# Comparison of Objective and Subjective Approaches for Verification of RIC Hearing Aids.

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## CERTIFICATE

This is to certify that the dissertation entitled 'Comparison of objective and subjective approaches for verification of RIC hearing aids' is the bonafide work submitted in part fulfillment for the degree of Master of Science (Audiology) of the student with Registration No. 16AUD001. This has been carried out under the guidance of a 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 the master’s dissertation entitled ‘Comparison of objective and subjective approaches for verification of RIC hearing aids’ has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier in any other University for the award of any Diploma or Degree.

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**DECLARATION**

This is to certify that this master's dissertation 'Comparison of objective and subjective approaches for verification of RIC hearing aids' is the result of my own study under the guidance of Dr. Manjula P., Professor of Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier in any other University for the award of any Diploma or Degree.

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## Abstract

A subjective way of measuring the improvement in performance is the functional gain measurement. An objective way of measuring the benefit provided by a hearing aid is the real ear probe tube microphone measurement. There are two methods for sound field equalization (SFE) during real ear measurements viz. Modified Pressure Concurrent Equalization (MPCE) and Modified Pressure Stored Equalization (MPSE) with the former being a popular approach and latter suggested for open fit hearing aids. This MPSE procedure is based on disabling the reference microphone which reduces the alteration of input signal from the loudspeaker because of leakage of the energy from the ear canal.

The aim of the present study was to compare the behavioral measures with the objective real ear measures for verification of Receiver in The Canal (RIC) hearing aid coupled with closed and open dome fitting using two approaches of sound field equalization, i.e., Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE). The REAG optimized using the MPSE and MPCE approaches for both the domes, and behavioral aided thresholds optimized using the same two approaches were measured. For the REAG data at 800 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz repeated measures ANOVA was used. Friedman and Wilcoxon signed rank tests were applied for 300 Hz and 500 Hz. For behavioral aided thresholds, repeated measures ANOVA was applied at all frequencies, except for 4000 Hz and 6000 Hz. For these two frequencies, Friedman and Wilcoxon signed rank tests were applied. The results indicated a significant difference in REAG at 1000 Hz for RIC hearing aid coupled to open dome optimized for MPSE and MPCE. Differences were also observed for closed dome for these two conditions. In other conditions, differences were observed for a few frequencies for REAG.

In behavioral aided thresholds, significant differences were not observed for any condition. Correlation between REAG and aided thresholds was significantly negative with open dome and significantly positive at low- to mid- frequencies for closed dome. Significant correlation were obtained for RMS output of REAG and SIS was for high frequency words with RIC hearing aid, coupled to open dome, optimized using MPSE. The test re-test reliability was good for REAG except for two frequencies; and was good for behavioral aided measures.

***Key words****: Modified Pressure Concurrent Equalization (MPCE), Modified Pressure Stored Equalization (MPSE), Receiver In the Canal (RIC), open dome, closed dome, Real Ear Aided Gain (REAG), aided thresholds*

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# CHAPTER 1

## Introduction

The major problems faced by individuals with sensorineural hearing loss (SNHL) is reduced audibility, reduced dynamic range, reduced frequency selectivity (Moore & Glasberg, 1997) and impaired temporal resolution (Nelson & Thomas, 1997). These give rise to poor speech intelligibility and listening discomfort, in quiet as well as in adverse listening situations. In SNHL, the damage to outer hair cells (OHC) produces cochlear amplifier function (Dallos, 1973), wider auditory filters (Glasberg & Moore, 1986), and neural asynchronous firing to varying acoustic cues (Tremblay, 2005). With the advent of digital hearing aids, amplification has been found useful for different types and degrees of hearing loss and also in different listening conditions.

In order to measure the benefit with hearing aids, selection and verification of the hearing aid are done. The subjective way of measuring the improvement in performance is the functional gain measurement. The functional gain (FG) was popularized by Pascoe (1975). It is a simple measure which is the difference between the hearing thresholds measured without hearing aid and with the hearing aid in the ear. Like any other behavioral measurement, this requires active participation of the individual. In functional gain measurement, it involves measuring both unaided and aided thresholds and hence the reliability may vary by 15dB or more under ideal test conditions as suggested by few authors (Hawkins, Montgomery, Prosek & Walden, 1987). Since, the behavioral aided threshold involves only one of the variable factors and not two, it is usually recommended (Fabry, 2003).

The other method of measuring the hearing aid benefit is objective way of measuring which does not require active subjective participation. An objective way of measuring the benefit provided by a hearing aid is the probe tube microphone measurement. In this, the Real Ear Insertion Gain (REIG) is being measured and used for verification of the hearing aid. The REIG is a real ear measurement, which is measured as the difference between the Sound Pressure Level (SPL) measured using the Real Ear Unaided Response (REUR) and Real Ear Aided Response (REAR), at the level of tympanic membrane (Ching & Dillon, 2003). There is a need to define few terminologies for the confusions regarding ‘R’ and ‘G’ i.e., Response and Gain respectively. These definitions were given in Mueller (2001) and are the definitions given by 1997 ANSI standard.

1. REUR (Real-Ear Unaided Response): It the SPL as a function of frequency, at a specified measurement point in the ear canal, for a specified sound field, with the ear canal unoccluded.
2. REUG (Real-Ear Unaided Gain): Difference in decibels between the SPL as a function of frequency at a specified measurement point in the ear canal and the SPL at the field reference point, for a specified sound field, with the ear canal unoccluded.
3. REAR (Real-Ear Aided Response): SPL as a function of frequency, at a specified measurement point in the ear canal, for a specified sound field, with the hearing aid (and its acoustic coupling) in place and "turned on."
4. REAG (Real-Ear Aided Gain): Difference in decibels between the SPL as a function of frequency at a specified measurement point in the ear canal and the

SPL at the field reference point, for a specified sound field, with the hearing aid (and it's acoustic coupling) in place and "turned on."

The REIG is adjusted in such a way that it matches the target gain curve and is a reliable measure of the hearing aid (Seewald, Moodie, Sinclair & Scollie, 1999). In the present study, the Real Ear Aided Gain (REAG) was used in place of REIG. This is because, the REUG is always deducted from the REAG, and REAG curves tend to be comparatively smooth. Hence, usually the bumps in the REUG become dips in REIG, and dips in the REUG become bumps in the REIG (Mueller, 2006). Hence, in the study REAG is chosen.

There has been a general shift to using the REAR rather than the REIG for verification (Mueller, 2006).  The REIG is not a valid measure for open canal fittings. This could be because instinctively, it doesn’t seem quite right to subtract the REUG from the REAG for the REIG calculation, when in fact the patient retains the majority of this open ear advantage (i.e., the REUG).

There are two methods for Sound Field Equalization (SFE) during real ear measurements of open fit hearing aids. According to the study by Shaw (2010), Modified Pressure Concurrent Equalization (MPCE), is one of the popular techniques for SFE. This measure makes sure that the output from the loudspeaker is continuously adjusted according to the sound that is to be delivered to the client’s ear. This is achieved with the help of an active reference microphone at the client’s ear. This accounts for any movement made by the client while testing. But in the view of Lantz, Jensen, Haastrup and Olsen (2007), this method is not suitable for open fit / non-occluding hearing aids. This is because, the sound escaping out of the ear canal due to non-occluding hearing aid can be detected by the reference microphone and the adjustments may be done accordingly, thereby inducing errors in the measurement. So an alternative method is suggested by them namely the Modified Pressure Stored Equalization (MPSE).

The MPSE method requires equalization of the sound field speaker output while the client wears the reference microphone. It is usually done while making REUR measurement. For further real ear measurements, the loudspeaker output is fixed based on the results and any movements of the head will not induce changes in the loud speaker signal. Hence, the client’s head needs to be positioned in the same position after the initial measure. The size of errors due to deviations in head position according to the study by Shaw (2010) are usually less than 3 dB. The value may be clinically insignificant, but, it is recommended to keep head constant to reduce inaccuracies in measurement. With open fit hearing aid, this approach might be employed as the reference microphone is disabled and hence doesn’t measure the sound escaping out. Hence, the output coming out from the loudspeaker is not varied.

The method of SFE used depends on the type of hearing aid for which the insertion gain measurement is to be conducted i.e., open or closed fit hearing aid. The Receiver In the Canal (RIC) is a type of hearing aid, where the receiver is housed/embedded within dome and located in the ear canal. The domes can be either open, closed or power dome (Winkler, Latzel & Holube, 2016). These different types of domes are used for various degrees of hearing losses. According to Aazh, Moore and Prasher (2012), when using an open dome with RIC, MPSE is a better method of measuring REIG. In this method, the reference microphone is switched off / disabled during the REIG measurements, and hence the amplified sound leaking out of the ear canal with open fit hearing aids does not affect the measurements i.e., since the reference microphone is disabled, the sound escaping out of the ear canal through the pores of the open dome, do not get picked up and hence does not subsequently result in the change in the output from the loudspeaker.

**Need for the study:**

According to the results of the study by Stelmachowicz and Lewis (1988), there are at least three situations where the functional gain and insertion gain measurements do not agree. They are when a high gain hearing aid has low maximum output, in non-linear hearing aids, and in some clients with severe to profound degree of losses. Therefore, it becomes imperative to find whether the two measures are same and also which of the two methods, is more reliable indicator for hearing aid benefit.

In the study by Aazh et al. (2012), they measured the difference between using measurement technique for MPSE and MPCE. The authors did not find significant difference between the two procedures for open fit hearing aid among the clients with mild to moderate hearing losses. This is attributed to the fact that the input level used was 65 dB SPL and also the REIG required was less than 20 dB. Also, they recommended using MPSE for REIG measurements of open fit hearing aid in cases where the fitting procedures recommend greater REIG for high frequencies and suggested that there might be differences in such cases.

In sloping configuration of hearing loss cases (as defined by Pitmann & Stelmachowicz, 2003), the hearing loss in low frequency regions is less with increasing amount of hearing loss in high frequency regions. For these cases, when a closed fit hearing aid is prescribed, it may lead to occlusion effect and hence the sound may appear 'boomy' which indicated own voice is sound loud (Dillon, 2012). This is disturbing in the cases where low frequency hearing is normal or near normal. Hence, usage of open fit hearing aid is recommended in such cases.

For verification with open fit hearing, according to studies mentioned above, there might be differences with the approach of the SFE used. In the present study, the difference in the REAG values with the two SFE methods need to be evaluated to find out the effective objective technique while testing for open fit hearing aid, along with the behavioral aided thresholds and Speech Identification Score (SIS). The earlier studies have employed REIG in their testing and the change in the REAG is not documented. In addition, if there is any difference in the two approaches in the open dome or closed dome hearing aid, while using clinically, the most appropriate method can be utilized.

The aim of the study was to compare the behavioral measures with the objective real ear measures for verification of RIC hearing aid coupled with closed and open dome fitting using two approaches of sound field equalization, i.e., Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE).

The objectives of the study were,

1. To compare the Real Ear Aided Gain (REAG) of RIC hearing aid optimized using MPSE and MPCE, when coupled to open and closed dome.
2. To compare the aided thresholds with RIC hearing aid optimized using MPSE and MPCE, when coupled to open and closed dome.

3. To find out the relationship between the aided thresholds and REAG of RIC hearing aid optimized with MPSE and MPCE, when coupled to open and closed dome.
4. To find out the relationship between the Root Mean Square (RMS) outputs measured during REAG and Speech Identification Score (SIS).
5. To evaluate for the test-retest reliability of the REAG, aided thresholds, and SIS with RIC hearing aid optimized using MPSE and MPCE when coupled to open and closed dome.

# CHAPTER 2

## Review of literature

The study is aimed at comparing the real ear measurement using two approaches of sound field equalization, namely Modified Pressure stored equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE) for open and closed dome and also comparing the aided thresholds done behaviorally after the application of these approaches during objective measurement. The objective procedure includes Real Ear Aided Gain (REAG) using probe tube measurements for both the sound field equalization approaches. The subjective procedure include measurement of aided thresholds for these procedure and also Speech Identification Scores (SIS) using phonemically balanced word lists (Manjula et al., 2015) and High frequency word lists (Yathiraj & Mascarehans, 2002).

The review of literature relevant to the topic of research is being given under the following headings and headings.

2.1 Hearing aid fitting

2.2 Pre-selection procedure

2.3 Selection procedure

2.4 Verification process

2.4.1 Functional gain

2.4.2 Real ear measurement

2.5 Validation procedure

2.6 Types of Sound Field equalization (SFE).

2.7 Objective optimization of insertion gain

## 2.1 Hearing aid fitting

The hearing aid fitting is a comprehensive procedure that involves the manufacturers of hearing aid, service provider and the hearing aid user as team members and is done for optimal outcomes with hearing aid and reducing the unacceptance of hearing aid.

The guidelines to be followed for hearing aid fitting for adults is given by ASHA Ad Hoc committee (1998) on hearing aid. The fitting procedure give guidelines regarding hearing aid fitting as part of an inclusive audiological rehabilitation plan. The audiologists in the committee have proposed a procedure that starts with comprehensive audiological assessment program which includes audiological testing and then assessment of candidacy for hearing aid. The assessment for candidacy includes a set of questionnaires that can be used to assess the amount of disability from the client's point of view. This provides a baseline for client's needs. The next procedure that is stated in the guidelines, involves hearing aid selection which involves determining physical and electroacoustic characteristics of desired hearing aids for a particular client. This process involves defining the electroacoustic characteristics, taking decisions about non-electroacoustic characteristics, verification of hearing aids through different means, orientation about hearing aid use, and validation.

The audiologists in the study mention that major use of measurement of input-output and frequency-gain characteristics of the hearing aid helps in determining the requisite electroacoustic characteristics using methods that are based on scientific knowledge. These specifications should be compatible with the auditory characteristics and the personal requirements of the client. The non-electroacoustic characteristics are those that include selection of a particular hearing aid, the side of aiding, programing options, and the settings related to hearing aid. The next process is the verification which is a measure made to conclude whether the hearing aids meet a set of standards. These standards include basic electro acoustics to see whether what the hearing aid is meant to deliver is being delivered, the cosmetic appeal, other factors like comfortable fit, and real-ear electroacoustic performance.

Many audiologists have advocated the use of real ear measurements as a primary verification process. This procedure involves checking for audibility, comfort level, and tolerance level which includes using different intensities of signals. The next step mentioned is orientation about the care and maintenance of hearing aids and realistic expectations of performance with hearing aids. The last step of the hearing aid fitting is validation. Even though verification helps to confirm that particular electroacoustic characteristic goals are met, validation measures are necessary to determine the impact of the intervention and also to check whether disability has been reduced. The tools for validation includes the questionnaires and measures of speech perception.

On similar lines, Oh and Lee (2016) formed a framework for Hearing Aid Fitting Management (HAFM) which is similar to the one mentioned previously and it includes pre- and post- fitting stages. There are three modules that are prescribed for the same and the **assessment module** is the first one where pre-fitting stages are included. It has a detailed audiological evaluation, identifying candidacy for hearing aid and also selecting hearing aids. The next module is the **fitting module** where adjustment and verification processes are carried out. Adjustment includes checking for physical integrity with the hearing aid and ear mold, selecting appropriate prescriptive module based on the audiogram of the client and also determining the electroacoustic characteristics. The **verification process** involves checking the benefit with hearing aid using any of the procedures like psychoacoustic measurements, questionnaires based on acoustic measures, coupler measurements, and real ear measurements. The last module that comes under post-fitting stage is the **follow-up module**. This includes the auditory training, validation through outcome measures and comprehensive report. This study basically gave a general guideline for standardizing the HAFM.

In the present study, the major focus is on the verification process of the hearing aid using real ear measurements and behavioral measurements. The remaining parts of the hearing aid fitting module will be discussed in brief before moving onto verification in detail.

## 2.2 Pre-selection procedure

Taylor and Mueller (2017), recommended the procedure for the pre-selection and is given as follows. This procedure **is divided into two parts where the first one involves the pre-fitting testing that needs to be undergone and the second part includes all the considerations that needs to be addressed once we have obtained** the pre-fitting testing.

The pre-fitting hearing assessment starts with case history and any of the “red flags” need to be referred to the otologist for clearance. The red flags include visible deformity of the outer ear, accumulation of cerumen, history or presence of active drainage from the ear, etc. A few questionnaires to know the attitudes of the subject toward hearing loss and the perceived handicap because of it, are a part of pre-selection. A thorough hearing evaluation including assessment of hearing thresholds, loudness discomfort level testing, speech audiometry, acceptable noise levels are done. These provide basis for further selection of hearing aids. The explanation for the same to the person can be done using speech banana/spectrum audiogram which shows the audiogram and the amount of phoneme information missed out because of the hearing loss in a particular frequency region.

The authors mention that the next part within the pre-selection includes the pre-fitting considerations like unilateral versus bilateral fitting, presence of cochlear dead regions, hearing difficulties with normal audiogram, auditory processing disorders(if any),and also if any auditory deprivation was involved. Based on these,the selection procedure will be carried out.

## 2.3 Selection procedure

In the opinion of Valente and Valente (2015) and Dillon (2012), the selection procedure involves choosing appropriate type of amplification devices based on the preference for style of hearing aid such as Behind-the-ear (BTE), In-the-ear (ITE), In-the-canal (ITC), Completely-in-the-canal (CIC), and Receiver-in-the-canal (RIC) types, based on the hearing loss, the selection of high gain or low gain hearing aids, the type of ear mold or ear piece for comfortable fitting, and all those factors that depend on the listening needs of the individual like the digital signal processing strategies, compression systems, signal enhancement strategies like directional microphones etc. These factors basically help in deciding about the physical characteristics with the hearing aids on and also the listening needs of the individual.

The next process in fitting is prescriptive based approach. According to Bentler, Mueller and Ricketts (2016), prescriptive methods of hearing aid fitting are based on the principle that the hearing aid gain can be prescribed using the client's pure-tone thresholds or suprathreshold measures, and this can result in best fitting. Through the years, to cater to this, various prescriptive formulae have been employed which have their own way of describing the amount of gain required for a hearing loss. It started off as mirroring the audiogram procedure in the 1940s to very latest ones which have different means of prescribing gain.

In the present study the prescriptive formula used is National Acoustic Laboratories' Non-linear fitting procedure version 1 (NAL NL1) developers being Byrne, Dillon, Ching, Katsch and Keidser (2001), is one of the generic fitting formulae for non-linear amplification. Byrne et al. (2001) state that this procedure is based on the principle of loudness equalization in which for a selected loudness level, loudness across the frequency bands are equalized. This was found to increase speech intelligibility as most of the frequencies are made into the audible range. The sounds were equalized for 3 input levels of 50, 65 and 80 dB SPL. The authors mention in their study that the procedure is based on loudness equalization principle where loudness across frequency bands are equalized for any selected loudness level which meant that making most of the frequencies to come into the audible range. This was found to increase speech intelligibility. And to not make all the sounds sound similar, it is done at three input levels of 50, 65, and 80 dB SPL. The NAL-NL1 proposes relatively less low-frequency gain for flat configuration of audiograms and relatively less high-frequency gain for steeply sloping audiograms. It also tends to advocate less compression than the other procedures.

## 2.4 Verification of hearing aid

Verification of hearing aid is a process to check whether the hearing aid is performing the way it is expected. There are many ways to verify the fitting such asthe probe microphone measures, functional gain measures, audibility measures, loudness ratings, speech intelligibility measures, speech intelligibility judgements, and speech quality judgements. However, Taylor and Mueller (2017) mention that the best way to measure is through probe microphone measurements.

Now the verification process will be discussed under the following subheadings.

**2.4.1 Functional gain.** This method of measurement is subjective way of verification process. Haskell (1987) in his study has listed the advantages of functional gain (FG) measurements. In functional gain measurement, the thresholds of the participant are measured, with and without hearing aid, and then compared and are done under the same measurement conditions. Some of the advantages are that it gives frequency-specific gain, accounts for all the variables that would act on the real ear and that since it is a behavioral measure, it is a reflection of what the subject actually hears. The disadvantages include its sensitivity to noise floor in the test environment, time consuming procedure, and requires active subject participation. The contamination of the responses because of the internal noise generated by the hearing aid and the external ambient noise are the major disadvantages.

Further, Macrae and Frazier (1980) in their study state that due to the presence of internal noise, the functional gain was sometimes 0dB or sometimes assumed negative values as well. This was attributed to the internal noise and ambient noise that was present which was responsible for poorer aided scores in comparison to unaided. This was especially seen in the frequency regions where the unaided thresholds were normal or near normal and that fitting even a high gain hearing aid for normal hearing individual would result in poorer functional gain.

To check the test re-test reliability of functional gain, Humes and Kirn (1990) in their study measured the sound field aided and unaided thresholds from 250, 1000Hz and 4000 Hz. The reliability of functional gain was again compared with the individual reliabilities of unaided and aided thresholds. The functional gain is not completely dependent upon the individual unaided and aided scores even though the values were derived from those two scores. The test re-test reliability for aided thresholds were high for the frequencies 1000 Hz and 4000 Hz. When the reliability was compared, the test re-test standard deviations were largest for functional gain measurement, followed by for aided thresholds and least for unaided thresholds. Though the difference between the standard deviations for aided thresholds and functional gain were non-significant, functional gain proved to have higher standard deviations. The authors themselves recommend the use of real ear measurement as it is more reliable according to literature. This has been supported by previous study by Hawkins, Montgomery, Prosek and Walden (1987).

Many studies have been carried out comparing the functional gain and insertion gain measurements. In one such study by Mason and Popelka (1986), the objective of it was to see if the functional gain was comparable with the insertion gain. Both of them were found to be in agreement within 5 dB difference, except at 1500 Hz. The authors propose reasons for this difference observed but themselves clarify as to why reasons do not satisfy the difference and hence have proposed this as a future direction for their study.

Similar study done by Harford (1981) with the objective of comparison of functional and insertion gain support the earlier results where it was observed that the functional gain was comparable with the insertion gain by 5 dB for all frequencies except at 4000 Hz.

For non-linear hearing aids, use of functional gain is not an appropriate measure. In the study by Stelmachowicz and Lewis (1988), they mention the disadvantages of use of functional gain in non-linear hearing aid. The behavioral measures that are done at threshold level may lead to inaccurate judgement of the sensation of average conversational speech as the compression of other non-linear features of the hearing aid may act on it and change the gain characteristics i.e., it can overestimate the gain for an average speech input because aided thresholds also occur at lower level. This adds on to the limitation of functional gain and hence based on these grounds, the authors prescribe Real Ear Measurements (REM) in which the measurements can be made in different intensities.

Though behavioral aided threshold is also a variable measure. It is considered a better measure than functional gain. In his study Fabry (2003) compared the REM and functional gain. The author advocates to use REM in place of behavioral measures. In the behavioral measure, the author reasons that optimal aided thresholds is a better measure than functional gain as it involves only one variable measure as opposed to two variables in functional gain (i.e., unaided thresholds and aided thresholds).

**2.4.2 Real ear measurements.** In the present study, the term real ear measurements refers to the objective testing of probe tube measurement. The terminology was standardized in the year 1986 and can be used as a synonym for probe tube measurement. Few authors in literature use it can interchangeable for behavioral measures which can be reasoned that, it too happens in the real ear. But in this study any use of Real Ear Measurement/s (REM) is the probe tube measurements.

Taylor and Mueller (2017) state that this measurement is an objective way of estimating the benefit from hearing aid. This procedure requires modest cooperation from the participant. The measures that can be used for verification in the real ear measurement are Real Ear Insertion Gain (REIG) and Real Ear aided response (REAR).According to studies by Ringdahl and Lejon (1984) and also by Hawkins, Alvarez and Houlihan (1991), the insertion gain measurement is a reliable way of verification. There test re-test reliability was found to be within 1 to 5 dB according to these studies. Earlier, the disadvantages related to the reliability of functional gain have been mentioned which is in contrast to the reliability of the REM. Hence, many of the studies recommend using more and more objective way of measurement for improving reliability.

The first step in real ear measurement is the Sound Field Equalization (SFE) or what is termed as leveling. The next part of the review is about the SFE and ways of carrying out SFE and how they might influence in the measurement.

**2.5 Validation procedure**

Bentler et al. (2016) state that this procedure involves answering clinical questions such as how the fitting helped the client, how it was helpful in reducing the handicap. This process involves measuring the outcome from the hearing aid. There are many methods of validating the intervention. Perceptual measures of sound quality and speech perception are checked after the client gets some experience with the hearing aid. A few others focus on significant other persons in understanding the success with hearing aid. The most popular of the procedure involves the self-report questionnaire which are many in number and can be used to assess the outcomes in the domains such as listening effort, use time, quality of life, naturalness of sound, satisfaction with the device, etc. Speech testing may also be employed for the same.

The major light of our study is to use the verification procedure for hearing aid fitting and that will be focused in the following section.

**2.6 Types of Sound Field equalization**

Revit (2002) has mentioned as to why the sound field equalization is necessary part of REM. The test environment is not ideal usually and the level and spectrum of the test sound field may vary from time to time. This becomes a problem as the same results are not replicated. To solve this problem a correction of sound field is done which is termed as Equalization. The goal of this kind of correction is to have a flat spectrum at the level of the reference point if the test signal itself has a flat spectrum.

Bentler et al. (2016), mention the uses of the reference microphone and why it helps in leveling. This reference microphone also termed as control microphone continuously regulates or monitors the test signal. The types of calibration listed in the text book is as follows,

a) Substitution method of equalization: In this type, the equalization is based on the data recorded prior to the sound field measurement at the position of the patient but without the patient.
b) Modified Pressure Concurrent Equalization (MPCE): In this type the reference microphone continuously measures the stimulus level all throughout the measurement process and controls the level in equalization process.
c) Modified Pressure Stored Equalization (MPSE): The reference microphone is in the test position with the hearing aid in place but switched off. Then the equalization is done which is stored for further measurements.

Few other authors like Revit (2002), state that the leveling is done before the measurement of REM and then this stored data is further used for the REM measurement. This has also been supported by the information given in the Fonix 8000 manual where the MPSE procedure makes use of the leveling value for further measurements. Hence, this has been used in the present study as well.

MPSE procedure is recommended by several authors for open fit hearing aids (Hawkins and Mueller, 1992, Bentler et al., 2016). With this background, the next part of the review will deal with few aspects of types of hearing aid and their fittings (open and closed fit) which will be followed by how these influence in the real ear measurement.

Open-fit hearing aids are defined according to the patent of Fretz, Stypulkowski, and Woods (2001, p. 9 column 3) as “An open ear canal hearingaid system comprises of an ear canal tube sized for positioning in an ear canal of a user so that the ear canal is at least partially open for directly receiving ambient sounds.” In closed fit or occluding type of aids, there are no additional sounds paths and fit the ear canal closing or occluding it.

Winkler et al. (2016) in their review article stated few differences in comfort and quality perceived with these open and closed type of fitting. One such major factor that contributes for the comfort is hearing their own sound as “boomy.” This is termed as occlusion effect is a feature of occluding type of fitting which causes increase in the sound pressure level of the low frequency energy which stay between the close tip/ ear mold/ dome and hence will cause this kind of boomy perception. With the use of open fit hearing aids, the occlusion will reduce and hence will lead to better comfort of fitting. This is especially true for hearing losses where they have normal or near normal low frequency hearing and the hearing loss is more at high frequencies like that of sloping type of configuration of hearing loss. However, the major disadvantage noted in such open fit hearing aids is that there is very little gain that can be given for higher frequencies before feedback occurs.

Alworth et al. (2010) in their study compared the uses of open fit Receiver In the Canal (RIC) or Receiver In the Ear (RIE) and Receiver In The Aid (RITA). Within them open fit RIC was better compared to RITA as there is scope to increase gain in the frequency region of 4000 Hz to 6000 Hz. There is also an improvement in the quality of hearing aid output, though there was no difference in the performance per se.

There are various approaches of carrying out the real ear measurement for the open and closed fit hearing aid, namely, the Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE). The major difference between the approaches is that during the insertion gain measurement, the reference microphone is enabled in the MPCE and it is disabled in the MPSE approach. The reasons for these changes are have some literature basis.

Lantz, Jensen, Haastrup and Ostergaard (2009) in their study mention the disadvantages of using the MPCE approach with open fit hearing aids. They state that using the MPCE can be inaccurate, when amplified sound leaks out of the ear canal and reaches the reference microphone. This is especially true when using open fit hearing aids where sound can leak out of the ear canal. The major function of the reference microphone is measuring the Sound Pressure Level (SPL) at the level of the ear. In cases of leakage, the reference microphone will detect an increased SPL and will decrease the output of the loudspeaker to maintain the desired level. The risk of having errors due to leaks increases if digital feedback suppression (DFS) is used, thus achieving higher feedback-free gain levels. For this purpose, the authors recommended to use a stored equalization method for real-ear measurements of hearing instruments with DFS and open fitting. In this type of method, the reference microphone is disabled and hence the SPL is independent of the leakage of sound.

Aazh, Moore, and Prasher (2012), measured the difference between using measurement technique for MPSE and MPCE. The authors did not find significant difference between the two procedures, for the clients with mild to moderate hearing losses for open fit hearing aid. This is attributed to the fact that the input level used was 65 dB SPL and also the REIG required was less than 20 dB. Also, they recommended using MPSE for REIG measurements of open fit hearing aid in cases where the fitting procedures recommend greater REIG for high frequencies and suggested that there might be differences in such cases.

As seen above a series of studies do state that there are differences observed between the two approaches for open fit hearing aids while few studies again contradict the findings. So the need of the study is to see the difference these approaches have on the open fit hearing aids and if found to be clinically significant can be incorporated in the clinic.

### 2.7 Objective optimization of insertion gain:

The real ear measurement suggests targets for insertion gain and mostly the initial fit recommended by the prescription formula does not meet up to the recommended insertion gain which is according to the individual's ear canal characteristics. Hence, it becomes imperative to perform objective optimization, i.e., matching the frequency gain to the level of the prescribed insertion gain. Usually this is done by modifying the gain in the programming screen and checking out if this change brings about better matching of the target gain.

There are some issues concerning the matching of the measured insertion gain with the target insertion gain displayed in the real ear instrument. The matching may not be appropriate at all the frequencies and there are some tolerances level given.

In one of the studies conducted by Aazh and Moore (2007), it was found that in around 83% of the participants the target insertion gain curve was matched within a tolerance of ±10 dB for all the frequencies. The remaining subjects couldn't achieve target within the tolerance. The major problem was observed for higher frequencies, especially 3000 to 4000 Hz, because of the inability of the hearing aid to increase gain in those frequencies and also due to feedback. Greatest issue with matching was for steeply sloping hearing loss and also those who had non-occluding type of mold.

Many supporting studies are present (Hawkins and Cook, 2003, Mueller, 2003) which prove that target matching occurs usually with a tolerance of ±10 dB with an exception of high frequencies where the measured insertion gain values never really reached the simulated values.

In one of the studies by Aazh, Moore and Prasher (2012), they assessed the accuracy with which target insertion gains were matched to open-fit hearing aid, both on initial fitting and after adjustment. The initial fitting was considered acceptable if the difference was less than 10 dB at all frequencies. If an initial fitting was not acceptable, the frequency-gain response was modified. Majority of the participants could not match up to prescribed insertion gain in first fit and even with frequency-gain adjustments, 18% of them still failed to achieve the target. The authors suggest that the target insertion gains for the open-fit hearing aids used here are rarely achieved with a first fitting but can usually be achieved through adjustments based on REIG measurements. This procedure has been used in the present study as matching the target REIG is imperative to have a proper hearing aid fitting.

# CHAPTER 3

# Methods

In order to achieve the aim of comparison of the behavioral measures with the objective real ear measures for verification of RIC hearing aid coupled with closed and open dome fitting using two approaches of sound field equalization, i.e., Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE), the method followed is provided.

## 3.1 Participants

Twelve adults with sensorineural hearing impairment were selected based on the following inclusion and exclusion criteria. Purposive convenient sampling was used for the inclusion of participants for the study. Ethical guidelines recommended by AIISH bio-behavioral research involving human subjects were followed (Venkatesan, 2009). The inclusion and exclusion criteria for selection of participants are given below.

**3.1.1 Inclusion criteria.** Adults in the age range from 16 to 55 years having sensorineural hearing loss were considered. The hearing loss was moderate to moderately-severe degree. The audiogram had a ‘sloping configuration’ which was operationally defined as thresholds that occurred at equal or successively higher levels from 250 to 8000 Hz, with the difference between thresholds at 250 and 8000 Hz being always greater than 20 dB (Pitmann & Stelmachowicz, 2003). Individuals with post-lingual deafness having adequate speech and language were considered. They were native speakers of Kannada language. Their Speech Identification Score (SIS) was more than 60%. They were naïve hearing aid users.

**3.1.2 Exclusion criteria.** Individuals having retro cochlear pathology, neurological, and cognitive complaints were not included as participants.

### 3.2 Material

1. Paired word list in Kannada, developed in the department of Audiology AIISH, Mysore, was used for speech recognition thresholds during routine speech audiometry.
2. Phonemically balanced word list in Kannada (Yathiraj & Vijayalakshmi, 2005). There are four lists with 25 bisyallabic words in each list. This was be used for SIS during routine speech audiometry.
3. Phonemically balanced word lists for adults in Kannada (Manjula, Antony, Kumar, & Geetha, 2015) for unaided and aided speech performance. Four lists out of the 24 word lists for use in quiet were used, each list consisted of 25 words. This was used for the actual aided testing during data collection.
4. Three word lists from high frequency Kannada speech identification test (Yathiraj & Mascarenhans, 2002), each list having 25 words. This was used for the actual aided testing during data collection.

### 3.3 Equipment

1. A calibrated sound field audiometer to measure the unaided and aided performance. The audiometer was connected to TDH 39 supra aural headphone with MX 41 AR ear cushion, B-71 bone vibrator, and loud speaker. The loud

speakers were located at 45$^o$Azimuth and at a distance of one meter from the participant.

2. Middle ear analyzer to check the middle ear status.
3. Hearing aid test system including hearing aid measurement along with real ear measurement.
4. Test hearing aid: A Receiver in The Canal (RIC) hearing aid having 5 to 8 channels, and mild to moderately-severe fitting range. The RIC was fitted to the ear of the participant with either open / closed dome.
5. Personal computer with NOAH software and the hearing aid programming module to program the test hearing aid, along with interfacing hardware and appropriate adaptor/cables.

**3.4 Procedure**

The data collection for the purpose of the study was carried out in three phases.

3.4.1 Phase I: Routine audiological evaluation to select the participants for the study.

3.4.2 Phase II: Objective and subjective measurements with RIC hearing aid coupled to open dome and closed dome, using MPSE approach. The Phase II was further sub-divided as follows:

3.4.2.1 Phase II(A): Measurement of Real Ear Aided Gain (REAG) of RIC optimized with MPSE approach.

3.4.2.2 Phase II(B): Measurement of aided thresholds of RIC optimized with MPSE approach.

3.4.3 Phase III: Objective and subjective measurements with RIC hearing aid coupled to open dome and closed dome, using MPCE approach. The Phase III was further sub-divided as follows:

3.4.3.1 Phase III(A): Measurement of REAG of RIC optimized with MPCE approach.

3.4.3.2 Phase III(B): Measurement of aided thresholds of RIC optimized with MPCE approach.

**3.4.1 Phase I: Routine audiological evaluation.** In order to ensure that the participants met the inclusion criteria, pure-tone audiometry, speech audiometry, and immittance evaluation were carried out.

***Pure-tone audiometry:*** A calibrated double channel audiometer was used to carry out the testing. The audiometric hearing thresholds were measured for the frequencies from 250 Hz to 8000 Hz for air-conduction, and from 250 to 4000 Hz for bone-conduction. This was done for both the ears of the participant, using the modified Hughson-Westlake procedure (Carhart & Jerger, 1959). The pure-tone average (PTA) was calculated for each of the test ears which is the average of the thresholds at four octave frequencies i.e., 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz.

***Speech Audiometry:*** The speech audiometry involved testing of Speech Recognition Thresholds (SRT) and Speech Identification Score (SIS). The SRT was done using the list of paired words in Kannada developed in the Department of Audiology. The SRT was established by using a starting presentation level of 20 dB SL (re. PTA) (Tillman &

Olsen, 1973). The instruction given to the participant was to repeat as many words as he/she could. Using the modified Hughson-Westlake procedure, the SRT was found out. The lowest intensity level at which, the participant correctly repeated at least 50% of the words was regarded as the SRT. This was done for each test ear.

The SIS was obtained at 40 dB SL (re: SRT) using the Phonemically Balanced (PB) word list in Kannada (Yathiraj & Vijayalakshmi, 2005). There were four PB word lists each having 25 words. The participant was instructed to repeat the words that he/she heard. The words were presented at a constant level through monitored live voice. The scoring involved the number of words repeated correctly. This was noted for each test ear of the participant. The SIS was noted as the number of words repeated correctly, out of the total of 25 words in each list. The SIS was converted into percent for the purpose of participant selection.

Another parameter that was measured included the Uncomfortable Level (UCL) for speech. The intensity level of the stimulus that was intolerable or uncomfortable for the participant was measured for each test ear. The intensity of the speech was gradually increased from most comfortable level. The participant was instructed to indicate the level at which the speech was uncomfortable. This intensity level of the speech was considered as the UCL.

***Immittance evaluation:*** This was done to rule out any middle ear pathology in the test ears. In this step, the tympanogram and reflexes were measured for each test ear. The procedure involved presenting a probe tone of 226 Hz, to measure admittance at the level of tympanic membrane. The pressure within the ear canal was varied and the peak pressure level where there is maximum admittance of the tympanic membrane was measured and plotted as tympanogram. The peak pressure and static admittance value served as the basis for deciding the type of tympanogram. The tympanogram was considered normal if the peak pressure ranged from -100 to +60 daPa and the admittance was between 0.5 and 1.75 mL. The acoustic reflex which measured the response of the auditory system for loud sound stimulus was also measured. The threshold for acoustic reflex was found out in ipsilateral and contralateral modes for each test ear. The reflex threshold for each of the ears, for ipsilateral and contralateral stimulus presentation, was found out at 500, 1000 Hz, 2000 Hz, and 4000 Hz. The criteria for normal functioning of the middle ear, “A” or “Ad” type of tympanogram with presence of reflexes in at least one or two frequencies.

Based on the inclusion criteria, 12 ears of 12 participants that fulfilled the selection criteria were considered for the study.

Fig 3.1 shows the mean of pure tone thresholds at each frequency when unaided thresholds through headphones for all participants taken together. Here the sloping configuration of the hearing loss is evident.

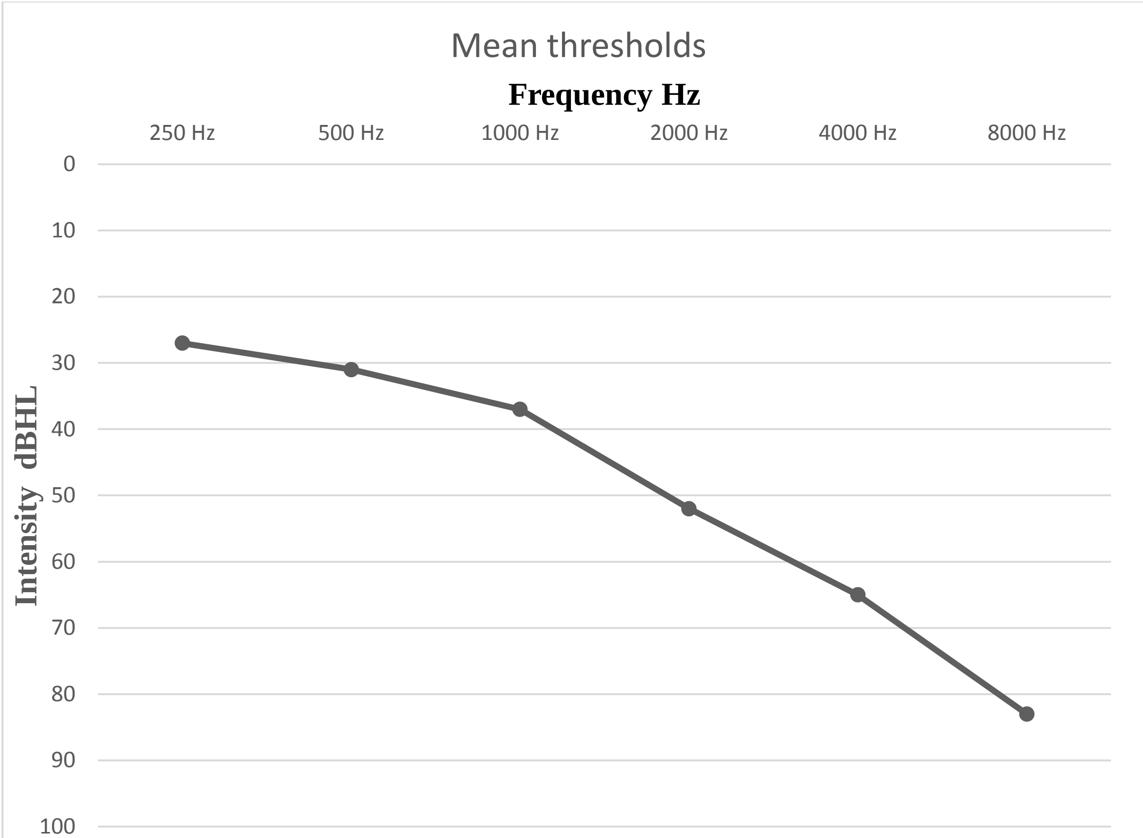


**Fig 3.1** ***Mean pure tone threshold of all the 12 participants at each frequency***

**3.4.2 Phase II: Objective and subjective measurements with RIC hearing aid coupled to open dome and closed dome using MPSE approach.** The objective measure included the measurement of real ear aided gain (REAG) using the MPSE procedure. This was followed by the behavioral measure of aided thresholds, and SIS for PB and high frequency word lists. The RIC hearing aid was programmed. The Phase II was further sub-divided i.e., Phase II(A) and Phase II(B). Before moving on to the actual procedure of MPSE, the hearing aid programming was done.

*Programming of the hearing aid:* The test hearing aid was the digital RIC hearing aid, having eight channels, and it had a fitting range to accommodate the hearing loss of the participants. The receiver that was used along with this hearing aid was the HP (high power) which had maximum output of 122 dB SPL. The wireless programming interface was used for programming the test hearing aid. The NOAH and the specific programming module/software in the personal computer were used for programming the RIC.

The patient details like the demographic details and the audiogram details were entered in the programming module. The module has the option of selecting the programming interface which was selected as Air link and the option of "connect" was selected to connect the hearing aid to the module. Prior to the connection, the hearing aid was made ready for connection which included putting a fresh battery in the battery compartment and closing the battery compartment to switch-on the hearing aid. The hearing aid was connected to the programming module and then NAL-NL1 fitting formula was selected. The target gain curves were displayed on the computer monitor. The physical configuration was selected as open dome and the size of the open dome was also selected appropriately. The noise reduction algorithm was disabled and feedback management was enabled based on the presence of acoustic feedback, if any. The acoustic feedback most likely occurred for most of the participants when an open dome was used with RIC. Hence, the feedback management was enabled.

*Setting up the hearing aid test system for measurement of real ear aided gain for RIC hearing aid:*

The Real Ear Unaided Response (REUR) and the Real Ear Aided Gain (REAG) measurements were done using the hearing aid test system. This hearing aid test system is a hearing aid analyzer cum real ear measurement system. The real ear measurement system has the provision of making measurement of sound pressure level inside the ear canal of the test ear of the participant. This is done in order to know the level of hearing aid output in the test ear of the participant. The procedure to perform the REAG measurement is given below.

The first step involved feeding in the audiometric details into the real ear system. The air- and bone- conduction hearing threshold levels (HTLs) at all the audiometric frequencies were fed in. After entering the HTLs, the UCLs were generated by the test system. The real ear insertion gain targets were created based on the hearing thresholds and the fitting formula selected. The National Acoustic Laboratories Non-Linear version 1(NAL-NL1) prescriptive formula was selected for the study.

The leveling of the sound field of the real ear measurement system was performed. The leveling was done to ensure that the input level to the hearing aid was controlled across the frequency spectrum. The ear hook integrated system, with the reference and the probe microphones, were held at one foot distance and $45^o$ azimuth from the loudspeaker of the real ear measurement system. It was ensured that the system was leveled, i.e., the measured signal was within 1 dB of actual levels. The menu/protocol of stimulus and measurement parameters are given in Table 3.1.

**Table 3.1:** ***Protocol for stimulus and measurement of REAG through MPSE and MPCE approaches***

| Parameters | MPSE | MPCE |
|---|---|---|
| **Stimulus parameters** | | |
| Type of stimuli | Digital speech - ANSI weighted | Digital speech - ANSI weighted |

| | | |
|---|---|---|
| Intensity of the stimulus | 60 dB SPL | 60 dB SPL |
| **Display parameters** | | |
| Graph options: Data/ Graph | 1. Graph display was selected for measurement of REAG.<br>2. Data option was selected to REAG data | 1. Graph display was selected for measurement.<br>2. Data option was selected to REAG data |
| Display: SPL/Gain | Gain | Gain |
| Output limit | 120 dB SPL | 120 dB SPL |
| Unaided | Custom | Custom |
| Auto/manual test | Manual | Manual |
| Reference mic | **OFF** | **ON** |
| Noise reduction | 4X | 4X |
| Fitting rule | NAL-NL1 | NAL-NL1 |
| Client age | Adult | Adult |
| Compression knee-point | 50 dB | 50 dB |
| Aid limit | Multichannel | Multichannel |
| Fit type | Unilateral | Unilateral |
| Sound field | 45° | 45° |
| Reference position | Undisturbed | Undisturbed |
| Static tone | Off | Off |

| | | |
|---|---|---|
| Average frequency | HFA 2500 | HFA 2500 |
| Bias tone | Off | Off |
| Composite type | Standard | Standard |
| Composite filter | ANSI | ANSI |
| Aid type | AGC | AGC |

The rest of the parameters in the menu were set to default settings. For the current testing, i.e., MPSE approach, the reference microphone was disabled or kept off in the menu option.

***3.4.2.1 Phase II(A): Measurement of Real Ear Aided Gain (REAG) of RIC optimized with MPSE approach.*** Before the commencement of the real ear aided measurement, otoscopy was performed in order to rule out any contraindication (debris/wax/foreign body) for carrying out the real ear measurement. The participant was made to sit comfortably on a revolving chair. A quiet test environment was ensured. The ear hook assembly of the real ear measurement system was placed on the test ear with the reference microphone on the superior posterior portion of the ear hook and the probe microphone at the bottom of the ear hook. For optimal positioning of the probe tube, the slider in the integrated ear hook was adjusted to adjust the height of the probe tube from the ear hook. The probe tube insertion was done using the geometric positioning method. Fig 3.1 shows the measurement for geometric positioning of the probe tube. In this, the length of insertion of the probe tube was around 5 mm more than the length of the dome. The measurement was done with the RIC hearing aid connected to open dome first. A black mark was made on the probe tube. It was ensured to keep this marking at the tragus notch while inserting the probe tube in the ear canal. Special care was taken to ensure that the length of the probe tube insertion was kept constant during the unaided and aided measurements.

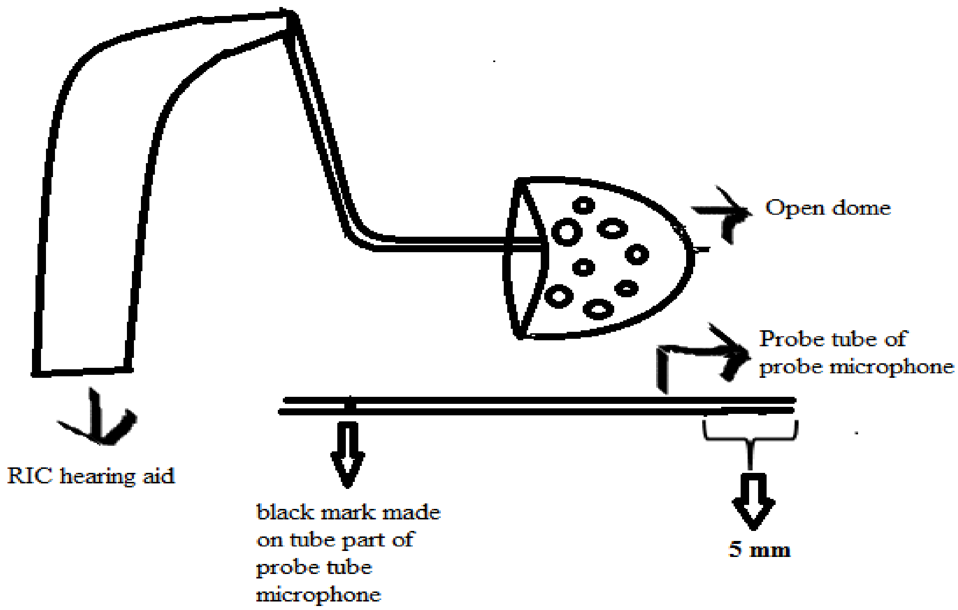


**Fig 3.2** ***The geometric positioning type of probe tube insertion into ear canal.***

The loudspeaker of the real ear measurement system was kept at a distance of one foot from the ear to be tested and at the level of the test ear of the participant by adjusting the slider of the loudspeaker stand. The loudspeaker was placed at 45°azimuth towards the test ear.

After setting up the test room, the equipment, and the participant for measurement, the real ear unaided gain (REUG), real ear aided gain (REAG), and real ear insertion gain (REIG) were measured. The REUG was measured by presenting the stimulus through the loud speaker of the real ear measurement system, with the probe tube microphone in place. The REUG measurement was done without the hearing aid in the ear. The type of signal used in the study was ANSI weighted digital speech.

The digital speech is an interrupted version of the composite signal. The composite signal is a continuous broadband signal containing 79 different frequencies presented simultaneously. The signal is ‘speech weighted’, i.e., the lower frequencies have a higher emphasis than the higher frequencies. Initially, the digital speech signal was presented at 60 dB SPL. This level matches the level of general conversation. This intensity was selected during behavioral testing also. With the ear hook and probe tube inside the ear canal, the participant was instructed to look straight at a marking on the wall in front of the participant. This was done in order to keep the head position constant. The reference microphone was disabled as this measurement was with MPSE approach.

The stimulus was presented through the loudspeaker of the real ear measurement system, as mentioned previously. The probe microphone measured this signal in the ear canal (without the hearing aid) of the participant. This was displayed as the REUG graph on the real ear measurement screen. The measurement or the display was frozen/stopped once the REUG curve stabilized.

Later, the RIC hearing aid along with open dome was placed in the ear canal, with the position of the probe tube held in the same place. This was done to avoid any displacement in the probe tube which might alter the SPL measured. The hearing aid was connected to the computer through the programming interface and cable. The next measurement involved the measurement of REAG with optimized settings of the hearing aid. The REAG measurement was performed with the same stimulus, i.e., digital speech signal at 60 dB SPL. Once the stimulus was ‘on’, optimization of hearing aid program was done by matching the hearing aid gain with that of the target gain based on NAL-NL1 prescription using the hearing aid programming software. Once the gain was optimized and the measurement was stabilized, the REAG was recorded.

The optimization of hearing aid gain was carried out by increasing or decreasing the gain through the programming module/software of the hearing aid. The gain of the hearing aid was manipulated/optimized in such a way that the gain of the hearing aid closely matched with the target insertion gain prescribed for the ear. Once the target gain curve was matched as close as possible, the REAG was recorded by the probe tube microphone in the test ear.

In a few high frequencies, it was difficult to match the two curves because of the maximum output limitation of the hearing aid or due to increase in acoustic feedback. If the feedback was present, more likely with open domes, the feedback management feature of the hearing aid was enabled. This further served as a limitation to increase the gain at higher frequencies. All through the testing, the participant was asked to keep his/her head constant so as to avoid changes in the SPL measured as a result of the movement of the head. Based on the REUG and the REAG measurements, a real ear insertion gain (REIG) graph was displayed on the screen of the real ear measurement system.

After completion of the measurement, the intensity values in the REAG data were noted down at different frequencies at 300, 500, 800, 1000, 1500, 2000, 3000, 4000, and 6000 Hz. The REAG data were tabulated for each test ear.

***3.4.2.2 Phase II(B): Measurement of aided thresholds of RIC optimized with MPSE approach.*** The sound field audiometer was utilized for the behavioral aided thresholds and SIS measures. The participant who was seated on a revolving chair was turned toward the clinician in the adjacent room where audiometer was placed. The loudspeaker of the calibrated sound field audiometer was placed at 45° Azimuth and at a distance of one meter from the participant. The unaided sound field thresholds at audiometric frequencies from 250 to 6000 Hz were found out using warble tone as the test stimulus.

The unaided thresholds were found out using modified Hughson-Westlake procedure (Carhart & Jerger, 1959). The testing was done initially with -10 dB and +5 dB steps. Near the thresholds, 1 dB step size was chosen in order to obtain the actual threshold. The threshold considered was the lowest intensity of the sound at which the participant responded to at least 50% of the time. Throughout the procedure, the non-test ear was blocked with the foam ear plug. The unaided Speech Identification Scores (SIS) was obtained using both the Phonemically Balanced word list for adults (Manjula et al., 2015) and word lists of High frequency Kannada speech identification test (Yathiraj & Mascarenhans, 2002). The recorded word lists were presented to avoid any speaker related bias. The recorded speech material was presented through the auxiliary input / external mode of the audiometer. The loudspeaker was elected as the output transducer. The presentation level selected was held constant at 45 dB HL, closely equivalent to 60 dB SPL, which is the conversation level. This intensity was selected to match the level of the stimulus used during the real ear measurements. The recorded PB word list I (Manjula et al., 2015) was played from the Personal computer (PC) routed through the audiometer. When the calibration tone was played, the volume was adjusted such that the level of the calibration tone was equal to the ‘0’ reading on the VU meter of the audiometer. The participant was instructed to repeat the words as he/she heard it. There were 25 words in each word list. The scoring was done by counting the number of words correctly repeated. Each correctly identified word was scored 1, with the maximum score being 25. The SIS was not converted to percentage. This was done for each test ear of each participant.

Similarly, the word list I of the high frequency word list (Yathiraj & Mascarenhans, 2002) was played through the audiometer through the external mode. The instruction given to the participant was again to repeat the words heard by him/her. The calibration tone was used to adjust the reading on the VU meter to ‘0’. This list contained 25 words for which a score of 1 was awarded for each correctly identified word, the maximum score being 25. The SIS was noted down for each test ear of each participant. After finding out the aided thresholds and SIS in the unaided condition, the aided thresholds and SIS were obtained.

The participant was made to wear the hearing aid, had the same hearing aid settings that were optimized using MPSE approach. The aided thresholds were found out from 250 to 6000 Hz, using warble tone as test stimulus. Initially, though -10 dB and +5 dB step size was used; the exact thresholds were found out in terms of 1 dB step size near the threshold.

The aided SIS was be established using the PB word list and high frequency word list presented at 45 dB HL, as was done in unaided condition. The procedure was the same as mentioned earlier with the difference just being that the hearing aid was secured in the test ear and switched-on. While presenting the word lists, word list II of PB words was used; and then word list II of high frequency word lists was used. The score for each of them was noted down separately.

**3.4.3 Phase III: Objective and subjective measurements with RIC hearing aid connected to open dome and closed dome, using MPCE approach.** Objective measurement of REAG for RIC hearing aid with open dome was done when the hearing aid was optimized using MPCE approach. The Phase III was further divided as Phase III(A) and Phase III(B).

***3.4.3.1 Phase III(A): Measurement of Real Ear Aided Gain (REAG) of RIC optimized with MPCE approach.*** In this phase, all the steps that were mentioned in the Phase II(A) were repeated. The only change was that in the menu option of the real ear measurement system, the reference microphone was switched ‘on’ for all the measurements. The ANSI weighted digital speech was used to find out the REUG and REAG; and objective optimization of the hearing aid was also done to match the target gain curves. All through the testing, the participant was instructed to not to alter his head position or do any movement of the head. The real ear aided gain (REAG) data were noted down. With the enabling of the reference microphone, the SPL measured at the reference microphone may vary depending on the sound that is escaping out of the open dome of the RIC hearing aid. The low frequency energy that is trapped inside the ear canal in case of occluded dome type is not the case in open dome. The low frequencies this escapes out which is detected by the reference microphone. The reference microphone measures this and reduces the SPL at the level of loudspeaker. Hence, changes occur at the probe tube microphone as well resulting in the difference.

***3.4.3.2 Phase III(B): Measurement of aided thresholds of RIC optimized with MPCE approach.*** The hearing aid setting retained as that in the Phase III(A), i.e., the RIC hearing aid optimized using MPCE approach. All the steps that were done in Phase II(B) were repeated in this phase too. The aided warble tone thresholds from 250 to 6000 Hz audiometric frequencies were found out using 10 dB step size initially and 1 dB step size later. The procedure for aided SIS measurement was also the same as previously mentioned in Phase II(B). The word list III for PB word list and HF word list III were selected for the measurement of SIS. The SIS was noted down for each of the word lists for each test ear of each participant.

Once the entire set of procedure for REAG, aided thresholds, aided SIS for PB words and high frequency words in Phase II and Phase III were carried out for RIC coupled to open dome, the same procedures were carried out for RIC hearing aid coupled to closed dome. The PB word list number IV and V were used for finding out SIS using PB words with RIC hearing aid coupled to closed dome when optimized using MPSE and MPCE respectively. Since there were only three high frequency word lists, the words in the high frequency word lists were iterated i.e., the order of the words within the list were randomly changed with the inter-stimulus interval maintained at the same duration. For finding out SIS using high frequency words with RIC hearing aid coupled to closed dome, iterated high frequency word list I and iterated high frequency word list II were used for MPSE and MPCE approaches respectively.

The aided data were tabulated for each test ear of each participant. This data included the RMS output, REAG, aided thresholds, SIS for PB words, and SIS for high frequency words for RIC hearing aids, connected to open and closed domes, optimized with MPCE and MPSE approaches.

Test re-test reliability data were collected from six participants (2 male and 4 female participants) out of total 12 (5 male and 7 female participants). The entire procedure from Phase II(A) & II(B), Phase III(A) & III(B) was followed. This was done within a gap of one week.

With all the data above, parametric test of Repeated measures Analysis of Variance (ANOVA), non-parametric test of Friedman test and correlation was used. Whenever data didn't follow normality or the standard deviations were high, non-parametric tests were used. Correlation was done to find out relation between objective measure of REAG and behavioral measures of aided thresholds and SIS.

# CHAPTER 4

## Results

The aim of the study was to compare the behavioral measures with the objective real ear measures for verification of Receiver In the Canal (RIC) hearing aid, coupled with closed and open dome fitting, optimized using two approaches of Sound Field Equalization (SFE), i.e., Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE).The specific objectives of the study were,

1. To compare the Real Ear Aided Gain (REAG) of RIC hearing aid optimized using MPSE and MPCE, when coupled to open and closed dome.
2. To compare the aided thresholds with RIC hearing aid optimized using MPSE and MPCE, when coupled to open and closed dome.
3. To find out the relationship between the aided thresholds and REAG of RIC hearing aid optimized with MPSE and MPCE when coupled to open and closed dome.
4. To find out the relationship between the Root Mean Square (RMS) outputs measured during REAG and Speech Identification Score (SIS).
5. To evaluate for the test-retest reliability of the REAG, aided thresholds, and SIS with RIC hearing aid optimized using MPSE and MPCE when coupled to open and closed dome.

The data for the study were collected in four aided conditions. They include:

a. RIC hearing aid with open dome optimized using MPSE

b. RIC hearing aid with open dome optimized using MPCE

c. RIC hearing aid with closed dome optimized using MPSE

d. RIC hearing aid with closed dome optimized using MPCE

The aided data were collected from 12 participants on the following parameters:

1. The RMS output and the REAG at nine frequencies viz. 300Hz, 500Hz, 800Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz, and 6000 Hz.
2. Behavioral aided thresholds at nine different frequencies 250Hz, 500Hz, 750Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz.
3. SIS for PB words and SIS for high frequency words.
4. Test-retest reliability for six participants on the above parameters.

The data were tabulated and analyzed using Statistical Package for Social Sciences (SPSS version 20) software. The following statistical analyses were applied:

1. Outlier analysis
2. Shapiro-Wilk test to check for distribution of data in order to decide about the application of parametric or non-parametric analyses.
3. Descriptive Statistics.
4. Inferential Statistics which included the following tests,

a. Repeated measures Analysis of Variance (ANOVA) for all the REAG measures (except at 300 Hz and 500 Hz) and all behavioral aided thresholds (except at 4000 Hz and 6000 Hz) was done to compare the MPSE and MPCE approaches. If there was a significant difference observed in this test, Bonferroni test was done for pair-wise comparison.

b. Friedman test was done for REAG at 300 Hz and 500 Hz; and for behavioral aided thresholds at 4000 and 6000 Hz was done to compare the MPSE and MPCE approaches. If there was a significant difference observed in this test, Wilcoxon signed rank test was done for pair-wise comparison.
c. Correlation was found out between aided thresholds and REAG for each of the nine frequencies.
d. Correlation was found out between the RMS output of REAG and SIS for PB words; and RMS output of REAG and SIS of high frequency words.

The results of the study will be provided under the following headings:

4.1 Distribution of data

4.1.1. Tests of normality

4.1.2. Descriptive statistics

4.2 Comparison of REAG of RIC hearing aid coupled to open and closed dome in the following conditions.

4.2.1 REAG of RIC hearing aid coupled to open dome optimized using MPSE and MPCE

4.2.2 REAG of RIC hearing aid coupled to closed dome optimized using MPSE and MPCE

4.2.3 REAG of RIC hearing aid coupled to open dome optimized using MPSE and RIC hearing aid with closed dome optimized using MPSE.

4.2.4 REAG of RIC hearing aid coupled to open dome optimized using MPCE and RIC hearing aid with closed dome optimized using MPCE.

4.3 Comparison of behavioral aided thresholds with RIC hearing aid coupled to open and closed dome in the following conditions.

4.3.1 Aided thresholds with RIC hearing aid coupled to open dome optimized using MPSE and MPCE

4.3.2 Aided thresholds with RIC hearing aid coupled to closed dome optimized using MPSE and MPCE

4.3.3 Aided thresholds for RIC hearing aid coupled to open dome optimized using MPSE and RIC hearing aid with closed dome optimized using MPSE.

4.3.4 Aided thresholds for RIC hearing aid coupled to open dome optimized using MPSE and RIC hearing aid with closed dome optimized using MPSE.

4.4 Correlation between behavioral aided thresholds and REAG of RIC hearing aid coupled to open dome and closed dome

4.4.1 Behavioral aided thresholds with REAG of RIC hearing aid coupled to open dome, optimized using MPSE.

4.4.2 Behavioral aided thresholds with REAG of RIC hearing aid coupled to open dome, optimized using MPCE.

4.4.3 Behavioral aided thresholds with REAG of RIC hearing aid coupled to closed dome, optimized using MPSE.

4.4.4 Behavioral aided thresholds with REAG of RIC hearing aid coupled to closed dome, optimized using MPCE.

4.5 Correlation of SIS with RMS output of REAG

4.5.1 SIS for PB words and high frequency words with RMS output of REAG of RIC hearing aid coupled to open dome, optimized using MPSE

4.5.2 SIS for PB words and high frequency words with RMS output of REAG of RIC hearing aid coupled to open dome, optimized using MPCE

4.5.3 SIS for PB words and high frequency words with RMS output of REAG of RIC hearing aid coupled to closed dome, optimized using MPSE

4.5.4 SIS for PB words and high frequency words with RMS output of REAG of RIC hearing aid coupled to closed dome, optimized using MPCE.

4.6 Test-retest reliability for the data.

4.6.1 Test-retest reliability of REAG.

4.6.2 Test-retest reliability of behavioral aided thresholds and SIS

## 4.1 Distribution of data

Before checking for normality, an outlier analysis was done. Box plots were analyzed for the same. As none of the participant included in the study was significantly deviant, all the participants were included for the study. In order to examine if the data collected were following normal distribution, test for normality of distribution was performed. This was done to decide the appropriate statistical tests, parametric or non-parametric tests, to be applied to the data.

**4.1.1 Tests of normality.** In order to examine if the data collected were following normal distribution, Shapiro-Wilk test was performed. In REAG and behavioral aided threshold measures, all the measurements followed normal distribution ($p > 0.05$). The Table 4.1 shows the significance values on normality test for REAG.

**Table 4.1** ***Significance p value for REAG for different frequencies at all conditions***

| Parameters | Statistic | Significance (*p*) |
|---|---|---|
| Open Dome MPSE 300 Hz | 0.955 | 0.709* |
| Open Dome MPSE 500 Hz | 0.950 | 0.644* |
| Open Dome MPSE 800 Hz | 0.889 | 0.113* |
| Open Dome MPSE 1000 Hz | 0.916 | 0.252* |
| Open Dome MPSE 1500 Hz | 0.893 | 0.131* |
| Open Dome MPSE 2000 Hz | 0.901 | 0.162* |
| Open Dome MPSE 3000 Hz | 0.886 | 0.104* |
| Open Dome MPSE 4000 Hz | 0.889 | 0.113* |
| Open Dome MPSE 6000 Hz | 0.952 | 0.664* |
| Open Dome MPCE 300 Hz | 0.864 | 0.055* |
| Open Dome MPCE 500 Hz | 0.947 | 0.592* |
| Open Dome MPCE 800 Hz | 0.935 | 0.435* |
| Open Dome MPCE 1000 Hz | 0.904 | 0.180* |
| Open Dome MPCE 1500 Hz | 0.862 | 0.052* |
| Open Dome MPCE 2000 Hz | 0.876 | 0.078* |
| Open Dome MPCE 3000 Hz | 0.939 | 0.489* |
| Open Dome MPCE 4000 Hz | 0.900 | 0.158* |

| | | |
|---|---|---|
| Open Dome MPCE 6000 Hz | 0.955 | 0.717* |
| Closed Dome MPSE 300 Hz | 0.908 | 0.203* |
| Closed Dome MPSE 500 Hz | 0.941 | 0.509* |
| Closed Dome MPSE 800 Hz | 0.918 | 0.271* |
| Closed Dome MPSE 1000 Hz | 0.921 | 0.290* |
| Closed Dome MPSE 1500 Hz | 0.972 | 0.934* |
| Closed Dome MPSE 2000 Hz | 0.960 | 0.779* |
| Closed Dome MPSE 3000 Hz | 0.915 | 0.250* |
| Closed Dome MPSE 4000 Hz | 0.895 | 0.135* |
| Closed Dome MPSE 6000 Hz | 0.828 | 0.020 |
| Closed Dome MPCE 300 Hz | 0.948 | 0.602* |
| Closed Dome MPCE 500 Hz | 0.959 | 0.776* |
| Closed Dome MPCE 800 Hz | 0.906 | 0.188* |
| Closed Dome MPCE 1000 Hz | 0.867 | 0.061* |
| Closed Dome MPCE 1500 Hz | 0.944 | 0.548* |
| Closed Dome MPCE 2000 Hz | 0.936 | 0.443* |
| Closed Dome MPCE 3000 Hz | 0.975 | 0.955* |
| Closed Dome MPCE 4000 Hz | 0.924 | 0.318* |
| Closed Dome MPCE 6000 Hz | 0.965 | 0.850* |

Note: * $p>0.05$ which indicates normality

The Table 4.2 shows the significance values of normality for behavioral aided thresholds.

**Table 4.2** ***Significance p value for behavioral aided thresholds for different frequencies at all conditions***

| **Parameters** | **Statistic** | **Significance (*p*)** |
|---|---|---|

| | | |
|---|---|---|
| Open Dome MPSE 250 Hz | 0.936 | 0.454* |
| Open Dome MPSE 500 Hz | 0.968 | 0.891* |
| Open Dome MPSE 750 Hz | 0.944 | 0.553* |
| Open Dome MPSE 1000 Hz | 0.866 | 0.058* |
| Open Dome MPSE 1500 Hz | 0.955 | 0.718* |
| Open Dome MPSE 2000 Hz | 0.924 | 0.325* |
| Open Dome MPSE 3000 Hz | 0.982 | 0.989* |
| Open Dome MPSE 4000 Hz | 0.777 | 0.005 |
| Open Dome MPSE 6000 Hz | 0.777 | 0.005 |
| Open Dome MPCE 250 Hz | 0.926 | 0.344* |
| Open Dome MPCE 500 Hz | 0.957 | 0.746* |
| Open Dome MPCE 750 Hz | 0.884 | 0.100* |
| Open Dome MPCE 1000 Hz | 0.902 | 0.167* |
| Open Dome MPCE 1500 Hz | 0.943 | 0.541* |
| Open Dome MPCE 2000 Hz | 0.958 | 0.756* |
| Open Dome MPCE 3000 Hz | 0.943 | 0.535* |
| Open Dome MPCE 4000 Hz | 0.930 | 0.383* |
| Open Dome MPCE 6000 Hz | 0.862 | 0.052* |
| Closed Dome MPSE 250 Hz | 0.932 | 0.405* |
| Closed Dome MPSE 500 Hz | 0.926 | 0.344* |
| Closed Dome MPSE 750 Hz | 0.961 | 0.797* |
| Closed Dome MPSE 1000 Hz | 0.908 | 0.202* |
| Closed Dome MPSE 1500 Hz | 0.823 | 0.017 |
| Closed Dome MPSE 2000 Hz | 0.916 | 0.253* |
| Closed Dome MPSE 3000 Hz | 0.921 | 0.296* |
| Closed Dome MPSE 4000 Hz | 0.870 | 0.066* |

| | | |
|---|---|---|
| Closed Dome MPSE 6000 Hz | 0.738 | 0.002 |
| Closed Dome MPCE 250 Hz | 0.907 | 0.194* |
| Closed Dome MPCE 500 Hz | 0.922 | 0.304* |
| Closed Dome MPCE 750 Hz | 0.957 | 0.735* |
| Closed Dome MPCE 1000 Hz | 0.921 | 0.295* |
| Closed Dome MPCE 1500 Hz | 0.918 | 0.273* |
| Closed Dome MPCE 2000 Hz | 0.881 | 0.089* |
| Closed Dome MPCE 3000 Hz | 0.957 | 0.737* |
| Closed Dome MPCE 4000 Hz | 0.859 | 0.047 |
| Closed Dome MPCE 6000 Hz | 0.730 | 0.002 |

Note: * $p>0.05$ which indicates normality

The Table 4.2 shows the normality of distribution of behavioral aided thresholds and if normally distributed is indicated with an asterisk mark. Except at 1500 Hz, 4000 Hz, and 6000 Hz, the aided thresholds at other frequencies have normal distribution. The descriptive statistics was applied to each of these measures to further decide about the type of test to be used.

**4.1.2 Descriptive statistics.** The mean, median, and standard deviation (SD) values of REAG at different frequencies in different conditions are tabulated (Table 4.3).

**Table 4.3** ***Mean, median, and standard deviation (SD) values of REAG at different frequencies in different conditions (n = 12).***

| **Parameters** | **Mean** | **Median** | **SD** |
|---|---|---|---|
| Open Dome MPSE 300 Hz | 6.092 | 4.350 | 9.6845* |
| Open Dome MPSE 500 Hz | 11.600 | 11.450 | 6.9425* |
| Open Dome MPSE 800 Hz | 20.133 | 21.400 | 6.3334 |

| | | | |
|---|---|---|---|
| Open Dome MPSE 1000 Hz | 22.825 | 21.950 | 5.8604 |
| Open Dome MPSE 1500 Hz | 28.475 | 31.100 | 7.5615 |
| Open Dome MPSE 2000 Hz | 36.008 | 38.500 | 6.3233 |
| Open Dome MPSE 3000 Hz | 45.733 | 48.050 | 9.0617 |
| Open Dome MPSE 4000 Hz | 35.000 | 40.700 | 14.4536 |
| Open Dome MPSE 6000 Hz | 28.958 | 28.550 | 12.0303 |
| Open Dome MPCE 300 Hz | 7.725 | 6.000 | 4.1196* |
| Open Dome MPCE 500 Hz | 13.517 | 12.600 | 5.7225 |
| Open Dome MPCE 800 Hz | 24.592 | 23.350 | 4.9649 |
| Open Dome MPCE 1000 Hz | 28.558 | 29.450 | 3.7872 |
| Open Dome MPCE 1500 Hz | 30.858 | 29.150 | 5.1936 |
| Open Dome MPCE 2000 Hz | 36.883 | 36.500 | 3.7976 |
| Open Dome MPCE 3000 Hz | 40.708 | 40.450 | 3.9255 |
| Open Dome MPCE 4000 Hz | 33.442 | 31.900 | 6.6534 |
| Open Dome MPCE 6000 Hz | 20.867 | 21.900 | 6.9770 |
| Closed Dome MPSE 300 Hz | 6.750 | 5.800 | 8.238* |
| Closed Dome MPSE 500 Hz | 8.517 | 7.250 | 8.8608* |
| Closed Dome MPSE 800 Hz | 15.183 | 15.650 | 8.5392* |
| Closed Dome MPSE 1000 Hz | 17.533 | 18.000 | 8.2699 |
| Closed Dome MPSE 1500 Hz | 26.817 | 26.050 | 5.6714 |
| Closed Dome MPSE 2000 Hz | 35.100 | 34.450 | 6.3882 |
| Closed Dome MPSE 3000 Hz | 46.400 | 47.800 | 6.2029 |
| Closed Dome MPSE 4000 Hz | 34.675 | 37.050 | 9.8527 |
| Closed Dome MPSE 6000 Hz | 34.700 | 39.000 | 9.9223 |
| Closed Dome MPCE 300 Hz | 15.400 | 16.950 | 6.6435 |
| Closed Dome MPCE 500 Hz | 16.217 | 15.850 | 5.0820 |

| | | | |
|---|---|---|---|
| Closed Dome MPCE 800 Hz | 22.267 | 23.350 | 6.4174 |
| Closed Dome MPCE 1000 Hz | 25.667 | 28.200 | 5.5249 |
| Closed Dome MPCE 1500 Hz | 32.800 | 33.100 | 2.7631 |
| Closed Dome MPCE 2000 Hz | 39.717 | 39.400 | 3.3809 |
| Closed Dome MPCE 3000 Hz | 48.208 | 48.300 | 5.9768 |
| Closed Dome MPCE 4000 Hz | 40.817 | 39.600 | 8.4000 |
| Closed Dome MPCE 6000 Hz | 36.033 | 35.850 | 7.9392 |

Note: * indicates high SD

As can be observed from Table 4.3, the standard deviation for 300 Hz is higher sometimes equaling the mean or even crossing it in three out of four conditions. At 500 Hz, the SD is higher in one condition out of four conditions. The SD is considered to be high when the SD value is more than 50% of the mean. The condition in which the SD is higher has been indicated by asterisk mark in the table. For these frequencies, non-parametric tests have been employed. For the rest of the frequencies, parametric tests have been employed.

The Table 4.4 shows the mean, median, and standard deviation of aided thresholds at different frequencies in all test conditions.

**Table 4.4** ***Mean, median, and standard deviation (SD) values of aided thresholds at different frequencies in different conditions (n = 12).***

| **Parameters** | **Mean** | **Median** | **SD** |
|---|---|---|---|
| Open Dome MPSE 250 Hz | 24.08 | 23.00 | 10.140 |
| Open Dome MPSE 500 Hz | 24.25 | 24.00 | 6.837 |
| Open Dome MPSE 750 Hz | 23.33 | 22.00 | 8.348 |
| Open Dome MPSE 1000 Hz | 22.75 | 20.00 | 9.555 |

| | | | |
|---|---|---|---|
| Open Dome MPSE 1500 Hz | 24.92 | 24.00 | 9.307 |
| Open Dome MPSE 2000 Hz | 22.50 | 21.00 | 6.922 |
| Open Dome MPSE 3000 Hz | 26.08 | 26.00 | 6.403 |
| Open Dome MPSE 4000 Hz | 32.50 | 29.50 | 14.507 |
| Open Dome MPSE 6000 Hz | 37.83 | 33.50 | 16.563 |
| Open Dome MPCE 250 Hz | 22.92 | 23.50 | 7.902 |
| Open Dome MPCE 500 Hz | 22.25 | 22.50 | 5.941 |
| Open Dome MPCE 750 Hz | 21.33 | 19.00 | 8.049 |
| Open Dome MPCE 1000 Hz | 21.75 | 20.00 | 8.935 |
| Open Dome MPCE 1500 Hz | 23.00 | 24.00 | 7.236 |
| Open Dome MPCE 2000 Hz | 21.42 | 21.50 | 6.302 |
| Open Dome MPCE 3000 Hz | 27.08 | 26.50 | 6.082 |
| Open Dome MPCE 4000 Hz | 34.08 | 32.00 | 14.016 |
| Open Dome MPCE 6000 Hz | 43.08 | 39.00 | 14.228 |
| Closed Dome MPSE 250 Hz | 23.92 | 25.00 | 8.618 |
| Closed Dome MPSE 500 Hz | 26.00 | 26.00 | 6.368 |
| Closed Dome MPSE 750 Hz | 24.17 | 24.00 | 7.744 |
| Closed Dome MPSE 1000 Hz | 25.33 | 25.50 | 6.624 |
| Closed Dome MPSE 1500 Hz | 25.42 | 23.50 | 6.529 |
| Closed Dome MPSE 2000 Hz | 22.08 | 21.00 | 6.459 |
| Closed Dome MPSE 3000 Hz | 25.33 | 25.50 | 5.836 |
| Closed Dome MPSE 4000 Hz | 33.58 | 29.50 | 15.042 |
| Closed Dome MPSE 6000 Hz | 35.25 | 27.00 | 17.421 |
| Closed Dome MPCE 250 Hz | 23.75 | 25.00 | 8.874 |
| Closed Dome MPCE 500 Hz | 25.42 | 23.50 | 6.403 |
| Closed Dome MPCE 750 Hz | 24.25 | 24.00 | 7.533 |

| | | | |
|---|---|---|---|
| Closed Dome MPCE 1000 Hz | 25.08 | 25.00 | 7.154 |
| Closed Dome MPCE 1500 Hz | 25.17 | 23.50 | 6.043 |
| Closed Dome MPCE 2000 Hz | 21.58 | 21.00 | 5.583 |
| Closed Dome MPCE 3000 Hz | 26.50 | 27.00 | 4.482 |
| Closed Dome MPCE 4000 Hz | 33.00 | 30.00 | 14.924 |
| Closed Dome MPCE 6000 Hz | 35.33 | 26.00 | 17.895* |

Note: *indicates high SD

From Table 4.4, it can be observed that the standard deviation is high only at 6000 Hz in one condition as indicated by an asterisk. Since the data at 4000 Hz and 6000 Hz thresholds did not follow normality of distribution in majority of the conditions, non-parametric tests were applied.

The non-parametric test used was Friedman test. The Wilcoxon signed rank test was performed when indicated. The parametric test used was repeated measures analysis of variance. The Bonferroni pair-wise comparison was performed when indicated.

**4.2 Comparison of REAG of RIC hearing aid coupled to open and closed dome**

**4.2.1 REAG of RIC hearing aid coupled to open dome optimized using MPSE and MPCE**. The comparison of REAG of RIC coupled to open dome optimized with MPSE is compared with that of optimized with MPCE measurement. This was studied at nine different frequencies viz. 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 4000 Hz and 6000 Hz. For 300 Hz and 500 Hz, Friedman test and Wilcoxon signed rank tests were administered. In Friedman test, the level of significance for 300 Hz and 500 Hz were 0.007 ($p$<0.05) and 0.010 ($p$<0.05) respectively. Hence, Wilcoxon signed rank test was administered. This indicated that, there was no significant difference between the two equalization conditions at 300 Hz i.e., $p>0.05$. However, based on the ranks, four participants out of 12 had lesser gain in MPCE in comparison to MPSE at 300 Hz and the remaining eight participants showed the reverse trend. In assigning the ranks for 500 Hz, it was observed that five out of 12 participants had lesser gain in MPCE than MPSE and rest of the participants showed vice versa.

In the other frequencies, since it followed normality and also the SD were within acceptable limits, repeated measures ANOVA was done. For frequencies 800 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz, in the repeated measures ANOVA, the level of significance ($p$) was less than 0.05 in all the conditions except 4000 Hz indicating a significant difference for these frequencies. Hence, Bonferroni pair-wise comparison was done. In this comparison, there was no significant difference between the two equalization conditions ($p>0.05$). For 1000 Hz, there was a significant difference between the two conditions ($p<0.05$).

The Table 4.5 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.5** ***Significance (p) value of each frequency for comparison of REAG of RIC hearing aid, coupled to open dome, optimized using MPSE and MPCE***

| Frequency | Test used | Test statistic | Partial eta squared | Significance ($p$) |
|---|---|---|---|---|
| 300 Hz | 1. Friedman test | | | 0.007* |

| | | | | |
|---|---|---|---|---|
| | 2. Wilcoxon signed rank test. | Z = -0.628 | - | 0.530 |
| 500 Hz | 1. Friedman test | | | 0.010* |
| | 2. Wilcoxon signed rank test. | Z = 0.583 | - | 0.583 |
| 800 Hz | 1. Repeated measures ANOVA | F (3,33) = 6.436 | 0.369 | 0.001* |
| | 2. Bonferroni comparison | | | 0.357 |
| 1000 Hz | 1. Repeated measures ANOVA | F (3,33) = 10.983 | 0.500 | 0.000* |
| | 2. Bonferroni comparison | | | 0.015* |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 5.311 | 0.326 | 0.004* |
| | 2. Bonferroni comparison | | | 1.000 |
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 3.857 | 0.260 | 0.018* |
| | 2. Bonferroni comparison | | | 1.000 |

| | | | | |
|---|---|---|---|---|
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 4.227 | 0.278 | 0.012* |
| | 2. Bonferroni comparison | | | 0.500 |
| 4000 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.163 | 0.164 | 0.111 |
| | 2. Bonferroni comparison | | | 1.000 |
| 6000 Hz | 1. Repeated measures ANOVA | F (3,33) = 7.480 | 0.405 | 0.001* |
| | 2. Bonferroni comparison | | | 0.439 |

Note: * significant difference at $p<0.05$

**4.2.2 REAG of RIC hearing aid coupled to closed dome optimized using MPSE and MPCE.** The REAG of RIC coupled to closed dome optimized with MPSE was compared with that of optimized with MPCE conditions. This was studied at nine different frequencies viz. 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 4000 Hz, and 6000 Hz. For 300 Hz and 500 Hz, Friedman test and Wilcoxon signed rank test (if indicated) were administered. In Friedman test, the level of significance at 300 Hz and 500 Hz were 0.007 ($p<0.05$) and 0.010 ($p<0.05$) respectively. Hence, Wilcoxon signed rank test was administered. There was a significant difference in REAG between the two equalization conditions at 300 Hz as well as 500 Hz; with level of significance being

0.002 (*p*<0.05) and 0.004 (*p*<0.05) respectively. Based on the ranks, all the 12 participants had higher gain in MPCE in comparison to MPSE at 300 Hz while for 500 Hz, it was observed that except for one participant, all the other participants had REAG greater in MPCE than MPSE.

For other frequencies, repeated measures ANOVA was administered. The level of significance (*p)* was less than 0.05. the repeated measures ANOVA at frequencies 800 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz, in all the conditions except at 4000 Hz, indicating significant difference at these frequencies. Hence, Bonferroni pair-wise comparison was done. There were significant difference for 800 Hz, 1000 Hz, 1500 Hz, and 2000 Hz in these two conditions with the level of significance being 0.001 (*p*<0.05), 0.001 (*p*<0.05), 0.006 (*p*<0.05), and 0.034 (*p*<0.05) respectively. For frequencies 3000 Hz, 4000 Hz and 6000 Hz, there was no significant difference between the REAG of RIC hearing aid optimized with MPSE or MPCE i.e., *p*>0.05.

The Table 4.6 gives the significance difference for individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.6** ***Significance (p) value of each frequency for comparison of REAG of RIC hearing aid, coupled to closed dome, optimized using MPSE and MPCE***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance |
|---|---|---|---|---|
| 300 Hz | 1. Friedman test | | | Friedman: 0.007* |

| | | | | |
|---|---|---|---|---|
| | 2. Wilcoxon signed rank test. | Z = -3.061 | - | Wilcoxon: 0.002* |
| 500 Hz | 1. Friedman test | | | Friedman: 0.010* |
| | 2. Wilcoxon signed rank test. | Z = -2.866 | - | Wilcoxon: 0.004* |
| 800 Hz | 1. Repeated measures ANOVA | F (3,33) = 6.436 | 0.369 | 0.001* |
| | 2. Bonferroni comparison | | | 0.001* |
| 1000 Hz | 1. Repeated measures ANOVA | F (3,33) = 10.983 | 0.500 | 0.000* |
| | 2. Bonferroni comparison | | | 0.001* |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 5.311 | 0.326 | 0.004* |
| | 2. Bonferroni comparison | | | 0.006* |
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 3.857 | 0.260 | 0.018* |
| | | | | 0.034* |

| | | | | |
|---|---|---|---|---|
| | 2. Bonferroni comparison | | | |
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 4.227 | 0.278 | 0.012* |
| | 2. Bonferroni comparison | | | 1.000 |
| 4000 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.163 | 0.164 | 0.111 |
| | 2. Bonferroni comparison | | | 0.067 |
| 6000 Hz | 1. Repeated measures ANOVA | F (3,33) = 7.480 | 0.405 | 0.001* |
| | 2. Bonferroni comparison | | | 1.000 |

Note: * significant difference at $p<0.05$

**4.2.3 Comparison of REAG of RIC hearing aid coupled to open dome, optimized using MPSE, and RIC hearing aid with closed dome optimized using MPSE.** This comparison was studied to know the effect of type of dome on the REAG at nine different frequencies viz. 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 4000 Hz, and 6000 Hz. For 300 Hz and 500 Hz. Friedman test and Wilcoxon signed rank tests were administered. In Friedman test, the level of significance ($p$) for 300 Hz and 500 Hz were 0.007 ($p<0.05$) and 0.010 ($p<0.05$) respectively. At other frequencies, the difference was not significant. Hence, Wilcoxon signed rank test was administered at the two frequencies. There was no significant difference between the conditions for 300 Hz

Comparison of open dome MPSE with closed dome MPSE for 300 Hz i.e., $p>0.05$. However, based on the ranks, five participants out of 12 had lesser gain in closed dome MPSE in comparison to open dome MPSE at 300 Hz and the remaining 7 participants showed the reverse trend. For 500 Hz, there was a significant difference between the two conditions with the level of significance being 0.010 ($p<0.05$). In assigning the ranks, it was observed that eight out of 12 participants had lesser gain in closed dome MPSE than open dome MPSE and vice versa for the rest of the participants were.

For other frequencies, repeated measures ANOVA was administered. For frequencies 800 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz, in the repeated measures ANOVA, the level of significance ($p$) was less than 0.05 in all the conditions except 4000 Hz indicating the significant difference for these frequencies. Hence, Bonferroni pair-wise comparison was done. There was no significant difference between the two conditions, for any of the frequencies ($p>0.05$). Table 4.7 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic, and partial eta squared values (in case of repeated measures).

**Table 4.7** ***Significance (p) value of each frequency for comparison of REAG of RIC hearing aid coupled to open dome, optimized using MPSE, and RIC hearing aid with closed dome optimized using MPSE.***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance (*p*) |
| --- | --- | --- | --- | --- |
| 300 Hz | 1. Friedman test | | | 0.007* |
| | 2. Wilcoxon signed rank test. | Z = -0.392 | - | 0.695 |
| 500 Hz | 1. Friedman test | | | 0.010* |
| | 2. Wilcoxon signed rank test. | Z = -0.785 | - | 0.433 |
| 800 Hz | 1. Repeated measures ANOVA | F (3,33) = 6.436 | 0.369 | 0.001* |
| | 2. Bonferroni comparison | | | 0.848 |
| 1000 Hz | 1. Repeated measures ANOVA | F (3,33) = 10.983 | 0.500 | 0.000* |
| | 2. Bonferroni comparison | | | 0.487 |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 5.311 | 0.326 | 0.004* |
| | 2. Bonferroni comparison | | | 1.000 |

| | | | | |
|---|---|---|---|---|
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 3.857 | 0.260 | 0.018* |
| | 2. Bonferroni comparison | | | 1.000 |
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 4.227 | 0.278 | 0.012* |
| | 2. Bonferroni comparison | | | 1.000 |
| 4000 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.163 | 0.164 | 0.111 |
| | 2. Bonferroni comparison | | | 1.000 |
| 6000 Hz | 1. Repeated measures ANOVA | F (3,33) = 7.480 | 0.405 | 0.001* |
| | 2. Bonferroni comparison | | | 1.000 |

Note: * significant difference at $p<0.05$

**4.2.4 REAG of RIC hearing aid coupled to open dome optimized using MPCE and RIC hearing aid with closed dome optimized using MPCE.** For REAG at 300 Hz and 500 Hz, even though it followed normality, the SDs were higher in these frequencies. Hence, non-parametric test was used viz. Friedman test was used. If *p* less than 0.05, then Wilcoxon signed rank test was administered. The Friedman test at 300 Hz and 500 Hz, the level of significance reached 0.007 ($p<0.05$) and 0.010 ($p<0.05$); and hence Wilcoxon signed rank test was done.

There was a significant difference between the REAG of RIC hearing aid coupled to open and closed domes, at 300 Hz, i.e., the level of significance was 0.005 ($p<0.05$). Ten out of 12 participants showed that closed dome had higher REAG in comparison to open dome in this frequency. For 500 Hz, there was no significant difference between these two domes with nine participants having greater REAG in closed dome and the rest having reverse trend.

For other frequencies, normality were present and also the SD were within acceptable limits and hence repeated measures ANOVA test was administered. For frequencies 800 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz, in the repeated measures ANOVA, the level of significance $p$ was less than 0.05, in all the conditions except at 4000 Hz. Hence, Bonferroni pair-wise comparison was done. In that for frequencies 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz, there was no significant difference between the two domes i.e., $p>0.05$. For 3000 Hz, 4000 Hz and 6000 Hz, the level reached significance, i.e., 0.003 ($p<0.05$), 0.001 ($p<0.05$) and 0.000 ($p<0.05$) respectively.

Table 4.8 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.8** ***Significance (p) value of each frequency for comparison of REAG of RIC hearing aid coupled to open dome, optimized using MPCE, and RIC hearing aid with closed dome optimized using MPCE.***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance (*p*) |
|---|---|---|---|---|
| 300 Hz | 1. Friedman test | | | 0.007* |
| | 2. Wilcoxon signed rank test. | Z = -2.825 | - | 0.005 |
| 500 Hz | 1. Friedman test | | | 0.010* |
| | 2. Wilcoxon signed rank test. | Z = -1.492 | - | 0.136 |
| 800 Hz | 1. Repeated measures ANOVA | F (3,33) = 6.436 | 0.369 | 0.001* |
| | 2. Bonferroni Comparison | | | 1.0000 |
| 1000 Hz | 1. Repeated measures ANOVA | F (3,33) = 10.983 | 0.500 | 0.000* |
| | 2. Bonferroni Comparison | | | 0.687 |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 5.311 | 0.326 | 0.004* |

| | | | | |
|---|---|---|---|---|
| | 2. Bonferroni Comparison | | | 0.790 |
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 3.857 | 0.260 | 0.018* |
| | 2. Bonferroni Comparison | | | 0.120 |
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 4.227 | 0.278 | 0.012* |
| | 2. Bonferroni Comparison | | | 0.003* |
| 4000 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.163 | 0.164 | 0.111 |
| | 2. Bonferroni Comparison | | | 0.001* |
| 6000 Hz | 1. Repeated measures ANOVA | F (3,33) = 7.480 | 0.405 | 0.001* |
| | 2. Bonferroni | | | 0.000* |

Note: * significant difference at $p<0.05$

### 4.3 Comparison of behavioral aided thresholds with RIC hearing aid coupled to open and closed dome in the following conditions

The behavioral aided thresholds were compared across condition for each frequency. The frequencies considered are 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz. The aided thresholds were obtained after optimization with the MPSE or MPCE approaches.

**4.3.1 Aided thresholds with RIC hearing aid coupled to open dome optimized using MPSE and MPCE.** For frequencies except 4000 Hz and 6000 Hz, parametric test of repeated measures ANOVA was used. If there was a significant difference with repeated measures, Bonferroni pair-wise comparison was done. For 4000 Hz and 6000 Hz, Friedman test was done as the normality was not followed in at least two out of four conditions and also in one condition in which SD was high.

The aided threshold at 500 Hz was significant better when the RIC hearing aid coupled to open dome was optimized using MPCE. Further, Bonferroni pairwise comparison revealed that there was no significant difference between the two conditions i.e., $p>0.05$. When Friedman test was used for 4000 Hz and 6000 Hz, it didn't show any significant difference between the two conditions i.e., $p>0.05$.

The Table 4.9 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.9** ***Significance p value of each frequency for comparison of aided thresholds with RIC hearing aid coupled to open dome optimized using MPSE and MPCE***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance (*p*) |
|---|---|---|---|---|
| 250 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 0.973 | 0.081 | 0.417<br><br>1.000 |
| 500 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 4.924 | 0.309 | 0.006*<br><br>0.699 |
| 750 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 2.075 | 0.159 | 0.122<br><br>0.148 |
| 1000 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 2.282 | 0.172 | 0.097<br><br>1.000 |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.866 | 0.073 | 0.469<br><br>0.880 |

| | | | | |
|---|---|---|---|---|
| | 2. Bonferroni Comparison | | | |
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.409 | 0.036 | 0.748 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.650 | 0.056 | 0.589 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 4000 Hz | 1. Friedman test | - | - | 0.624 |
| 6000 Hz | 1. Friedman test | - | - | 0.109 |

Note: * significant difference at $p<0.05$

**4.3.2 Aided thresholds with RIC hearing aid coupled to closed dome optimized using MPSE and MPCE.** There was a significant difference in aided threshold at 500 Hz. Further, Bonferroni pair-wise comparison revealed that there was no significant difference between the two conditions i.e., $p>0.05$. When Friedman test was used for 4000 Hz and 6000 Hz, it didn't show any significant difference i.e., $p>0.05$.

Table 4.10 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.10** ***Significance p value of each frequency for comparison of aided thresholds with RIC hearing aid coupled to closed dome optimized using MPSE and MPCE***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance (*p*) |
|---|---|---|---|---|
| 250 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 0.973 | 0.081 | 0.417<br>1.000 |
| 500 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 4.924 | 0.309 | 0.006*<br>1.000 |
| 750 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 2.075 | 0.159 | 0.122<br>1.000 |
| 1000 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 2.282 | 0.172 | 0.097<br>1.000 |

| | | | | |
|---|---|---|---|---|
| 1500 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 0.866 | 0.073 | 0.469<br>1.000 |
| 2000 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 0.409 | 0.036 | 0.748<br>1.000 |
| 3000 Hz | 1. Repeated measures ANOVA<br>2. Bonferroni Comparison | F (3,33) = 0.650 | 0.056 | 0.589<br>1.000 |
| 4000 Hz | 1. Friedman test | - | - | 0.624 |
| 6000 Hz | 1. Friedman test | - | - | 0.109 |

Note: * significant difference at $p<0.05$

**4.3.3 Aided thresholds for RIC hearing aid coupled to open dome optimized using MPSE and RIC hearing aid with closed dome optimized using MPSE.**

For only 500 Hz, there was significant difference and the further tests reveal the pairwise comparison using Bonferroni test. In that there was no significant difference between the two conditions i.e., $p>0.05$. When Friedman test was used for 4000 Hz and 6000 Hz, it didn't show any significant difference i.e., $p>0.05$ and hence Wilcoxon signed rank test was not administered.

Table 4.11 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.11** ***Significance p value of each frequency for comparison of aided thresholds for RIC hearing aid coupled to open dome optimized using MPSE and RIC hearing aid with closed dome optimized using MPSE.***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance (*p*) |
|---|---|---|---|---|
| 250 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.973 | 0.081 | 0.417 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 500 Hz | 1. Repeated measures ANOVA | F (3,33) = 4.924 | 0.309 | 0.006* |
| | 2. Bonferroni Comparison | | | 0.635 |
| 750 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.075 | 0.159 | 0.122 |
| | 2. Bonferroni Comparison | | | 1.000 |

| | | | | |
|---|---|---|---|---|
| 1000 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.282 | 0.172 | 0.097 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.866 | 0.073 | 0.469 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.409 | 0.036 | 0.748 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.650 | 0.056 | 0.589 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 4000 Hz | 1. Friedman test | - | - | 0.624 |
| 6000 Hz | 1. Friedman test | - | - | 0.109 |

Note: * significant difference at $p<0.05$

**4.3.4 Aided thresholds for RIC hearing aid coupled to open dome optimized using MPCE and RIC hearing aid with closed dome optimized using MPCE.**

Repeated measures ANOVA revealed that there was a significant difference at 500 Hz.

Further, the Bonferroni pair-wise comparison did not reveal any significant difference between the two conditions i.e., $p>0.05$. When Friedman test was used for 4000 Hz and 6000 Hz, it did not show any significant difference i.e., $p>0.05$.

Table 4.12 gives the individual frequencies at which the comparisons were made and the test used in each with the values of the level of significance, test statistic and partial eta squared values (in case of repeated measures).

**Table 4.12** ***Significance p value of each frequency for comparison of aided thresholds for RIC hearing aid coupled to open dome optimized using MPCE and RIC hearing aid with closed dome optimized using MPCE.***

| Frequency | Test used | Test statistic | Partial Eta squared | Significance ($p$) |
|---|---|---|---|---|
| 250 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.973 | 0.081 | 0.417 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 500 Hz | 1. Repeated measures ANOVA | F (3,33) = 4.924 | 0.309 | 0.006* |
| | 2. Bonferroni Comparison | | | 0.141 |
| 750 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.075 | 0.159 | 0.122 |

| | | | | |
|---|---|---|---|---|
| | 2. Bonferroni Comparison | | | 0.774 |
| 1000 Hz | 1. Repeated measures ANOVA | F (3,33) = 2.282 | 0.172 | 0.097 |
| | 2. Bonferroni Comparison | | | 0.504 |
| 1500 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.866 | 0.073 | 0.469 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 2000 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.409 | 0.036 | 0.748 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 3000 Hz | 1. Repeated measures ANOVA | F (3,33) = 0.650 | 0.056 | 0.589 |
| | 2. Bonferroni Comparison | | | 1.000 |
| 4000 Hz | 1. Friedman test | - | - | 0.624 |
| 6000 Hz | 1. Friedman test | - | - | 0.109 |

Note: * = significant difference at $p<0.05$

## 4.4 Correlation between behavioral aided thresholds and REAG of RIC hearing aid coupled to open dome and closed dome

Behavioral aided thresholds and REAG were correlated to find if there was any positive or negative correlation between the two. The correlation is given under different subheadings.

**4.4.1 Behavioral aided thresholds with REAG of RIC hearing aid coupled to open dome, optimized using MPSE.** In Table 4.13, the correlation between behavioral aided thresholds and REAG for each frequencies is given in terms of correlation co-efficient (r). Since the data did not follow normality in at least two out of four conditions, for 4000 Hz and 6000 Hz, Spearman's rank correlation co-efficient is considered. For all the other frequencies, Pearson's correlation co-efficient was obtained.

**Table 4.13** ***Correlation at different frequencies between aided thresholds and REAG of RIC hearing aid coupled to open dome, optimized using MPSE.***

| Parameter | Correlation co-efficient (r) |
|---|---|
| 300 Hz REAG with 250 Hz aided threshold | -0.234 |
| 500 Hz REAG with 500 Hz aided threshold | -0.017 |
| 800 Hz REAG with 750 Hz aided threshold | 0.066 |
| 1000 Hz REAG with 1000 Hz aided threshold | -0.207 |
| 1500 Hz REAG with 1500 Hz aided threshold | -0.046 |
| 2000 Hz REAG with 2000 Hz aided threshold | -0.364 |

| | |
|---|---|
| 3000 Hz REAG with 3000 Hz aided threshold | -0.104 |
| 4000 Hz REAG with 4000 Hz aided threshold | -0.570 |
| 6000 Hz REAG with 6000 Hz aided threshold | -0.653* |

*Note: * = correlation significant at $p<0.05$ level.*

In Table 4.13, except between 800 Hz REAG with 750 Hz aided threshold, all other frequencies were negatively correlated. This means that with the increase in REAG values, the aided thresholds reduced or the aided thresholds became better. However, in all frequencies except 6000 Hz, a low correlation was observed.

**4.4.2 Behavioral aided thresholds with REAG of RIC hearing aid coupled to open dome, optimized using MPCE.** In Table 4.14, correlation between behavioral aided thresholds and REAG for each frequencies is given in terms of correlation co-efficient (r). Since the data did not follow normality in at least two out of four conditions, at 4000 Hz and 6000 Hz, Spearman's rank correlation co-efficient was considered. For all the other frequencies, Pearson's correlation co-efficient was used.

**Table 4.14** ***Correlation at different frequencies between aided thresholds and REAG of RIC hearing aid coupled to open dome, optimized using MPCE.***

| Parameter | Correlation co-efficient (r) |
|---|---|
| 300 Hz REAG with 250 Hz aided threshold | 0.338 |
| 500 Hz REAG with 500 Hz aided threshold | 0.545 |
| 800 Hz REAG with 750 Hz aided threshold | 0.166 |

| | |
|---|---|
| 1000 Hz REAG with 1000 Hz aided threshold | -0.063 |
| 1500 Hz REAG with 1500 Hz aided threshold | -0.059 |
| 2000 Hz REAG with 2000 Hz aided threshold | -0.484 |
| 3000 Hz REAG with 3000 Hz aided threshold | -0.048 |
| 4000 Hz REAG with 4000 Hz aided threshold | -0.601* |
| 6000 Hz REAG with 6000 Hz aided threshold | 0.162 |

*Note: * = correlation significant at $p<0.05$ level.*

In Table 4.14, correlation between REAG and aided thresholds is positive in four sets of frequencies indicating that with the increase in REAG, the aided thresholds increase or become poorer. For frequencies of 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz and 6000 Hz, though it is negatively correlated, i.e., with increase in REAG the aided thresholds becoming better, it is not significant. At 4000 Hz, there is significant negative correlation between REAG and behavioral aided threshold.

**4.4.3 Behavioral aided thresholds with REAG of RIC hearing aid coupled to closed dome, optimized using MPSE.** In Table 4.15, correlation between behavioral aided thresholds and REAG for each frequency is given in terms of correlation co-efficient (r). Since the data at 4000 Hz and 6000 Hz did not follow normality in at least two out of four conditions, Spearman’s rank correlation co-efficient was considered. For all the other frequencies, Pearson’s correlation co-efficient was used.

**Table 4.15** ***Correlation at different frequencies between aided thresholds and REAG of RIC hearing aid coupled to closed dome, optimized using MPSE.***

| Parameter | Correlation co-efficient (r) |
|---|---|
| 300 Hz REAG with 250 Hz aided threshold | 0.226 |
| 500 Hz REAG with 500 Hz aided threshold | -0.084 |
| 800 Hz REAG with 750 Hz aided threshold | 0.650* |
| 1000 Hz REAG with 1000 Hz aided threshold | 0.740* |
| 1500 Hz REAG with 1500 Hz aided threshold | 0.044 |
| 2000 Hz REAG with 2000 Hz aided threshold | 0.095 |
| 3000 Hz REAG with 3000 Hz aided threshold | -0.067 |
| 4000 Hz REAG with 4000 Hz aided threshold | -0.480 |
| 6000 Hz REAG with 6000 Hz aided threshold | -0.123 |

Note: * = correlation is significant at $p < 0.05$ level.

In this condition, there is a significant positive correlation observed between 800 Hz REAG and 750 Hz aided thresholds, and between REAG and aided threshold at 1000 Hz. This indicated that the aided thresholds become poorer with the increase in REAG for these frequency regions. For other frequencies it is not significantly correlated.

**4.4.4 Correlation between aided thresholds with REAG of RIC hearing aid coupled to closed dome, optimized using MPCE.** In Table 4.16, correlation between behavioral aided thresholds and REAG for each frequencies is given. Since the data at

4000 Hz and 6000 Hz did not follow normality in at least two out of four conditions, for, Spearman's rank correlation co-efficient was considered. For all the other frequencies, Pearson's correlation co-efficient was utilized.

**Table 4.16** ***Correlation at different frequencies between aided thresholds and REAG of RIC hearing aid coupled to closed dome, optimized using MPCE.***

| Parameter | Correlation co-efficient (r) |
|---|---|
| 300 Hz REAG with 250 Hz aided threshold | 0.627* |
| 500 Hz REAG with 500 Hz aided threshold | 0.463 |
| 800 Hz REAG with 750 Hz aided threshold | 0.647* |
| 1000 Hz REAG with 1000 Hz aided threshold | 0. 726* |
| 1500 Hz REAG with 1500 Hz aided threshold | -0.559 |
| 2000 Hz REAG with 2000 Hz aided threshold | -0.052 |
| 3000 Hz REAG with 3000 Hz aided threshold | 0.338 |
| 4000 Hz REAG with 4000 Hz aided threshold | -0.437 |
| 6000 Hz REAG with 6000 Hz aided threshold | -0.102 |

Note: * = Correlation is significant at $p<0.05$ level.

In Table 4.16, there is a significant positive correlation between aided thresholds and REAG observed for frequencies 300 Hz, 800 Hz and 1000 Hz. This indicates that with increase in REAG at these frequencies, behavioral thresholds tend to become poorer. For frequencies 500 Hz and 3000 Hz, though a positive correlation is observed, it is not significant. For the remaining frequencies a negative correlation is observed but not a significant.

## 4.5 Correlation between RMS output of REAG and SIS

Correlation is applied between the RMS output of REAG and the SIS. The SIS was measured using PB word list and high frequency word list. The correlation was is measured between RMS output of REAG and SIS for PB word list; and RMS output of REAG and SIS for high frequency words, under each of the conditions. The correlation results are provided under different headings.

**4.5.1 Correlation between RMS output of REAG and SIS for PB words & SIS for high frequency words with RIC hearing aid coupled to open dome, optimized using MPSE.** In this condition, correlation is measured between the RMS output of REAG in open dome MPSE condition and SIS measured using PB words and also SIS measured using high frequency words. The correlation co-efficient used is Pearson's correlation co-efficient.

**Table 4.17** ***Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to open dome, optimized using MPSE***

| Parameters | Correlation co-efficient (r) |
|---|---|
| RMS output of REAG and SIS for PB words | 0.294 |
| RMS output of REAG and SIS for high frequency words | 0.662* |

Note: * = correlation is significant at $p<0.05$ level.

A significant positive correlation was noted for RMS output of REAG and SIS for high frequency words.

**4.5.2 Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to open dome, optimized using MPCE.** In this condition, the Pearson's correlation between the RMS output of REAG and SIS for PB words and SIS for high frequency words was measured.

**Table 4.18** ***Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to open dome, optimized using MPCE***

| Parameters | Correlation co-efficient (r) |
|---|---|
| RMS output of REAG and SSI for PB words | -0.064 |
| RMS output of REAG and SIS for high frequency words | 0.441 |

Note: * = correlation significant at $p<0.05$ level.

In this condition, RMS output of REAG has a low negative correlation with SUIS for PB words while there is a positive moderate correlation between RMS output of REAG and SIS for high frequency words. The positive correlation indicates that with increase in RMS output of REAG, the SIS using high frequency words tends to increase.

**4.5.3 Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to closed dome, optimized using MPSE.** In this condition, Pearson's correlation was measured between the RMS output of REAG in closed dome MPSE condition and SIS measured using PB words and SIS measured using high frequency words.

***Table 4.19 Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to closed dome, optimized using MPSE***

| Parameters | Correlation co-efficient (r) |
|---|---|
| RMS output of REAG and SIS for PB words | 0.014 |
| RMS output of REAG and SIS for high frequency words | -0.037 |

Note: * = correlation is significant at $p < 0.05$ level.

In this condition, there is no strong correlation between RMS output of REAG and the SIS measured using PB words and also with SIS for high frequency words, measured using closed dome MPSE.

**4.5.4 Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to closed dome, optimized using MPCE.** In this condition, Pearson's correlation co-efficient was measured between the RMS output of REAG in closed dome MPCE condition and SIS using PB words and SIS using high frequency words.

**Table 4.20** ***Correlation between RMS output of REAG and SIS for PB words and SIS for high frequency words with RIC hearing aid coupled to closed dome, optimized using MPCE.***

| Parameters | Correlation co-efficient (r) |
|---|---|
| RMS output of REAG and SIS for PB words | -0.032 |
| RMS output of REAG and SIS for high frequency words | 0.198 |

Note: * = correlation is significant at $p < 0.05$ level.

## 4.6 Test re-test reliability

Test re-test reliability was evaluated on six out of 12 participants. All the data were collected again using the same procedure to check for the test re-test reliability of the data. To test re-test reliability, Cronbach's alpha reliability co-efficient was estimated. It was found that there was good test re-test reliability, i.e., the Cronbach's alpha ranged between 0.7 and 1. This section is subdivided in the following sections.

**4.6.1 Test re-test reliability of REAG with RIC hearing aid**. The test re-test reliability in the REAG measures were all within the acceptable range of 0.7 to 1 except for two conditions. That is, the Cronbach's alpha reliability co-efficient for open dome MPCE condition at 6000 Hz was in terms of negative and for closed dome MPCE at 2000 Hz was 0.26. This suggests that except for these two frequency in the above mentioned conditions, the REAG values indicated good test re-test reliability.

**4.6.2 Test re-test reliability of behavioral aided thresholds and SIS with RIC hearing aid.** In the behavioral aided thresholds data and SIS using PB words and SIS using high frequency words, the Cronbach's alpha reliability co-efficient in all the conditions ranged between 0.8 and 1. This suggests that there was a good test re-test reliability with the behavioral measures in the study.

To summarize the findings,

1. Even though significant differences were not observed for REAG for RIC hearing aid coupled to open dome optimized using MPSE and MPCE, the general trend what followed was that at low frequencies REAG with MPCE was higher than MPSE. Significant difference was observed at 1000 Hz in this condition.
2. Even though significant differences were not expected for REAG for RIC hearing aid coupled to closed dome optimized using MPSE and MPCE, it was present for frequencies 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz and in all of these conditions, REAG with MPCE was higher than MPSE.
3. When comparison of RIC hearing aid with coupled to closed dome and RIC hearing aid coupled to open dome was done, in the conditions were significant differences and also mean differences were present (even though not significant), closed dome had higher REAG than open dome whether optimized with MPSE or MPCE. This was true except for one frequency of 500 Hz where RIC hearing aid coupled to closed dome optimized using MPSE had lesser REAG in comparison to where RIC hearing aid coupled to open dome optimized using MPSE.

4. For behavioral aided thresholds, when comparison was made across conditions, significant differences was not observed for any frequency and when mean values were compared, differences were observed only at 6000 Hz.
5. When comparing behavioral aided and REAG across conditions, significant negative correlations were seen for 6000 Hz and 4000 Hz for RIC coupled to open dome optimized using MPSE and RIC coupled to open dome optimized using MPCE respectively. For RIC coupled to closed dome, significant positive correlations between REAG and aided thresholds were found for low to mid frequencies.
6. Except for one condition having significant positive correlation for RMS output of REAG for RIC coupled to open dome optimized with MPSE and SIS using high frequency words with RIC coupled to open dome optimized with MPSE, none of the other conditions had any significant correlation between RMS output of REAG and SIS.

Table 4.21 summarizes the conditions where statistical significant differences and also clinical significance (when mean values were compared) was seen

**Table 4.21** ***Conditions where statistical significant differences and clinical significance were seen***

| Conditions | Statistical significant difference | Clinical significant difference |
| --- | --- | --- |

| | | |
|---|---|---|
| REAG of RIC coupled to open dome when optimized using MPSE and MPCE | At 1000 Hz<br>MPCE > MPSE | At 300 and 500 Hz<br>MPCE > MPSE |
| REAG of RIC coupled to closed dome when optimized using MPSE and MPCE | At 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz<br>MPCE > MPSE | At 4000 Hz.<br>MPCE > MPSE |
| REAG of RIC coupled to open dome and closed when optimized using MPSE | 500 Hz<br>Open dome > closed dome | 300 Hz, 800 Hz<br>Closed dome > open dome |
| REAG of RIC coupled to open dome and closed when optimized using MPCE | 300 Hz, 3000 Hz, 4000 Hz and 6000 Hz<br>Closed dome > open dome | 500 Hz,<br>Closed dome > open dome |
| Behavioral aided thresholds in all the conditions | No statistical significance | 6000 Hz<br>RIC hearing aid coupled to open dome and optimized using MPCE > RIC hearing aid coupled to open dome and optimized using MPSE |

| | | |
|---|---|---|
| | | RIC hearing aid coupled to open dome and closed dome when optimized using MPCE > RIC hearing aid coupled to open dome and closed dome when optimized using MPSE |
| REAG and behavioral aided thresholds | Open dome MPSE: Significant negative at 6000 Hz<br>Open dome MPCE: Significant negative at 4000 Hz<br>Closed dome MPSE and MPCE: low to mid frequencies significant positive | - |
| RMS output of REAG and PB words and high frequency words | Open dome MPSE: Significant positive for high frequency words | - |

# CHAPTER 5

# Discussion

In the present study, the aim was to compare the behavioral measures with the objective real ear measures for verification of Receiver In the Canal (RIC) hearing aid, coupled with closed and open dome fitting, optimized using two approaches of Sound Field Equalization (SFE), i.e., Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE).

The discussion will be carried out in the following headings,

5.1 REAG of RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE.

5.2 Behavioral aided thresholds with RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE.

5.3 Comparison of behavioral measures and the REAG with RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE.

5.4 Test-retest reliability measure for REAG and behavioral measures.

## 5.1 REAG of RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE

To summarize the findings in the measurement of REAG, there was significant difference observed in the following conditions,

a) The difference in mean REAGs at 1000 Hz of RIC hearing aid coupled to open dome, optimized using MPSE and MPCE.

b) At 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz, when comparing REAG of RIC hearing aid coupled to closed dome optimized using MPSE and MPCE.

c) At 500 Hz, when comparing REAG of RIC hearing aid coupled to open dome and closed dome optimized using MPSE.

d) In 300 Hz, 3000 Hz, 4000 Hz and 6000 Hz, when comparing REAG of RIC hearing aid coupled to open dome and closed dome optimized using MPCE.

In one of the studies conducted by Aazh, Moore, and Prasher (2012), they did not observe any significant difference between the two approaches i.e., MPSE and MPCE with open dome. The measure which they adopted was Real Ear Insertion Gain (REIG). The mean values between the conditions across all frequencies in their study showed how closely they approximated each other. In the present study, the measure used was REAG and here too, the mean values between the two conditions were comparable for all the frequencies.

On the other hand, in another study done by Lantz, Jensen, Haastrup, and Ostergaard (2009), contradictory findings have been established. The objective of their study was to check MPCE approach of SFE was suitable for open fit hearing aid and found that the REIG measurements in MPCE was lesser in comparison to MPSE. In that study they tested with manufacturer prescribed gain for the individual's hearing thresholds as the first condition and maximum gain without audible acoustic feedback (the maximum stable gain, MSG) as the second condition. With the increase in gain the difference between the two approaches was said to increase.

Mueller and Ricketts (2006) in their study stated that when the measured REIG was below 25 dB, there was no difference between the MPCE and MPSE methods where differences were not observed. This could be the reason why in our study the difference was not statistically significant.

In the findings of our study, the REAG at 1000 Hz frequency between the two conditions i.e., RIC hearing aid coupled to open dome and optimized using MPSE and MPCE, is significantly different. When the mean values were compared between the two approaches, the mean with MPCE was higher in comparison to MPSE. Usually the sound leaking from the ear canal elevates the Sound Pressure Level (SPL) at the reference microphone, leading to a reduction in the sound generated by the loudspeaker. In the study by Aazh et al. (2012), it has been opined that the reverse of this can sometimes occur at specific frequencies, at the reference microphone, the leakage signal is out of phase with the signal from the loudspeaker and hence might result in cancellation. This will lead to a decrease in the intensity at the level of reference microphone and subsequent increase in the loudspeaker level. In their study, they don’t mention the frequencies at which it can occur. In the present study, this could be speculated as the reason for the difference.

When comparison across frequencies was done for REAG coupled to open dome optimized using MPSE and MPCE, significant differences were not observed which was also highlighted before. However, if Wilcoxon signed rank test results were considered for 300 Hz and 500 Hz, majority of the participants had higher REAG for RIC coupled to open dome optimized with MPCE in comparison to MPSE. When the mean values for the rest of the frequencies of one condition were compared to their counterparts in the other condition, they were comparable and did not differ much. In a master dissertation done by Sean Lau (University of Southampton), the author quotes that MPCE procedure with open dome might have significant implications for the REM verification because the examiner may not be aware of the fact that the output displayed is invalid when using the MPCE method. This might result in increasing the gain to meet the prescribed fitting target, causing an over-amplification of the frequency region, where the mistake is taking place. This could have led to the differences in the MPCE having higher gain than MPSE in our study though it not statistically significant.

There have been no studies that are done with closed fitting of hearing aid using both the approaches of SFE i.e., MPSE and MPCE. In the present study this was done to check for any differences present when the conditions were used in RIC hearing aid when coupled to closed dome. In the present study, at 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz, the two conditions were statistically different. This kind of result was unexpected given that with closed dome and proper fitting, there is no leakage of sound that occurs and hence with reference microphone enabled or disabled, the REAG shouldn’t be different. In all the frequencies in which significant difference is present, the mean values with MPSE were lesser than that of MPCE procedure. In the study by Aazh et al. (2012), the order of testing which they used was like in our study, i.e., first MPSE and then MPCE. The Lantz et al. (2009) used MPCE procedure first and then MPSE was used for the SFE. This has been quoted as the reason why the different findings has been observed in Aazh et al. (2012) and Lantz et al. (2009). Aazh et al. (2012) state that the reason as to why REIG measured using MPSE were lesser in comparison to REIG measured using MPCE, even though not statistically significant. They state that, the shorter the time interval between measurement of the REUG and the REIG, the less is the likelihood of any significant changes occurring in the sound field. For this reason, in their study it was decided to use the MPSE method before the MPCE method. Though the testing in their study is done using only open dome, the reasons can be generalized to closed dome in the present study. The RIC hearing aid coupled to closed dome optimized using MPSE was the third condition out of the four conditions in the present study. The MPSE approach made use of the leveling value that was done initially and hence could have led to differences in the two conditions i.e., REAG of RIC hearing aid coupled to closed dome optimized using MPSE and MPCE.

When comparing REAG of RIC hearing aid coupled to open dome and closed dome optimized using MPSE, significant difference was observed only for 500 Hz in which majority of the participants had lesser REAG for RIC hearing aid coupled to closed dome optimized using MPSE in comparison to REAG for RIC hearing aid coupled to open dome optimized using MPSE. The reason for the same is unknown and highlights further scope of research.

At 300 Hz, even though statistical significance was not observed, in majority of the participants, REAG for RIC hearing aid coupled to closed dome optimized using MPCE was higher than REAG for RIC hearing aid coupled to open dome optimized using MPSE. The low frequency energy that is trapped inside the ear canal in case of closed dome could be the reason for increase in the REAG at 300 Hz in case of closed dome. In the rest of the frequencies, when comparison was made of the means for the two conditions i.e., REAG for RIC hearing aid coupled to closed dome optimized using MPSE and REAG for RIC hearing aid coupled to open dome optimized using MPSE, though the mean values for RIC hearing aid coupled to open dome was slightly lesser than the mean values for RIC hearing aid coupled to closed dome, they were comparable.

In the last condition i.e., comparison of REAG for RIC hearing aid coupled to closed dome optimized using MPCE and REAG for RIC hearing aid coupled to open dome optimized using MPCE, REAG for 300 Hz was significantly different with ten out of 12 participants having higher REAG in RIC hearing aid coupled to closed dome in comparison to REAG in RIC hearing aid coupled to open dome. In cases of open dome, it is expected for the low frequency energy to escape out which might cause a reduction in the Sound pressure level (SPL) of that frequency. In addition, the sound escaped out will be detected by the reference microphone which reduces the output from the loudspeaker.

For the frequencies 3000 Hz, 4000 Hz and 6000 Hz, activation of feedback management could be one of the reasons. The feedback management was employed for open dome alone as it was impossible to increase the gain of the hearing aid without feedback occurring i.e., Maximum Stable Gain without feedback occurring was lesser. After the feedback management was activated, the amount of gain that could be given in the higher frequency regions reduced. Hence, the REAG in the higher frequency regions for the RIC hearing aid coupled to open dome was lesser than RIC hearing aid coupled to closed dome.

In other frequencies, i.e., 500 Hz, 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz, there was no significant difference that was observed in the REAG. However at 500 Hz, when

Wilcoxon signed rank test was done for pair-wise comparison, majority of the participants had higher REAG for RIC hearing aid coupled to closed dome in comparison to REAG for RIC hearing aid coupled to open dome. This could also be reasoned out that the trapping of low frequency energy within the ear canal in case of closed dome might have led to increase in the REAG. When mean values at 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz were compared between the two conditions i.e., REAG for RIC hearing aid coupled to open dome and REAG for RIC hearing aid coupled to closed dome, and it was seen that they were comparable and did not differ much.

### 5.2 Behavioral aided thresholds with RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE.

When behavioral aided thresholds for each of the conditions were compared, in none of the frequencies and also in none of the conditions, significant differences were observed. When the mean values were compared, in all the comparisons made, the mean values were comparable except at 6000 Hz. At 6000 Hz, the mean values differed when comparisons were made for behavioral aided thresholds with RIC hearing aid coupled to open dome and optimized using MPSE and MPCE and also aided thresholds with RIC hearing aid coupled to open dome and closed dome when optimized using MPSE and MPCE. However, differences were not observed for aided thresholds with RIC hearing aids coupled to closed dome optimized using MPSE and MPCE. As cited earlier in this chapter, Mueller and Ricketts (2006) in their study observed that when the measured REIG was below 25 dB, there was no difference observed between the MPCE and MPSE approaches. However, at 6000 Hz, as the hearing loss in majority cases were more, the target REIG required exceeded 25 dB. When the REIG was matched, the REAG values differed between the conditions. This could have led to differences in the behavioral thresholds as well. In their study, they discussed about the open fit condition only and in the present study too, differences were observed only for RIC hearing aid coupled to open dome.

**5.3 Comparison of behavioral measures and the REAG with RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE.**

When correlation was done for behavioral measures and REAG, the following observations were made,

a) Significant negative correlation between REAG for RIC hearing aid coupled to open dome optimized using MPSE and behavioral aided thresholds with RIC hearing aid coupled to open dome optimized using MPSE at 6000 Hz.
b) Significant negative correlation between REAG for RIC hearing aid coupled to open dome optimized using MPCE and behavioral aided thresholds with RIC hearing aid coupled to open dome optimized using MPCE at 4000 Hz.
c) Significant positive correlation between REAG for RIC hearing aid coupled to closed dome optimized using MPSE and behavioral aided thresholds with RIC hearing aid coupled to closed dome optimized using MPSE at 800 Hz and 1000 Hz.
d) Significant positive correlation between REAG for RIC hearing aid coupled to closed dome optimized using MPCE and behavioral aided thresholds with RIC

hearing aid coupled to closed dome optimized using MPCE at 300 Hz, 800 Hz and 1000 Hz.

e) Significant positive correlation between REAG RMS output for RIC hearing aid coupled to open dome optimized using MPSE and behavioral SIS using high frequency words with RIC hearing aid coupled to open dome optimized using MPSE.

The negative correlation when comparing REAG and behavioral aided thresholds indicate that when REAG increase, the behavioral aided thresholds become better. As the REAG for RIC hearing aid coupled to open dome optimized using MPSE and behavioral aided thresholds with RIC hearing aid coupled to open dome optimized using MPSE at 6000 Hz and REAG for RIC hearing aid coupled to open dome optimized using MPCE and behavioral aided thresholds with RIC hearing aid coupled to open dome optimized using MPCE at 4000 Hz show significant negative correlation, it can be reasoned as to why open fitting hearing aids are considered a better option for sloping hearing loss cases. According to Mueller and Ricketts (2006), if the hearing aid settings remain constant, one can expect “free” high-frequency gain for open fittings, compared with a closed fitting. A practical expectation of an advantage of 5 to 10 dB around the region of peak of REAG is possible.

In case of RIC hearing aid coupled to closed dome, significant positive correlation was observed for 300 Hz, 800 Hz and 1000 Hz. This means to say that, contrary to the expectation, with increase in REAG in these frequency regions, aided thresholds also became poorer. This could be reasoned out that, at low frequencies where the unaided thresholds itself is normal or at least near normal, even with amplification the aided thresholds cannot be any better than the unaided thresholds because the internal noise of the hearing is present. This is the case with closed dome as the amplified low frequencies are trapped within the ear canal and as a result have a masking effect. The concept of cases where aided thresholds becoming poorer than unaided thresholds have been mentioned by Stelmachowicz, Hoover, Lewis and Brennan (2002). In the rest of the frequency comparisons, small to almost no correlations were observed.

A significant positive correlation between RMS output of REAG for RIC hearing aid coupled to open dome optimized using MPSE and behavioral SIS using high frequency words with RIC hearing aid coupled to open dome optimized using MPSE was obtained. This means to say that when RMS output increased, the SIS also increased. The reason that can be stated is because in MPSE approach optimized for RIC hearing aid coupled to open dome fitting, the low frequency energy escapes out of the ear canal and hence does not cause any upward spread of masking of the words. The improvement is more in the high frequency words as the low frequency contents in it itself is low and could have led to better scores and hence positive correlation between the two conditions was noted. In other conditions of correlation between RMS output of REAG and SIS using PB words and high frequency words, the correlations were very small or almost not existing.

### 5.4 Test re-test reliability of REAG and behavioral measures

The Cronbach's alpha to measure the test re-test reliability in the REAG measures were all within the acceptable range from 0.7 to 1 except for two conditions. The Cronbach's alpha reliability co-efficient for open dome MPCE condition at 6000 Hz was in terms of negative. The Cronbach's alpha was measured using closed dome MPCE at 2000 Hz was 0.26. This suggests that except for these two frequencies in the above mentioned conditions, the REAG values are high indicating a good test re-test reliability. According to studies by Ringdahl and Lejon (1984) and also by Hawkins, Alvarez and Houlihan (1991), the insertion gain measurement is a reliable way of verification. The test re-test reliability is good and the REIG was found to be within 1 to 5 dB according to these studies. The reason for reduced Cronbach's co-efficient for REAG of RIC hearing aid coupled to closed dome optimized using MPCE could be indicated by the ear canal resonance characteristics getting affected in case when closed dome. When the ear canal length reduces, the resonant frequency also reduces to a lower frequency. This concept is supported by Muller and Rickets (2006). The resonant frequency is again dependent on the individual's ear canal dynamics. This might have contributed in the poor test re-test reliability in that frequency. However, poor test re-test reliability at 6000 Hz is still remains unexplained.

In the behavioral aided thresholds data and SIS using PB words and SIS using high frequency words, the Cronbach's alpha reliability co-efficient in all the conditions were ranging from 0.8 to 1. This suggests that there was a good test re-test reliability with the behavioral measures in the study. Humes and Kirn (1990) in their study drew conclusion that the test re-test reliability is poor for behavioral aided thresholds. However, in the present study, a good test re-test was observed for behavioral aided thresholds.

# CHAPTER 6

## Summary and Conclusions

The aim of the study was to compare the behavioral measures with the objective real ear measures for verification of Receiver In the Canal (RIC) hearing aid, coupled with closed and open dome fitting, optimized using two approaches of Sound Field Equalization (SFE), i.e., Modified Pressure Stored Equalization (MPSE) and Modified Pressure Concurrent Equalization (MPCE).

The Real Ear Aided Gain (REAG) and behavioral aided thresholds data for the study were collected in four aided conditions. They include -

a) RIC hearing aid with open dome optimized using MPSE
b) RIC hearing aid with open dome optimized using MPCE
c) RIC hearing aid with closed dome optimized using MPSE
d) RIC hearing aid with closed dome optimized using MPCE

The data were tabulated and analyzed using Statistical Package Social Sciences (SPSS version 20) software. Summary of the findings are given in the following section.

### 6.1 REAG of RIC hearing aid coupled to open dome and closed dome across different aided conditions i.e., when optimized using MPSE and MPCE

1. Even though significant differences were not observed for REAG for RIC hearing aid coupled to open dome optimized using MPSE and MPCE, the general trend what followed was that at low frequencies REAG with MPCE was higher than MPSE. Significant difference was observed at 1000 Hz in this condition.

2. Even though significant differences were not expected for REAG for RIC hearing aid coupled to closed dome optimized using MPSE and MPCE, it was present for frequencies 300 Hz, 500 Hz, 800 Hz, 1000 Hz, 1500 Hz and 2000 Hz and in all of these conditions, REAG with MPCE was higher than MPSE.
3. When comparison of RIC hearing aid with coupled to closed dome and RIC hearing aid coupled to open dome was done, in the conditions were significant differences and also mean differences were present (even though not significant), closed dome had higher REAG than open dome whether optimized with MPSE or MPCE. This was true except for one frequency of 500 Hz where RIC hearing aid coupled to closed dome optimized using MPCE had lesser REAG in comparison to where RIC hearing aid coupled to open dome optimized using MPSE.

### 6.2 Behavioral aided thresholds with RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE

For behavioral aided thresholds, when comparison was made across conditions, significant differences was not observed for any frequency and when mean values were compared, differences were observed only at 6000 Hz.

### 6.3 Comparison of behavioral measures and the REAG with RIC hearing aid coupled to open dome and closed dome across different conditions i.e., when optimized using MPSE and MPCE.

1. When comparing behavioral aided and REAG across conditions, significant negative correlations were seen for 6000 Hz and 4000 Hz for RIC coupled to open

dome optimized using MPSE and RIC coupled to open dome optimized using MPCE respectively. For RIC coupled to closed dome, significant positive correlations between REAG and aided thresholds were found for low to mid frequencies.

2. Significant positive correlation between RMS output of RIC hearing aid coupled to open dome optimized using MPSE and behavioral SIS using high frequency words with RIC hearing aid coupled to open dome optimized using MPSE.

### 6.4 Test-retest reliability of REAG and behavioral measures

1. The test retest reliability in the REAG measures were all within the acceptable range of 0.7 to 1 except for two conditions. The Cronbach's alpha reliability co-efficient for open dome MPCE condition at 6000 Hz was in terms of negative and for closed dome MPCE at 2000 Hz was 0.26. This suggests that except for these two frequency in the above mentioned conditions, the REAG values are high and indicated good test retest reliability.
2. In the behavioral aided thresholds data and SIS using PB words and high frequency words, the Cronbach's alpha reliability co-efficient in all the conditions were within 0.8 to 1. This suggests that there was good test re-test reliability with the behavioral measures in the study.

### 6.5 Clinical implications

a) The study did not find statistical significant differences with the use of MPSE and MPCE approach for open dome measurement condition. However clinical differences seen.

b) However, there were differences found for MPSE and MPCE approach for closed dome measurement condition.

## 6.6 Future directions

a) The study could be replicated on a larger group of adults, older adults. Further, to take up more participants to make the test findings more valid.

b) The unexplained differences in a few conditions could be taken up as further study.

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