feedback Intercept - on' and in 'Active Feedback Intercept - off' conditions. Later, a damper of resistance 4700 Ω was inserted into the tubing of the ear mould connected to the hearing aid at a distance of 9 mm from the tubing end. The damper was placed as close as possible to the earhook end of the hearing aid. With the use of dampers, the volume control setting that was attainable without the occurrence of feedback was noted and REAR was obtained with this volume setting without the activation of feedback management method. It must be noted that the same volume control setting was used for measuring the SIS from the participant.

The Real Ear Insertion Gain (REIG) was obtained which is the difference between the REAR and REUR across all the frequencies for the three aided conditions, namely with and without feedback management and with damper, for each test ear. Two other measures were included which were calculated based on the real ear gain obtained at different frequencies. The two measures were the High Frequency Average Real Ear Insertion Gain (HFAREIG in dB) and Added Stable Gain (ASG in dB). The high frequency average real ear insertion gain (HFAREIG) was obtained by averaging the real ear gain values across the speech frequencies, i.e., 1000 Hz, 1600 Hz and 2500 Hz. It was calculated with the assumption that the high frequency average gave a better estimate of speech perception abilities than other frequency averages (Lenzen, 2008). The ASG in dB was calculated by subtracting the REAG obtained in 'without feedback management' condition from REAG obtained in 'with feedback management condition' i.e., REAG (WFBM) - REAG (WOFBM) or subtracting REAG in 'without feedback management' condition from REAG in 'with damper' condition i.e., REAG (WDAMP) - REAG (WOFBM). This measure was obtained as it could be used as a quantitative measure to compare the benefit from different feedback management options, in comparison with no feedback management. Also, the effect of the available gain on the improvement in speech identification scores could be quantified.

Phase III: Behavioural Testing

The closed-set Speech Identification Scores (SIS) were obtained in quiet through monitored live voice presentation of the phonemically balanced word lists for children developed by Vandana (1998). For this, the gain was set at just below the level causing feedback. The stimuli were presented through a loudspeaker of the audiometer from 00 Azimuth placed at a distance of 1 meter from the head of the participant at 45 dBHL. The response mode was pointing to the appropriate picture out of a group of four pictures. The scoring was done based on the number of words correctly identified out of the total number of 25 words presented. This was done for feedback suppression algorithm activated and subsequently with the use of dampers with appropriately adjusted volume control settings. Thus, for each participant, the data on REAR, in dB SPL; HFAREIG, in dB); Added Stable Gain (ASG, in dB and Aided SIS (maximum score being 25) were collected.

Statistical Analysis

Appropriate statistical analysis was carried out for the data to verify the objectives of the study. The mean and standard deviation of the REAR (in dB SPL), HFAREIG (in dB), ASG in dB and SIS (with maximum score of 25) were obtained. The scores obtained using REAR (in dB SPL), ASG, HFAREIG (in dB) were compared across the three aided conditions (WOFBM, WFBM & WDAMP) and were compared across eleven discrete frequencies from 200 Hz to 8000 Hz. Data on SIS were compared across the three aided conditions (WOFBM, WFBM and WDAMP) to check for the significant differences, if any.

Results and Discussion

The data collected were tabulated and subjected to statistical analysis using Statistical Package for Social Sciences (SPSS 17.0 for windows version). Descriptive statistics and analysis of variance were computed to evaluate the objectives of the study. The results are discussed under Insertion Gain Measures and Behavioural Measure.

Insertion Gain Measures

The data on insertion gain measure obtained for all the 60 ears were analyzed in the three aided conditions, viz., without feedback management with the feedback management and by inserting the damper in the ear mould.

Real Ear Aided Response, REAR (in dB SPL)

Real Ear Aided Response (in dB SPL) was obtained at eleven discrete frequencies across the frequency range from 200 Hz to 8000 Hz, for 60 ears in three aided conditions. Descriptive statistics was used to compare the mean and standard deviation measures of the REAR values (Table 1) in the three aided conditions. Figure 1 shows the mean REAR values across the eleven frequencies for the three conditions (WOFBM, WFBM and WDAMP).

From Tables 1 and Figure 1, it is evident that the mean REAR values were highest for WFBM condition followed by WDAMP condition and then by WOFBM condition, across all the frequencies except for 1000 Hz and 7000 Hz. Further, Table 2 shows the mean REAR values of different frequencies in the three aided conditions.

As indicated in Table 2, a high mean REAR value was evidenced in the condition with feedback management (WFBM) compared to without feedback management (WOFBM) and with damper (WDAMP) conditions. To determine if this difference in REAR in the three aided conditions was significant, one-way repeated measure ANOVA was done. Results revealed a high significant difference between the three aided conditions [$F(2,118) = 113.55$, $p<0.01$]. As a high significant difference was evident on the repeated measure ANOVA, Bonferroni's multiple group comparison was carried out to evaluate the pairs of conditions which showed a significant difference. Table 3 shows the results of Bonferroni multiple group comparison showing the level of significance for the three pairs of conditions.

As indicated in Table 3, there was a highly significant difference between the WOFBM and WFBM conditions, and WFBM and WDAMP ($p<0.01$). In addition, significant difference was also noted between WDAMP and WOFBM ($p<0.05$).

The observed differences between the conditions along with WFBM having a significantly greater output compared to other two conditions (WOFBM and WDAMP) may be attributed to a greater available gain; and hence a greater output with the activation of the feedback management (Freed & Soli, 2006). These differences in the REAR is possible due to the use of digital technology in hearing aids, because of which mathematical estimations of the feedback path can be made and used to compensate for the feedback, essentially without affecting the input signal, while ideally preserving the desired output. Such a method provides an added 6 to 10 dB average headroom improvement and possibly avail more useable gain compared to without the feedback management activated (Olson, Musch & Struck, 2001).

The type of feedback management method used in the hearing aid in the present study was 'Active Feedback Intercept' which is based on the principle of working of phase cancellation algorithms. Since phase cancellation algorithms simply cancel out unwanted feedback, there is no gain reduction associated with elimination of feedback. On the contrary, this technique results in ASG, i.e., an increase in maximum gain with feedback management enabled compared to that with feedback management disabled. Thus, there was an increase in the output with the activation of feedback management method (Freed & Soli, 2006; Merks, Banerjee & Trine, 2006). The mean REAR values were higher

Table 1: Mean and Standard Deviation (SD) values of REAR (in dB SPL) for the three aided conditions (WOFBM, WFBM and WDAMP), across eleven discrete frequencies from 200 Hz to 8000 Hz (N=60 ears)

Conditions	REAR in dB SPL - Mean(S.D)										
	200 Hz	500 Hz	1000 Hz	1500 Hz	2000 Hz	3000Hz	4000 Hz	5000 Hz	6000 Hz	7000 Hz	8000 Hz
WOFBM	87.42(5.76)	95.98(6.71)	102.99(6.23)	102.02(7.90)	103.54(6.73)	93.45(5.97)	87.21(7.22)	80.89(8.51)	73.15(9.07)	67.96(9.76)	56.79(7.96)
WFBM	95.55(5.69)	105.24(5.57)	110.14(6.23)	109.15(5.71)	111.99(5.72)	101.26(5.26)	96.61(5.89)	92.51(7.46)	84.20(7.43)	77.32(10.13)	68.44(9.88)
WDAMP	90.43(6.72)	96.99(6.01)	100.14(6.15)	106.24(6.44)	107.71(6.50)	94.88(6.20)	90.95(6.99)	83.41(8.41)	78.68(9.12)	67.59(10.56)	61.13(10.8)

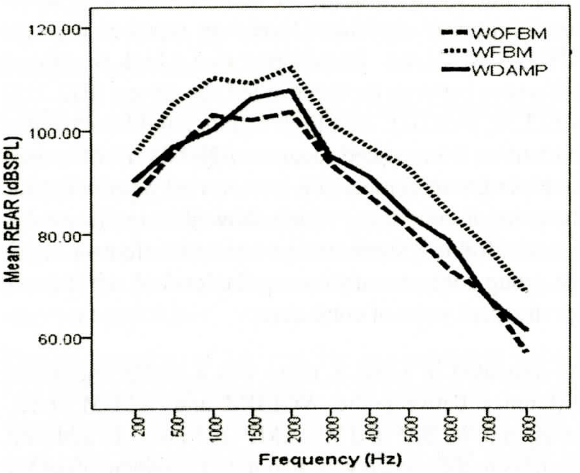

Figure 1: Mean REAR (in dB SPL) for the three aided conditions (WOFBM, WFBM and WDAMP).

Table 2: Results of descriptive statistics for Rear Ear Aided Response (REAR in dB SPL) indicating mean and SD values across the three aided conditions (WOFBM, WFBM and WDAMP)

REAR (in dB SPL)	
Conditions	Mean across frequencies(Standard Deviation)
Without feedback management (WOFBM)	86.49(15.42)
With feedback management (WFBM)	95.67(14.14)
With damper (WDAMP)	88.92(14.99)

Table 3: Results of Bonferroni multiple group comparison showing the level of significance across the pairs of conditions

Difference between conditions	p values
WOFBM & WFBM	0.000*
WFBM & WDAMP	0.000*
WDAMP & WOFBM	0.025**

*Note: *: $p < 0.01$=highly significant difference.*
***: $p < 0.05$= significant difference*

in the aided condition 'with dampers' for all the frequencies compared to 'without feedback management' method. This increase in the REAR values (and thus the real ear insertion gain values) may be because the dampers give a higher gain at higher frequencies and smoothen the frequency response at mid- to high- frequencies where the resonances caused by feedback results in sharp peaks in the frequency response (Valente, 1984). In the WOFBM method, the prescribed gain is reduced till the point where feedback does not occur, the gain across all the frequencies will be effectively lesser compared to WDAMP condition. Hence, a reduced output and thus the gain is the most likely outcome in the Aided condition without feedback management. The dampers reduce the sharp peaks caused due to the feedback and hence they reduce the gain and output SPL especially at low- to mid- frequencies (Valente, 1984). Hence, there are reduced REAR values in WDAMP condition compared to WFBM condition.

Also, frequency differences were noted for REAR (in dB SPL) across the three aided conditions. There was a greater output at mid- and high- frequencies from 500 Hz to 4000 Hz (with an average REAR of 105.73 dB SPL) compared to lower frequencies below 500 Hz (with an REAR of 95.55 dB SPL). Because the frequency response becomes sharper with the occurrence of feedback, there may be a significant difference of REAR across the frequencies in the without feedback management condition (Valente, 1984).

Because the feedback management methods provide added stable gain, the frequency response changes accordingly across the two conditions, viz., with and without feedback management conditions (Freed & Soli, 2006; Merks et al., 2006). Since the phase cancellation method is functional at 1500 Hz to 6000 Hz and more effectively it operates at 3000 Hz to 6000 Hz (Dyrlund, Henningsen, Bisgaard & Jensen, 1994), the peaks caused due to the presence of feedback are reduced. And this explains the observed differences in REAR values across the conditions for different frequencies. According to Valente (1984), there will be smoothening and hence a change in the frequency response with the use of dampers compared to WOFBM and WFBM, hence a significant difference is expected across the three conditions.

There are only certain frequencies where the feedback management method operates (Dyrlund et.al., 1994) and only certain frequency range that is smoothened by dampers (Valente, 1984). In addition, the frequency range where the feedback management method and dampers operate, may be different, that is there may be a difference in the REAR values across the frequency range for the three aided conditions.

A similar finding was noted in a study by Kuk and Ludvigsen (2002), who reported an increase in the available gain and hence the output across the frequency range of 200 Hz to 8000 Hz with the phase cancellation method. According to Martin and Robert (2006), phase cancellation not only preserves gain, but also because of its increased feedback margin, makes approximately 10 to 15 dB SPL more amplification available in the mid- to high- frequencies.

In a study by Lenzen (2008), the mean ASG ranged from 1.6 dB for low frequency band to 2.8 dB for the high frequency band. The mean difference of 1.2 dB in ASG between the low frequency band and the mid-frequency band was statistically significant (two tailed proportion $p<0.001$). Also, it was reported that the mean difference of 0.9 dB in ASG between the mid-frequency band and the high frequency band was statistically significant (two tailed proportion ($p<0.001$). There were no significant differences in mean ASG between the low frequency and high frequency band. The reason attributed to the reduced added stable gain values was that the maximum gain was reached initially and hence further improvement was not effective due to the 'ceiling effect'.

The ear mould dampers have an effect of smoothening the peaks from 1000 Hz to 3000 Hz (Taylor & Teter, 2009). As a result of this, the peaks are reduced and a smoother frequency response with higher gain is possible at mid frequencies (Dillon, 2001).

High Frequency Average Real Ear Insertion Gain (HFAREIG) calculated for the frequencies 1, 1.6 and 2.5 kHz, in all the three conditions

The data was obtained for all the three conditions across the frequencies 1, 1.6 and 2.5 kHz for 60 ears. Table 4 shows the descriptive statistics for the HFAREIG values at 1000 Hz, 1600 Hz and 2500 Hz obtained across the three aided conditions (WOFBM, WFBM and WDAMP).

Table 4 indicates that the mean HFAREIG value for WFBM condition is greater than the mean HFAREIG values for WOFBM and WDAMP conditions. Repeated measure ANOVA was done to find out the significant differences across conditions (WOFBM, WFBM and WDAMP), if any. A high significant difference was noted on repeated measure ANOVA for HFAREIG

Table 4: Descriptive statistics showing Mean and Standard Deviation for the HFAREIG values across the three conditions (WOFBM, WFBM and WDAMP)

HFAREIG (in dB)	
Conditions	Mean(Standard Deviation)
Without feedback management	34.99 (6.09)
With feedback management	42.04 (5.25)
With damper	37.69 (4.34)

Table 5: Results of Bonferroni's pair-wise comparison for HFAREIG across the three conditions (WOFBM, WFBM and WDAMP)

Conditions	Level of Significance HFAREIG (dB) (p)
WOFBM & WFBM	0.000*
WFBM & WDAMP	0.000*
WDAMP & WOFBM	0.002*

*Note: *: $p < 0.01$=high significant difference*

across the three conditions, WOFBM, WFBM and WDAMP [$F (2,118) = 55.92$, $p < 0.01$]. Bonferroni's pair-wise comparison was done to assess the significant differences between the HFAREIG for different conditions. Table 5 indicates results of Bonferroni's pair-wise comparison done across the three conditions for HFAREIG.

A highly significant difference was present across the three pairs of conditions for HFAREIG values as revealed from Table 5. The significant difference across the conditions may be attributed to the frequency range at which the feedback management is functional. It is supported by the fact that most of the feedback management is activated at frequencies between 1500 Hz to 6000 Hz. Accordingly, there would be a gain enhancement in this frequency range. This reason can be attributed to the observed differences between the HFAREIG values in WOFBM and WFBM conditions.

A study by Flynn and Flynn (2006) showed greater available gain with feedback management strategy at frequencies from 1.5 kHz to 3 kHz and thus might have resulted in a significant difference between the two conditions.

The present study shows an increase in HFAREIG by 7 dB, with and without feedback management conditions. This supports the findings of the study by Merks et al. (2006). He compared the feedback reduction performance of two hearing aids on 20 ears in terms of ASG derived by subtracting the Maximum Stable Gain (MSG) with feedback management deactivated from

Table 6: Mean ASG (in dB) across eleven discrete frequencies for WFBM and WDAMP conditions

Mean ASG for conditions(in dB)	Frequencies (in Hz)										
	200	500	1000	1500	2000	3000	4000	5000	6000	7000	8000
WFBM	8.13	9.26	7.14	8.44	7.80	9.40	11.61	11.04	11.04	9.36	11.64
WDAMP	3.01	1.01	-2.85	4.16	1.42	3.74	2.52	3.52	3.52	-0.37	4.33

that when it was activated. The MSG was calculated by averaging the real ear gain at 1 kHz, 1.6 kHz, and 2.5 kHz. The authors found that ASG ranged between 9 and 12 dB across the two hearing aids. The average difference in ASG between the two hearing aids used in the study was 3 dB (Lenzen, 2008).

The difference in HFAREIG values for WOFBM and WDAMP conditions was 2.7 dB. There was a high significant difference between WOFBM and WDAMP conditions which may be because dampers decrease the gain and the maximum output (Valente, 1984). Since they are more effective in reducing the peaks from 1 to 3 kHz, there will be reduction in the gain at this frequency range, compared to that obtained from WFBM condition. However, the gain reduction with the use of 'yellow' colour coded dampers was on an average 9 dB (Valente 1984), which was lesser compared to the gain reduction caused in an attempt to reduce the feedback in WOFBM condition.

Added Stable Gain (ASG) across the frequency range from 200 to 8000 Hz (for eleven discrete frequencies

As the ASG gives an idea of an increase in the available gain with feedback management and with dampers, comparison of the obtained ASG was made to account for the efficacy of the feedback management methods. Tables 6 shows the ASG for the two conditions (WFBM and WDAMP), across the eleven frequencies. Figure 2 shows the gain (in dB) across the frequencies for the three conditions (WOFBM, WFBM and WDAMP). Through this, the added stable gain can be calculated across the frequency range.

Figure 2 indicates that the gain for WFBM was greater compared to without feedback management and with damper. This finding was evident across the frequency range from 200 Hz to 8000 Hz. Significant differences between the two conditions were determined using pairwise comparison, if indicated.

Table 6 indicates that the mean ASG for WFBM condition was greater than WDAMP condition across all the frequencies. Also, mean ASG values were found to be greater for higher frequencies compared to mid- and low- frequencies. To find the average value of ASG across the frequencies, descriptive statistics was used. Table 7 shows the results of descriptive statistics giving mean and standard deviation for the ASG averaged across the eleven frequencies.

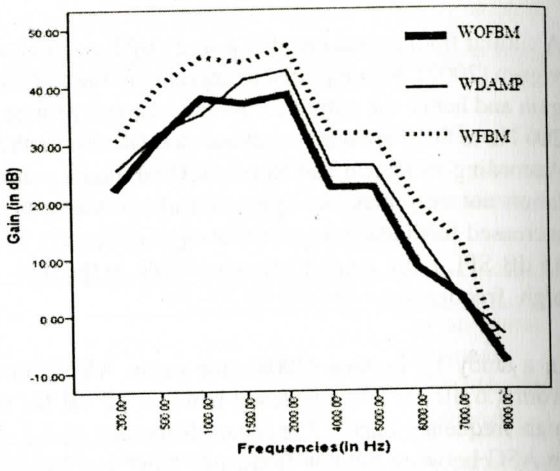

Figure 2: Gain (in dB) across the frequency range from 200 Hz to 8000 Hz, for the three conditions (WOFBM, WFBM and WDAMP)

Table 7: Mean and SD (in brackets) values of Added Stable Gain (ASG) for the two conditions (WFBM and WDAMP

	ASG (in dB)
Conditions	Mean(Standard Deviation)
With feedback management	9.17(1.65)
With damper	2.24(2.26)

From Table 7, it is evident that the mean values for WFBM condition were greater than WDAMP. A difference of 6.0 to 7.0 dB was evidenced for ASG across the two conditions. Paired t-test was carried out to compare the ASG values for the two conditions WFBM and WDAMP. Results indicated a high significant difference between the two conditions on ASG values [$t(10) = 10.03$, $p < 0.01$]. Several studies have reported the ASG values obtained with and without feedback management methods. The increase in ASG values with feedback management method can be attributed to the principle of working of the phase cancellation, which effectively reduces the feedback without reducing the gain. Moreover, it gives a greater available gain across the frequency range. Mean ASG values obtained through the method of feedback management varies across the frequencies. A few studies reporting the amount of ASG obtainable across the frequency range are discussed below.

According to Martin and Robert (2006), it was seen that the ASG was maximum at around 1 kHz and 3 kHz followed by higher frequencies. In addition, the study done by Martin and Robert (2006) reported greater ASG at higher frequencies (from 2 k to 5 kHz). Approximately 10 to 15 dB more amplification was made available in the mid-high frequencies through the phase cancellation method. According to Maxwell and Zurek (1995), the maximum added wideband stable gain was approximately 12 dB through the method of phase cancellation.

Field trials of a feedback-cancellation system built into a BTE hearing aid have shown increases of 8 to 10 dB in the gain used by individuals with severe hearing impairment (Bisgaard, 1993) and increases of 10 to 13 dB in the gain margin measured in real ears (Dyrlund et al., 1994). Computer simulations and prototype digital systems indicate that increases in gain between 6 and 20 dB can be achieved in an adaptive system before the onset of oscillation, and no loss of high-frequency response is noted (Engebretson & St.George, 1993).

Greenberg, Zurek, and Brantley (2000) reported that ASG ranged between -1 to 25 dB with a mean ASG of 8.5 dB for the experimental algorithm and approximately 5 dB for the other algorithms. Banerjee, Recker, and Paumen (2006) compared the feedback reduction performance of two hearing aids on 20 ears. Maximum stable gain (MSG) was calculated by averaging the gain at 1, 1.6, and 2.5 kHz. The authors found that the ASG ranged between 9 and 12 dB across the two hearing aids. However, a study by Lenzen (2008) indicated that the mean ASG ranged from 1.6 dB for low frequency band to 2.8 dB for the high frequency band. A mean difference of 1.2 dB in ASG between the low frequency band and the mid frequency band was statistically significant (two-tailed proportion $p < 0.001$). There were no significant differences in mean ASG between the low frequency and high frequency band.

Merks et al., (2006) did not report average ASG, but reported that ASG ranged from 3.5 to 16.3 dB. Banerjee et al. (2006) reported that ASG ranged between 2 to 18 dB with an average of 9 to 12 dB. Freed and Soli (2006) did not report average ASG, but reported that ASG ranged between 0 to 18 dB across all frequencies. Greenberg et al. (2000) reported an ASG ranging between -1 to 25 dB with an average ASG of 8.5 dB for one experimental algorithm and approximately 5 dB for the other experimental algorithms.

According to Kuk et al. (2002), there is an increase in Added Stable Gain in a wide range from 2 to 4 kHz, from as little as 8 dB to as much as 19 dB. An average of 12 to 13 dB was noted for the group. No increase in ASG was noted below 1 kHz, possibly because feedback being a high frequency phenomenon usually occurs above 1 kHz and target gain is typically reached below 1 kHz. Thus, there is probably no need for further increase in gain. Thus, the mean ASG values obtained in the present study was in accordance with the previous reports. However, the ASG obtained for the WDAMP condition was lesser compared with WFBM condition. This may be because of dampening effect from 1 to 3 k Hz which might have resulted in lower gain compared to the gain from WFBM condition.

Behavioural Measure

SIS values for the three conditions (WOFBM, WFBM and WDAMP)

The mean and standard deviation values of the Speech Identification Scores for each participant in three aided conditions were obtained. The maximum SIS was 25. Table 8 gives the mean and SD of the SIS.

Table 8: Mean and SD (SD) values of SIS (Max. 25) in three aided conditions (WOFBM, WFBM and WDAMP) WDAMP

	SIS
Conditions	Mean(Standard Deviation)
Without feedback management	17.45(2.15)
With feedback management	22.25(2.39)
With damper	20.78(2.54)

From Table 8, it is evident that the mean SIS for WFBM condition was greater than the SIS values for WOFBM and WDAMP conditions. It was found that the SIS was better in the WFBM condition than WOFBM and WDAMP conditions. Figure 3 shows the mean SIS scores with standard error (95% confidence level) across the three conditions.

Figure 3 shows the mean SIS values across the three aided conditions. The SIS in the WFBM condition was greater compared to SIS in the WDAMP and WOFBM conditions. In order to see if there was a significant difference, repeated measure ANOVA was done. It was found that there was a high significant difference between the three conditions on the SIS scores [$F(2, 118) = 275.85$, $p < 0.01$]. Following this, Bonferroni's pair-wise comparison was done to find the pair of conditions which showed a significant difference. Table 9 shows the results of Bonferroni's pair-wise comparison with significance levels.

Table 9 revealed that a highly significant difference existed across the conditions on SIS. This could be attributed to the added stable gain which was more in WOFBM condition than for the WFBM than WDAMP condition. The increase in ASG allows majority of

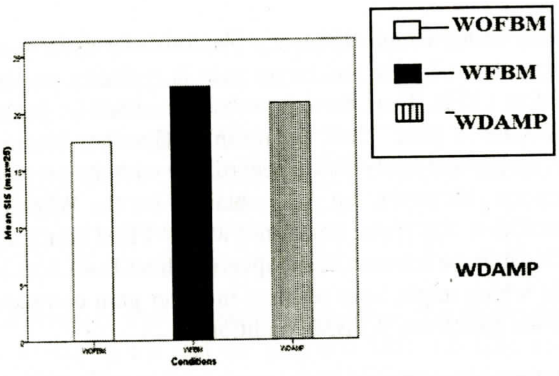

Figure 3: Mean SIS (Max.=25) for 60 ears across the three conditions (WOFBM, WFBM and WDAMP) (two-tailed with 95% confidence level).

wearers to achieve their desired gain without feedback in many more listening situations. The ability to use the target gain more consistently could result in better speech intelligibility, better sound quality, and a hassle-free listening experience.

Table 9: Results of Bonferroni's pair-wise comparison for SIS across three conditions (WOFBM, WFBM and WDAMP)

SIS scores across conditions	Level of Significance(p)
WOFBM & WFBM	0.000*
WFBM & WDAMP	0.000*
WDAMP & WOFBM	0.000*

*Note: *: p < 0.01=high significant difference*

In addition, the HFAREIG values were 7 dB greater for WFBM condition and 4.35 dB greater for WDAMP condition compared to WOFBM condition. The increase in the available gain at higher frequencies leads to better speech perception.

Dyrlund et al. (1994) reported that since there is a greater ASG at high frequencies, an improvement in speech identification performance is evidenced without causing feedback. Since feedback is a high frequency phenomenon, phase cancellation method would result in more of high frequency gain by cancelling the peaky responses (Martin & Robert, 2006). Christensen, Winfrey, and Stelmachowitz (2006) investigated the effectiveness of phase cancellation method and it was noted that a high frequency gain and improved perception of high frequency consonants resulted. The authors concluded that using feedback management helps to meet the mid- and high- frequency targets while providing maximum audibility for speech sounds. Hence, an improvement in SIS was noted in the WFBM condition.

The SIS in WDAMP condition was better than WOFBM condition. Peaks and troughs in the gain frequency response adversely affect the speech intelligibility and quality of amplified sound. Since smoothening of the frequency response takes place with the use of dampers and the peaks in the frequency response are reduced, an improvement in SIS was seen in WDAMP condition in comparison with WOFBM condition. However, the SIS obtained in WFBM condition was significantly better than the SIS obtained in WDAMP condition. This may be attributed to the added stable gain that is possible with the phase cancellation method. Where as in WDAMP condition, only the peaked responses are reduced providing a more stable output, without providing the ASG equivalent to that of the WFBM condition. This is expected since the purpose of the two is different. Hence, a significant difference was noted across the two conditions (WFBM and WDAMP).

Thus, the improvement on insertion gain measures with the activation of feedback management methods, viz., the feedback reduction strategy and the use of dampers, leads to a parallel improvement in terms of speech perception as well.

Conclusions

From the study it can be inferred that there is a highly significant improvement with the feedback management condition than without the feedback management in hearing aids. The improvement in the WFBM condition was due to the principle of working of phase cancellation method, because of which gain is not compromised while reducing the feedback. On the contrary, available gain increases with the activation of phase cancellation. Hence, greater output and gain value result with phase cancellation (Freed & Soli, 2006; Merks et al., 2006). With dampers, the amount of gain available and hence the output given also is significantly higher because of the effect of smoothening of the peaks in the frequency response. This leads to increased high- and mid- frequency response as the hearing aid wearers can increase the volume control. This is mainly because the peaks in the frequency response are reduced (Valente, Dunn & Roeser, 2000).

Increase in the Added Stable Gain and high frequency average real ear insertion gain led to better speech identification scores in feedback management activated condition than when it was de-activated. Dyrlund et al. (1994) reported that since there is a greater ASG at high frequencies, there is an improvement in speech identification performance without causing feedback. The SIS obtained in the WDAMP condition was better than in WOFBM condition, due to increased gain available in mid- and high- frequencies (Valente, Dunn & Roeser, 2000). However, the amount of gain available was lesser compared to WFBM condition.

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