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Real Ear to Coupler Differences in Children and The Effects of Hearing and Microphone Location

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THESIS APPROVAL

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ABSTRACT

An abstract of the thesis of Cindy Richardson for the Master of Science in Speech Communication: Speech and Hearing Science presented July 18, 1997.

Title: Real Ear to Coupler Differences in Children and the Effects of Hearing Aid Microphone Location.

The early identification of hearing loss and selection of appropriate amplification are the most important goals for children with hearing impairment. Selection of appropriate amplification for a pediatric population involves maximizing the hearing impaired child's residual hearing, for development of speech and language. In addition, it is important to consider the acoustic differences between the 2 cc coupler versus the real ear.

During the hearing aid selection process, it is customary to predict how a hearing aid will respond in the real ear, based upon a given 2 cc coupler response. Killion and Monser (1980) developed a formula for converting the 2 cc coupler response of a hearing aid to a real ear insertion response, or conversely, a real ear insertion response to a 2 cc coupler response. This formula was designed to account for the real ear to coupler difference and the effects of hearing aid microphone location. A body of standardized corrections for the real ear to coupler difference and hearing aid microphone location effects is available. However, due to errors which may be introduced when utilizing standardized corrections, several researchers have recommended the use of individualized corrections.

The primary purpose of the present study was to quantify real ear to coupler differences in a pediatric group, and evaluate a technique for deriving hearing aid microphone location effects in hearing impaired children. The real ear to coupler difference was measured in ten children and the hearing aid microphone location effects were measured for fourteen behind-the-ear hearing aids.

Results demonstrated that the RECD was statistically significant and increased as a function of frequency. Large individual variation in the RECD was noted, particularly in the high frequencies. These results demonstrate the limitations of the 2 cc coupler in predicting the real ear response.

The hearing aid microphone location effect results revealed large negative values and large intersubject variability. Inspection of these data, indicate little consistency with other published studies. The RECD and hearing aid microphone location effect results indicate that corrections are necessary when selecting amplification for children. The implications of using standardized versus individualized corrections are discussed for the RECD and aid microphone effect.

REAL EAR TO COUPLER DIFFERENCES IN CHILDREN
AND THE EFFECTS OF HEARING AID MICROPHONE LOCATION

by

CINDY RICHARDSON

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Chapter 1

Introduction

The early identification of hearing loss and selection of appropriate amplification are perhaps the most important goals for hearing impaired children. Children depend upon their visual, auditory, and kinesthetic experiences to achieve many developmental milestones. Auditory experiences, however, are the most important for the development of speech and language. A hearing loss results in a reduction of sound, and consequently the auditory modality is a less effective means of learning for a hearing impaired child.

The effects of a severe sensorineural hearing loss on children are well documented (e.g., McCaffrey & Sussman, 1994; Steffens, Eilers, Fishman, Oller, & Urbano, 1994; Waldstein & Baum, 1994). Sensorineural hearing loss not only results in a reduction of the acoustic signal perceived by the child, but degradation or loss of clarity of the signal often occurs as well. It appears that the degraded acoustic signal denies the child access to information regarding the content, form, and use of language (Seyfried, Hutchinson, & Smith, 1989). Thus, in hearing impaired children, the normal progression of speech and language is disrupted depending upon the extent of the hearing loss (Ross, Brackett, Maxon, 1991).

The past and present research demonstrates that even a mild conductive or sensorineural hearing impairment can have detrimental effect on a child's life. The goal for every hearing impaired child is to provide them with appropriate amplification in order to facilitate cognitive, speech and language, and academic growth. This requires that the child's residual hearing be maximized to ensure that the spectrum of speech is audible (Ross & Seewald, 1988).

Presently, many children may not be receiving appropriate amplification from their hearing aids (Gilmer, 1995; Snik & Stollman, 1995). There are two main reasons why this may occur. First, the majority of prescriptive hearing aid fitting formulas require audiological information which young children may be incapable of providing, such as most comfortable loudness (MCL) and loudness discomfort levels (LDL). In addition, even when prescription formulas require only the child's audiometric thresholds, this information is often limited since thresholds may be based on results from soundfield testing, auditory brainstem response (ABR) testing, and otoacoustic emissions (OAE's). Auditory Brainstem Response testing and otoacoustic emissions are useful because they allow audiologists to test infants and young children who are unable to provide a response necessary for behavioral tests. However, these tests are somewhat limited because they only allow objective assessment of auditory function. Furthermore, soundfield tests, ABR, and OAE tests do not provide frequency specific information which can be provided by a traditional pure tone audiogram.

A second reason why hearing impaired children may not be fit with appropriate amplification is because selection of specific devices is often based upon average data measured in a 2 cc coupler. Prescriptive fitting formulas provide a recommended real-ear frequency response based upon the subject's audiometric information. However, selecting a hearing aid to match this prescription involves converting the recommended real-ear target to a 2 cc coupler based target. This is necessary because hearing aid specifications are always reported as coupler based responses.

The 2 cc coupler is a hard-walled metal cavity with a total volume of two cubic centimeters. The purpose of the coupler is to promote standardization during the manufacturing process of hearing aids, and allow hearing aid dispensers a means of confirming that the electroacoustic responses of hearing aids meet manufacturers specifications. In addition, the coupler allows verification of the hearing aid response with a prescribed target prior to fitting. The coupler was not designed to simulate the acoustic resonating characteristics of the human ear, (Egolf, Kennedy, & Larson, 1992; Green, 1988; Killion & Monser, 1980) in particular a child's ear.

In the hearing aid selection process, audiologists typically attempt to predict the real ear insertion response of a hearing aid from a 2 cc coupler response. The real ear insertion response of a hearing aid is derived from a conversion formula which accounts for the acoustic differences between the coupler and the real ear. The formula includes corrections for four critical factors: (a) the real ear to coupler difference, (b) the loss of pinna and ear canal resonance characteristics due hearing aid insertion, (c) the hearing aid microphone location effect, and (d) the tubing and venting effects of the hearing aid plumbing (Fikret-Pasa & Revit, 1992). These conversion formulas are typically based upon the acoustic characteristics of an average adult ear. Unfortunately, large differences can be expected in the acoustic response of a child versus an adult ear (Nelson-Barlow, Auslander, Rines, & Stelmachowicz, 1988; Feigin, Kopun, Stelmachowicz, & Gorga; 1989). Thus, utilizing available conversion formulas can introduce large errors into the hearing aid selection process for a pediatric patient (Egolf, Kennedy, & Larson, 1992).

In an attempt to avoid errors introduced through the use of standardized conversions, several researchers have recommended the use of individualized conversion values to predict real ear responses from 2 cc coupler responses (Egolf, Kennedy, & Larson, 1992; Moodie, Seewald, & Sinclair, 1994; Fikret-Pasa & Revit, 1992). Of the four characteristics described above, estimation of an individual's insertion loss is easily derived during the real ear measurement process (Kruger & Ruben, 1987). Clinical measurement of the real ear to coupler difference has been described, but it has not been a widely used process (Moodie, Seewald, & Sinclair, 1994). No feasible means of clinically predicting microphone location or plumbing effects have been described in the literature.

The primary goal of this study was to (a) quantify the real ear to coupler differences in a pediatric group, and (b) evaluate a technique for deriving hearing aid microphone location effects in hearing impaired children. It was also hoped that the present study would offer insight regarding the feasibility of improving the hearing aid selection process for hearing impaired children, through the use of individualized real ear to coupler conversions.

Chapter II

Review of the Literature

This review includes a summary of hearing aid selection formulas and discusses a method for predicting the response of hearing aids in real ears. Hearing aid verification procedures are also discussed, with particular emphasis on probe microphone measurements. The remainder of the review includes a discussion of the real ear to coupler difference and factors which comprise the real ear to coupler difference. The implications of the real ear to coupler difference will be addressed in terms of meeting the amplification needs of children.

Hearing loss affects nearly all facets of a child's life. Research has demonstrated that hearing impaired children may have deficiencies in visual-perceptual ability (Clark & Leslie, 1971; Marshall, 1970), psycholinguistic ability (Balow, Fultin, & Peploe, 1971), psychosocial development (Meadow, 1976), semantic-pragmatic skills (Skarakis & Prutting, 1977), and academic achievement (Webster & Ellwood, 1985; Furth, 1966). Reading is a specific area of deficiency which has been well-studied in hearing impaired children (Boothe, Lasky, & Kricos, 1982; Furth, 1966; Myklebust, 1960, Trybus & Karchmer, 1977). Several researchers have suggested that inadequate reading skills may be one of the main reasons for reduced academic achievement (Boothe, Lasky, & Kricos, 1982; Furth, 1966; Myklebust, 1964, Trybus & Karchmer, 1977, Vernon, 1972). There appears to be a strong relationship between the severity of hearing loss and academic performance (Ross, Brackett, & Maxon, 1982). The more severe the hearing loss, the greater the likelihood for developmental deficiencies. The goal for every child with a hearing impairment, is to maximize their cognitive, speech and language, and academic potential. It is critical that the hearing loss be identified early and appropriate amplification be selected for the fitting.

The selection of appropriate amplification requires the use of formalized hearing aid selection formulae specifically designed for children. In addition, specific measures should be taken to account for the acoustic differences between the real ear and 2 cc coupler, as hearing aid characteristics are specified in terms of the 2 cc coupler. Objective verification of hearing aid performance in the real ear may be achieved with probe microphone measurements. Finally, in order ensure that children receive optimal benefit from their hearing aids, re-assessment of the child's hearing and monitoring of amplification should be routinely performed by the audiologist.

Hearing aid selection procedures

The most widely accepted approach to hearing aid selection involves the use of prescriptive formulas. Several popular prescription formulas include the National Acoustics Laboratory-Revised method (NAL-R), (Byrne & Dillion, 1986), Prescription of Gain and Output (POGO), (McCandless & Lyregaard, 1983), and the Desired Sensation Level approach (DSL), (Seewald, Ross, & Spiro, 1985).

The basic rationale behind prescriptive procedures is that an optimal hearing aid fitting should result when conversational speech is amplified to within the individual's most comfortable listening range. A consistently audible and undistorted speech signal is an important consideration in any hearing aid fitting. However, providing an audible and undistorted speech signal is particularly important for infants and young children with hearing loss to facilitate speech and language development. The Desired Sensation Level (DSL) approach is one prescriptive formula specifically designed for children (Seewald, Ross, & Spiro, 1985).

Hearing aid prescription formulas typically prescribe an estimated real ear insertion response and/or real ear insertion gain of hearing aids. The real ear insertion response (REIR) refers to the net increase in sound pressure level provided to the ear canal by a hearing aid, as compared to the natural open ear, for a given sound source outside the ear (Valente, 1994). The real ear insertion gain (REIG) refers to the *difference* in dB, as a function of frequency, between the real ear unaided response and the real ear aided response at the same point near the tympanic membrane (Stach, 1997).

Since hearing aid manufacturers specify the gain and output characteristics of hearing aids in a 2 cc coupler, it is necessary to transform the estimated real ear insertion response to target 2-cc coupler values and make corrections for acoustic differences between a real ear and the 2 cc coupler (RECD).

Correcting for the RECD

Killion & Monser (1980) proposed a method for transforming a prescribed real ear insertion response (REIR) to a target 2 cc coupler response. This method is formally referred to as CORFIG, or coupler response for flat insertion gain. The CORFIG correction was designed to describe the 2-cc coupler response which is required of a hearing aid to produce a flat real-ear insertion response curve for a hypothetical "average subject" (Killion & Revit, 1993). The formula was designed to correct for the natural resonance of the pinna, concha, and external ear which is lost when the hearing aid is inserted in the ear, the increase in sound pressure level entering the hearing aid microphone due to various hearing aid microphone locations, and the impedance and volume difference between a real ear and the 2-cc coupler.

The 2 cc coupler underestimates gain relative to real ear gain at most frequencies. Therefore, the CORFIG correction is subtracted from a coupler curve to predict the real ear insertion response of a hearing aid. Conversely, the CORFIG curve may be added to a real ear insertion response to predict a 2 cc coupler response.

Several researchers have published normative data (CORFIG's) for behind-the-ear (Burnett, 1989; Hawkins, Montgomery, Prosek, & Walden, 1987; Zemplenyi, Dirks, & Gilman, 1985), in-the-ear (Burnett & Beck, 1987; Mason & Popelka, 1986), and in-the-canal hearing aids (Bentler & Pavlovic, 1989; Lybarger

& Teder, 1986). Many commercial probe microphone measurement systems automatically apply a set of average correction curves when determining the desired real ear insertion response of a hearing aid.

The use of standardized correction factors have gained wide acceptance and are presently used in most clinics where hearing aid dispensing occurs. However, some researchers have questioned the accuracy of applying standardized correction factors to individual real ear to coupler differences (Egolf, Kennedy, & Larson, 1992; Fikret-Pasa & Revit, 1992). The published data of standardized correction curves are all based upon average adult data (Bentler & Pavlovic, 1989; Burnett, 1989; Burnett & Beck, 1987; Hawkins, Mason & Popelka, 1986; Montgomery, Prosek, & Walden, 1987; Zemplenyi, Dirks, & Gilman, 1985; Lybarger & Teder, 1986). Only one study has established normative data to correct for the RECD in children (Seewald, Ross, & Stelmachowicz, 1987). Egolf, Kennedy, & Larson (1992) stated that "due to the variability of ear-canal geometry and eardrum impedance among individuals, the possibility of any one person exhibiting average characteristics is unlikely, especially if that person is a child and/or has a conductive pathology" (p. 2813).

Several researchers have advocated the use of individual real ear to coupler difference measures as opposed to standardized corrections to improve the accuracy of hearing aid fittings (Egolf, Kennedy, & Larson, 1992; Fikret-Pasa, & Revit, 1992; Moodie, Seewald, & Sinclair, 1994). However, at the present time, there are no studies comparing the accuracy of applying individual versus standardized corrections.

Hearing aid Verification

Since 1940, research efforts have been directed at developing a way to scientifically measure the benefits of amplification (Carhart, 1946; Watson & Knudson, 1940). Traditional approaches of hearing aid verification were primarily subjective measures which involved the comparison of several pre-selected hearing instruments. Carhart (1946) developed an approach in which the aided performance of speech testing was compared in several hearing aids. In this method, several hearing aid circuits were compared and the hearing aid which yielded the highest speech recognition score was ultimately chosen for the patient. Other comparison approaches followed, which were essentially modifications of Carhart's procedure, such as the master hearing aid (Berger, 1980; Watson & Knudson, 1940), and paired comparison approach, Zerlin's study (as cited in Kuk, 1994).

Another subjective verification technique which is still used in many clinical audiology settings is functional gain. Functional gain testing is a psychoacoustic or behavioral measure and refers to the difference in decibels between aided and unaided sound field thresholds (McCandless, 1994).

Functional gain is a convenient clinical verification strategy particularly for young children since it can be performed using visual reinforcement audiometry

(Hawkins & Northern, 1992, p. 166). However, this verification method has several limitations. First, functional gain testing is a behavioral measure and, therefore, is subject to variables associated with client participation, such as listener motivation and familiarity with the task. Second, functional gain does not allow the examiner to obtain ear specific information unless the non-test ear is masked or occluded. While the use of headphones for masking can easily be used with an adult, young children often will not tolerate the use of headphones to mask the non-test ear. Therefore, the audiologist can not be certain whether thresholds from a soundfield test with a child, are a binaural response or a response, of the ear with better hearing. Third, some studies have demonstrated that functional gain testing shows high inter-subject variability (Hawkins, Montgomery, Prosek, & Walden, 1987; Humes & Kirn, 1990). Hawkins, Montgomery, Prosek, & Walden investigated aided sound field thresholds and found that in order for two sets of aided thresholds to be statistically different, a 15 dB difference between the two sets of aided thresholds must be present. The results of this study indicate that the test-retest reliability of soundfield thresholds is poor.

There is general acceptance among researchers that an objective means of verifying hearing aids is necessary. As early as 1942, Romanow developed the 2 cc coupler which later became the reference for standardized electroacoustic hearing aid measurements for the American National Standards Institute (ANSI S3.7-1973; ANSI S3.22-1987). The development of the 2 cc coupler eventually led to the design of the Zwislocki coupler which attempted to simulate characteristics of a real ear (Zwislocki, 1970). Further advances in objective hearing aid verification occurred with the invention of the Knowles Electronics Manikin for Acoustic Research (Burkhard & Sachs, 1975).

Comparison of Hearing aid Verification Techniques

The most recent objective verification method was developed by Harford in 1982, and is referred to as probe microphone measurement or more commonly, real ear measurement. Real ear measurement involves placement of a thin plastic probe-tube in the ear canal close to the tympanic membrane. The probe tube is connected to a recording microphone which measures the sound pressure level in the ear canal.

There are many benefits to using real ear measurement, particularly with young children. Seewald (1990) summarized three distinct benefits of real ear measurement as opposed to traditional subjective verification techniques. Real ear measurement offers (a) better frequency resolution, (b) enhanced reliability and efficiency, and (c) requires a lower level of cooperation from the child. Northern and Downs (1991) noted additional advantages including verification of the hearing aid maximum power output, knowledge of the sensation level of the long term spectrum of speech, and the ability to analyze amplification provided to each ear separately. One of the most significant contributions that real ear measurement has offered, is knowledge of intersubject and intrasubject variabilities which exist with regard to ear canal volume, external ear resonance, and eardrum impedance (Tecca, 1994).

There are several studies which have compared subjective and objective hearing aid verification techniques. The majority of these studies have indicated that real ear measurement provides the highest degree of accuracy and reliability of any verification method (Nelson-Barlow, Auslander, Rines, Stelmachowicz; 1988; Dillion & Murray, 1987; Green, 1988; Humes & Kirn, 1990; Westwood & Bamford, 1995; Hawkins, Montgomery, Prosek, & Walden, 1987).

For example, Dillion and Murray (1987) investigated several subjective and objective hearing aid verification methods and compared the accuracy of these methods in estimating real ear gain. A total of 12 methods were examined which involved four different methods of functional gain, four probe microphone systems, and three coupler designs, along with KEMAR.

Their results indicated that probe microphone measurements yielded more accurate and reliable results when compared to any of the coupler types or the functional gain methods. In addition, all of the couplers showed more accurate real ear gain than the functional gain methods, and the real ear gain of KEMAR was approximately equal to the couplers.

Although real ear measurement is regarded as the most accurate means of assessing real ear hearing aid performance, the 2 cc coupler remains an important part of the hearing aid fitting process. The 2 cc coupler is useful to manufacturers because it serves as a reference for determining the electroacoustic response of each hearing aid designed. It is also useful to audiologists for monitoring the functional status of the hearing aid and verifying that the hearing aid meets technical specifications. However, using the 2 cc coupler does not ensure that appropriate amplification will be delivered to the individual with a hearing impairment. Use of the 2 cc coupler in combination with real ear measurement allows audiologists to individualize the hearing aid fitting. Adjustments to the hearing aid or earmold can be made according to how the hearing aid amplifies in the real ear versus the 2 cc coupler.

Real Ear to Coupler Difference

The theoretical basis for measuring the real ear to coupler difference is that in order to increase the likelihood that a hearing aid will provide accurate amplification, all potential sources of variability should be taken into consideration. The real ear to coupler difference (RECD) is one source of variability and is comprised of three factors: (a) ear canal volume, (b) external ear resonance, and (c) eardrum impedance. The RECD is defined as "the difference between the sound pressure level developed in an ear canal versus a coupler owing to differing acoustic load impedances" (Valente, 1994, p. 409). Additional sources of variability include the hearing aid microphone location effect, and the acoustic coupling device and venting of the hearing aid.

Considerable research efforts have focused on quantifying RECD's (Berniger, Overgard, & Svard, 1992; Hawkins, Cooper, & Thompson, 1990; Hayes, 1993; Mason & Popelka, 1986). In 1972, Sachs & Burkhard studied RECD's in five adult ears and found that coupler gain consistently underestimated real gain for frequencies above 1 kHz by as much as 15 dB. Hawkins, Cooper, & Thompson (1990) measured RECD's of up to 11 dB. Wetzell and Harford (1983) reported RECD's up to 10 dB above 1 kHz, and Dillion & Murray (1987) showed RECD's of as much as 20 dB in the high frequencies.

The magnitude of the difference (dB) between the 2 cc coupler and the real ear can not easily be predicted. Wetzell and Harford (1983) performed a regression analysis in order to assess the accuracy of the 2 cc coupler in predicting the real ear insertion gain of a hearing aid. Their results indicated that a hearing aid with a coupler gain of 30 dB at 1 kHz, may have an insertion gain anywhere from 7 to 40 dB.

These studies have also found large intersubject standard deviations indicating the wide range of RECD's among adults. For example, Sachs and Burkard (1972) and Hawkins, Cooper, and Thompson (1990) found intersubject standard deviations of 1-5 dB and 2-5 dB, respectively. Dillion & Murray (1987) measured standard deviations of approximately 4-5 dB.

The majority of published literature on RECD's has been performed with the adult population. Few studies have documented RECD's in children, particularly very young children and infants. Furthermore, most pediatric studies have dealt only with specific factors contributing to a portion of the RECD such as the external ear resonance or the real ear unaided response (Kruger & Ruben, 1987; Dempster & Mackenzie, 1990; Bentler, 1989) and the ear canal volume (Northern & Downs, 1978).

Research of the real ear unaided response (REUR) in young children generally shows that the primary frequency of ear canal resonance is higher in comparison to adults. Kruger & Ruben (1987) studied the REUR of infants and found that the average frequency of ear canal resonance was approximately 6 kHz. They also observed that the resonance frequency decreased with age. As infants reached the age of two, the predominant resonance frequency had decreased to 2.5 kHz, which is the average REUR of adults.

Other researchers have supported Kruger and Ruben's findings by demonstrating higher resonant frequencies in young children, which begin to approximate adult values at 9 to 12 months (Upfold & Byrne, 1988; Westwood, & Bamford, 1995). However, Dempster & Mackensie (1990) studied children aged 3 to 12 years and found that the mean resonance frequencies were 3002 Hz for three-year-olds, and 2626 Hz for children above age nine. The age at which the resonance frequency of children in this study approximated the mean adult value was nearly age 7. These results are inconsistent with REUR studies previously discussed.

The predominant frequency of ear canal resonance is believed to be attributed to the length and volume of the external ear (Kruger & Ruben, 1987; Dempster & Mackenzie, 1990). The average length of the external auditory canal (EAC) is approximately 2.5 to 3.0 cm in adults (Bateman & Mason, 1984). In contrast, Kruger et al. found that the length of the EAC in infants under age two ranged from 1.2 cm to 3 cm.

Studies of ear canal volume in children also demonstrate smaller volumes as compared to adults. Margolis and Heller (1987) studied the ear canal volume (ECV) in children aged 3 to 5 years and found a mean ECV of 0.7 cc. Nelson-Barlow, Auslander, Rines and Stelmachowicz (1988) found a mean ECV of .85 cc in children aged 3 to 15 years. Okabe, Tanaka, Hamada, Miura, & Funai (1988) studied ECV's of three-year-old children and found volumes between .3 and .6 cc. The ECV data available for neonates is somewhat limited, although one study showed that the canal volume of neonates never exceeded 0.5 cc (Geddes, 1987). In contrast, adult ECV's are, on average, slightly larger (1.0 cc) (Hall, 1979; Shanks & Lilly, 1981; Zwislocki, 1970).

The studies investigating real ear unaided response and ear canal volume demonstrate that children may have significantly different external ear characteristics when compared to the adult population. In addition, the age at which the external ear canal is fully developed can vary widely among individuals.

Consequently, these differences influence the magnitude of the real ear to coupler difference.

Real ear to coupler differences in children

There are five published studies which have measured RECD's in the pediatric population. One study showed that the average RECD of children aged 3 to 15 years was 11 dB, with a maximum disparity of 23 dB (Nelson-Barlow, Auslander, Rines, & Stelmachowicz; 1988). Feigin, Kopun, Stelmachowiz, & Gorga (1989) studied children under age five and also found discrepancies between the real ear and 2 cc coupler of up to 23 dB in the high frequencies. Two additional studies demonstrated maximum RECD's of 16 dB, which did not exceed RECD's of adults, yet still represents the poor performance of the 2 cc coupler in predicting the real ear response (Harris & Adams, 1989; Westwood & Bamford, 1995).

Some researchers have hypothesized that the small ear canal volume observed in infants and young children is the primary reason for larger RECD's observed in this population (Westwood & Bamford, 1995; Bratt, 1980). To investigate the relationship between the RECD and ear canal volume, Feigin, Kopun, Stelmachowicz, & Gorga (1989) studied 31 children under the age of five. However, their results indicated a negative correlation between ear canal volume and the RECD at all octave test frequencies. They concluded that ear canal volume is not a clinically useful predictor of the RECD and proposed that other factors, particularly middle ear impedance, may account for a greater portion of the total

RECD. Additional researchers have supported this notion (Martin, Westwood, & Bamford, 1996).

Impedance and the RECD

Studies which have specifically examined the relationship between acoustic impedance of the ear and the RECD are limited. However, a number of researchers have compared the acoustic impedance in child and adult ears and found notable differences (Dirks & Kincaid, 1987; Egolf, Feth, Cooper, Franks, 1995; Joswig, 1993; Stinson, Shaw, & Lawton, 1982; Okabe, Tanaka, Hamada, Miura, & Funai, 1988; Keefe, Bulen, Hoberg-Arehart, & Burns, 1993).

Keefe et. al. (1993) studied acoustic impedance of adults and several groups of infants at 1, 3, 6, 12, and 24 months of age. These results showed that the impedance levels between 500 and 4000 Hz of the infants were significantly higher than the adults. For the one month old infants, the impedance levels exceeded adult levels by 9 to 19 dB (0 dB re: 1 cgs ohm). This difference gradually decreased with age, although impedance levels of the 24 month old infants still exceeded adults by 1 to 6 dB.

Okabe, Tanaka, Hamada, Miura, and Funai (1988) studied ear canal impedance in children between 3 and 11 years by measuring both reactance and resistance levels. Reactance refers to the opposition to the flow of energy due to storage whereas resistance refers to the opposition to the flow of energy due to dissipation (Stach, 1997).

The results of Okabe et.al. indicated that the mean resistance levels for all aged children were similar to adults (300 to 350 cgs acoustic ohms). However, the reactance levels of these children were as much as 550 cgs ohms lower than adults for frequencies below 1 kHz, which demonstrates lower compliance. The reactance levels observed in the older children in this study were higher and began to approach adult levels with external and middle ear growth.

Only one study has specifically investigated the relationship between the RECD and acoustic impedance. Martin, Westwood, and Bamford (1996) studied the effects of otitis media with effusion (OME), a high impedance pathology, on the RECD in 14 children between 4 and 7 years of age. They compared one group of children with OME, to a control group of children who did not have OME. These results indicated that the mean RECD's of children with OME were up to 3.5 dB greater between 200 to 3,000 Hz than for children without OME.

It is well-known that there is a high prevalence of otitis media with effusion in children. Estimates of the incidence of OME show wide variability, although most studies suggest that approximately 75% of children will experience at least one episode of otitis media during their preschool years (Feagans, 1992). In addition, as many as one third to one half of all children will experience three episodes of otitis media per year (Feagans, Blood, & Tubman, 1988). It is anticipated that RECD's be greater in children who experience chronic OME, since fluid in the middle ear space, increases the impedance of the eardrum. However, additional studies are necessary in order to determine the degree to which OME increases the RECD.

The studies previously mentioned by Keefe (1993) and Okabe (1988) demonstrate that even infants and children who have normal middle ear function, show higher impedance when compared to adults. Several researchers have provided potential explanations for these findings. Keefe (1993) proposed that the pediatric population may show higher impedance due to ear-canal wall vibration and size of the middle-ear space. He hypothesized that ear canal wall motion may cause significant dissipation of sound energy in the canal walls, which may be greater than the power transfer of sound to the middle ear.

Another reason for higher impedance levels observed in children, may be the size of the middle ear cavity. Moller (1983) reported that the middle-ear cavity of a human adult is significantly larger in volume compared with infants and young children. Keefe et.al. (1993) stated that "the smaller volume of infants and children as compared to adults suggest that the stiffness of the middle ear should be correspondingly larger" (p. 2632). It is presumed that as growth of the middle ear cavity occurs, impedance of the middle ear space decreases. Moller's hypothesis would explain the decrease in the RECD observed in older children.

Hearing Aid Microphone Location Effects

The published literature on hearing aid microphone location and it's influence on the real ear to coupler difference is limited. Hearing aid microphone location effects may have received less attention because this factor typically accounts for less of the total RECD than the other factors. Furthermore, the published studies available for review have utilized several different methods of measuring the effects of hearing aid microphone location. Consequently, making inferences regarding the results of these studies has been somewhat problematic.

Most of the studies measuring microphone location effects have used a direct methods (e.g., Fikret-Pasa & Revit, 1992; Kuhn, 1979). Direct methods measure the sound pressure level in a diffuse field by placing a probe microphone near the pinna for a behind-the-ear (BTE) hearing aid, or at the entrance in an occluded ear canal for an in-the-ear (ITE) aid. For an in-the-canal hearing aid, the probe microphone would be inserted deeper within the canal. The earliest studies investigating microphone location effects used miniature microphones at different locations on the body since probe microphones were not available at the time (Brammer & Percy, 1977; Weiner's study, as cited in Shaw, 1974).

Direct measurements offer the most convenient and reliable way of measuring the sound pressure level at a specified microphone location. However, they may not necessarily provide the most accurate results. Shaw (1974), discussed two problems with direct measurements. First, when probe or miniature microphones are placed near or in an occluded ear as with BTE or ITE hearing aids, the contribution of the pinna, concha, and external ear canal are excluded. Thus, the transfer function from the outer ear to the eardrum can not be determined.

Secondly, direct measurements do not take into account head and body baffle or diffraction effects, since they are performed in a diffuse rather than sound field environment. When a hearing aid is placed in the ear, the surfaces of the body, head, and pinna reflect and absorb sound energy. High frequency energy is often reflected off the head and pinna due to shorter wavelength. The result is an increase in the input level at the hearing aid microphone. The extent of the high frequency boost depends upon how close the hearing aid microphone is to the opening of the ear canal (Revit, 1994).

The indirect method of measuring hearing aid microphone location effect, involves a sound pressure transformation from the sound field to eardrum (Shaw, 1974). Indirect measurements, in contrast to direct measurements, include baffle and diffraction effects. This method is best performed in an anechoic chamber with the subject seated a specified distance from the sound source.

The indirect method involves measuring the sound pressure level with a probe tube microphone or miniature microphone in the ear canal close to the tympanic membrane. A second recording of the sound level in the sound field is made by placing the microphone in the exact location which the subject occupied. The difference between these two measurements is referred to as the free field to eardrum transformation.

Theoretically, an indirect measurement represents the most valid way of determining the effects of hearing aid microphone location because the potential sources of variability are accounted for. Unfortunately, sound field measurements introduce errors due to sound shadows and standing waves which may compromise reliability (Gulick, Gesheider, & Frisina, 1989). Sound shadows occur when sound is reflected off the subject's head and body. While some acoustic energy is absorbed, much is reflected since a human head and body are very dense in comparison to the surrounding medium. Standing waves occur in the ear canal when there is interference between sound waves of the same frequency causing through the addition and subtraction of waves. This results in different amplitudes at various points in the ear canal.

Some studies have compared the aided sound field spectra of different hearing aid types as a means of measuring effects of microphone location (Cox & Risberg, 1986; Gartrell & Church, 1990). These studies placed a miniature microphone close to the microphone of a BTE hearing aid, or embedded the microphone in putty occluding the concha to simulate an ITE hearing aid without the venting. Broadband stimuli was presented in a sound field and the input at each microphone location was stored in a spectrum analyzer. The spectrum measured for the BTE hearing aid microphone was subtracted from the spectrum measured for the ITE hearing aid resulting in a difference curve.

The results of many studies investigating hearing aid microphone location were summarized by Bentler & Pavlovic (1989), and later by Fiket-Pasa & Revit, (1992). Results from a study by Byrne & Dillion in 1986, demonstrated an ITE versus over-the-ear (OTE) advantage of 1-8 dB between 2 and 6 kHz. Libby (1986), indicated an ITE versus OTE advantage of 5-11 dB also occurring between 2 and 6 kHz. The studies utilizing sound field spectra showed less substantial ITE advantages with results of approximately 3-6 dB between 2 and 6 kHz (Cox & Risberg, 1986; Gartrell & Church, 1990). Sullivan (1989) investigated hearing aid microphone locations of in-the-canal (ITC) hearing aids. His results indicated that an ITC hearing aid may provide 5-8 dB of additional gain to the advantage already provided by an ITE aid.

The variability in the amount of acoustic gain associated with behind-the-ear, in-the-ear, and in-the-canal microphone locations ranges from 1 to nearly 20 dB in the high frequencies. The source of variability among studies may be due to the differences in procedures utilized. Nevertheless, these results suggest the need for correction factors. An agreement as to most accurate method for measuring the effects of hearing aid microphone location requires further research. Each procedure discussed has it's limitations, but understanding these limitations may assist in the development of a more precise method.

Acoustic Coupling/Venting and the RECD

Most studies measuring RECD's have utilized insert ear phones to avoid the effects of different earmold types and venting on the RECD (Feigin, Kopun, Stelmachowicz, & Gorga, 1989; Hawkins, Cooper, & Thompson, 1990; Moodie, Seewald, & Sinclair; 1994; Sachs & Burkhard, 1972). Bergman and Bentler (1991) however, cautioned against the use of insert phones when measuring the RECD because the type of earmold and amount of venting also influence the magnitude of the RECD.

Ricketts and Bentler (1995) studied the effects of using standard earmolds on the RECD. The earmolds used in this study were a full-shell type, with a 1-mm parellel vent, a canal length ranging from 12 to 16 mm, and standard #13 tubing. This earmold type was chosen based upon a survey given to all U.S. hearing aid manufacturers regarding the most common earmold type ordered. They compared the output of a moderate-gain behind-the-ear hearing aid coupled to an HA-1 coupler using the standard earmold and the output of the hearing aid on an HA-2 coupler. The HA-1 coupler is a "direct access metal 2 cc coupler for testing ITE and ITC hearing aids and can be used to test a BTE hearing aid when attached to with a custom earmold" (Valente, 1994, p. 404). The HA-2 coupler is designed to test BTE hearing aids and includes 10-mm of standard # 13 tubing which attaches the BTE aid to the coupler.

Their results indicated that when coupling the BTE hearing aid to an HA-1 coupler using the standard earmold, the output of the hearing aid was approximately 7-9 dB less in the 2 kHz range than when the hearing aid was coupled to the HA-2 coupler. Ricketts and Bentler stated that the use of an earmold may cause loss of amplified sound to the hearing aid user at 2 kHz. Therefore, if the output of a BTE hearing aid is measured on an HA-2 coupler, the amount of high-frequency output may be over-estimated by up to 9 dB. This has important clinical implications when selecting the desired gain and frequency response of BTE hearing aids.

The effects of earmold venting on the RECD were extensively studied by Dillion (1991). Dillion published a detailed study investigating the venting affects on real ear insertion gain and coupler gain. In this study, the vent size of one standard earmold was systematically varied and coupler measures as well as real ear measures were performed on five subjects. The results indicated that venting had predictable effects on the real ear response of hearing aids in the low-frequencies. However, the effects of venting are often unpredictable in frequencies above 1 kHz. Dillion reported that the variable affects of venting in the high frequencies may be caused by interaction between the acoustic wavelength of the sound being amplified and the resonance of the vent.

In summary, the real ear to coupler difference is a source of variability which can contribute to large errors in the selection of amplification, particularly in a pediatric population. The real ear to coupler difference consists of the differences in volume, impedance, and resonance characteristics of the 2 cc coupler versus the real ear. The location of the hearing aid microphone and acoustic venting and coupling of the hearing aid are two additional sources of variability, which may also introduce errors into the hearing aid selection process. Researchers have advocated making individual RECD measurements prior to hearing aid selection, and applying individual versus standardized corrections (Egolf, Kennedy, & Larson, 1992; Fikret-Pasa, & Revit, 1992; Moodie, Seewald, & Sinclair, 1994). At present, however, there are no studies verifying that the application of individual RECD corrections result in a more accurate hearing aid fitting.

Summary and Conclusions

Hearing loss affects nearly all facets of a child's life including cognitive, academic, and speech and language development. In order to maximize the hearing impaired child's cognitive, academic, and speech and language development, early identification of the hearing loss with selection and fitting of appropriate amplification are critical. The selection of appropriate amplification requires the use of formalized prescriptive formulae specifically designed for children and use of probe microphone measurements verifying the hearing aid prescriptions have been met. Specific measures should be taken to account for the acoustic differences between the real ear and 2 cc coupler, as well as the effects of hearing aid microphone location and acoustic coupling and venting of the hearing aid. Finally, in order to ensure that children receive optimal benefit from their hearing aids, the audiologist should perform periodic re-assessment of the child's hearing and monitoring of amplification.

Chapter III

Methods

Subject Recruitment

Ten children between the ages of four and eight with unilateral and/or bilateral sensorineural hearing loss served as participants in this study. Eight of the children were recruited from the Washington and Oregon schools for the deaf. One child was recruited from the Portland State University Aural Rehabilitation Clinic and one child was referred to the study by a local otolaryngology clinic. A total of 16 ears were included in the study. This study required only probe microphone measurements of each participant to measure the real ear to coupler difference and hearing aid microphone location effects. The real ear to coupler difference and hearing aid microphone location effect are independent of the child's degree of hearing loss. Therefore, the audiometric thresholds of each child were irrelevant.

Instrumentation

Real ear measurement equipment utilized for data collection involved the Fonix 6500-CX Hearing aid test system. The system is comprised of a main computer processor with color video monitor, acoustic test box, and a loudspeaker which is connected to a floor stand. Necessary accessories to the Fonix system were the MI550E condenser microphone, remote control module, ear level hearing aid adapter, dual microphone cable, (reference and probe a microphones) and several connecting cables.

Equipment Calibration

The Fonix equipment was professionally calibrated prior to data collection. A total of six calibration checks were completed over a period of four months throughout the data collection process.

To calibrate the probe microphone, a standard plastic tube was connected to the body of the probe microphone. The tube was carefully threaded through a 14 mm calibration adapter allowing the probe tube to extend approximately 3 mm beyond the edge of the adapter. To secure the probe tube, a small piece of putty was applied where the tube extended from the adapter. The 14 mm adapter was placed within a 1-inch metal adapter and both were inserted into a Bruel & Kjaer (B&K) piston phone. Figure 1 shows a cross section of the probe tube in the probe calibrator adapter. The B&K piston phone was set to produce a reference signal of 124 dB SPL. Probe microphone output level was revealed on the video monitor and adjustments were made on the rear panel of the remote module to assure a measured level of 124 dB SPL. Each calibration check was completed once daily prior to performing any probe microphone measurements.

Design and Procedure

Data were collected at three different test sites. Six of the children were tested at the Washington and Oregon Schools for the Deaf and the remaining four children were tested at the Portland State University Audiology Clinic. At all test sites, data were collected in sound-treated booths. Each session required approximately 20 to 30

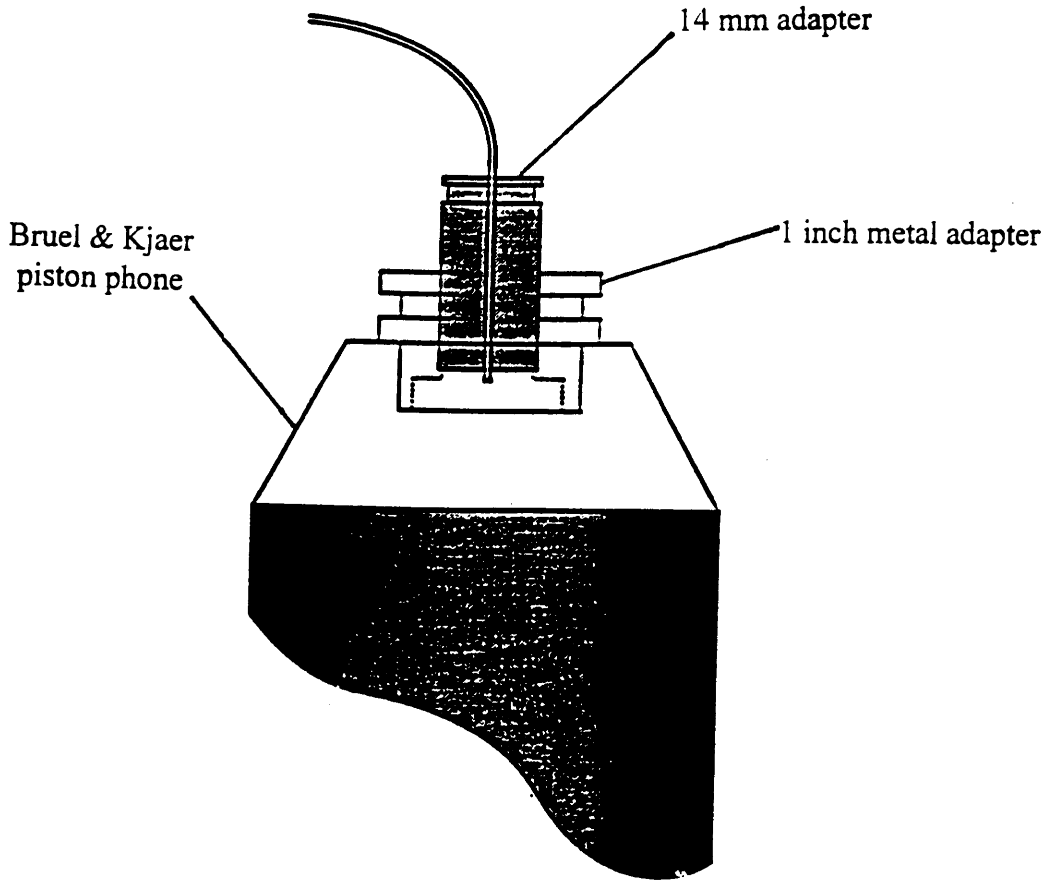


Figure 1. Cross section of probe tube in probe calibrator adapter.

minutes per child. Prior to performing real ear measurement tests, otoscopy and tympanometry were completed in order to rule out the presence of cerumen or middle ear pathology. Tympanograms met criteria for this study if static compliance results were between .25 to 1.5 mmhos and resting middle ear pressure was between -200 daPa and +50 daPa. Two subjects showed tympanograms with borderline-normal resting pressure values, but were included in the study. In addition, two other subjects showed excessive cerumen in the external canal. In these cases, parents of the children were advised to seek cerumen removal by their family physician. These children returned for testing at a later date following cerumen management.

A note was made as to the type and model of each BTE hearing aid to be tested, the hearing aid microphone location, and the volume control setting where test measurements would be made. For all participants, the test volume control settings were lower than use gain settings. The majority of children included in this study were severe to profoundly hearing impaired and, therefore, wore high-power aids at high volume control settings. A low volume control setting was selected in order to avoid the possibility of saturation on the electroacoustic response of the hearing aid during testing.

Soundfield Equalization

Real ear measurement systems customarily use a comparison method of soundfield equalization. A substitution method, as opposed to a comparison method, was utilized in this study in order to include baffle and diffraction effects of the head and body in the total measurement. The Fonix 6500 equipment remained unleveled throughout all probe tube measurements and the reference microphone was disabled.

The soundfield equalization method used in this study was based on that reported by Madsen (1986). The substitution method required suspending the probe microphone body which was attached to the probe tube, from the ceiling of the soundbooth in the exact location that the participant would occupy during probe microphone measurements. Each child was instructed to seat themselves in a chair located approximately 12 to 15 inches from a loudspeaker, which was faced at 45 degrees azimuth. After confirming the appropriate distance between the loudspeaker and the child, the child was removed from the soundbooth. A 70 dB SPL speech-weighted composite signal was produced by the loudspeaker and picked up by the probe microphone. The input to the probe microphone was stored in data form in the memory of the Fonix equipment. For all ten subjects, the soundfield measurement was repeated in order to monitor the stability of the soundfield recording.

<u>Real Ear Measurements</u>

Following the soundfield measurement, each child was seated in the soundbooth at the original location and the distance between the child's head and the loudspeaker was reconfirmed. To make real ear measurements, the probe microphone was secured by a velcro earhook below the pinna. A probe tube was marked according the length of each child's personal earmold so that when it was inserted in the ear canal, the probe tube extended approximately 5 mm from the tip of the earmold. The 70 dB composite signal was presented and measured by the probe tube in the ear canal. The resulting sound pressure level as a function of frequency is the field to eardrum transfer function and for this study was referred to as the real ear unaided response (REUR). This was stored in the memory of the Fonix test equipment.

Next, the child's personal earmold was attached to his or her BTE aid and carefully inserted into the ear canal insuring that the probe tube was not displaced. In some cases, a small amount of petroleum jelly was applied to the earmold to allow easier insertion and to avoid closure of the tube. The hearing aid volume control was secured with adhesive tape to maintain the same position throughout all tests. The same composite signal was presented and the real ear aided response (REAR) was recorded and stored.

Measuring Real Ear to Coupler Difference

In order to measure the real ear to coupler difference an eartip/probe assembly was prepared for each subject. This procedure entailed the use of a soft, foam eartip through which a probe tube was threaded. The probe tube was allowed to extend approximately 5 mm beyond the end of the eartip (Fry Electronics, 1992). Reference marks were made at two points along the probe tube as shown in Figure 2. The eartip/probe assembly was carefully rolled and inserted into the subject's ear canal so that the foam was flush with the ear canal entrance, as seen in Figure 3. The tubing of the eartip was attached to a pair of 10 ohm ER-3A insert phones and plugged into the loudspeaker output on the rear panel of the Fonix. (The Fonix equipment had an impedance load of 50 ohms, which resulted in an impedance mismatch between the Fonix and the ER-3A insert phones. A 40 ohm resistor was soldered to a cable where

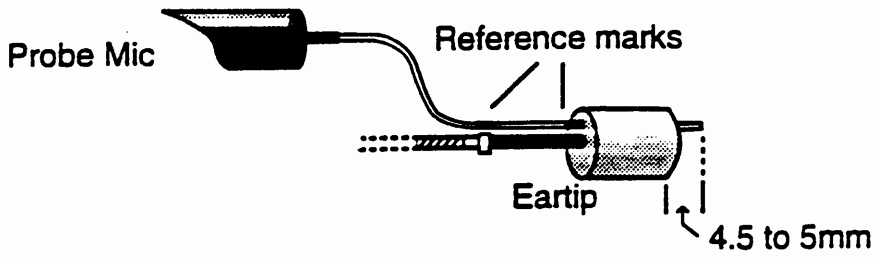


Figure 2. Eartip/probe assembly

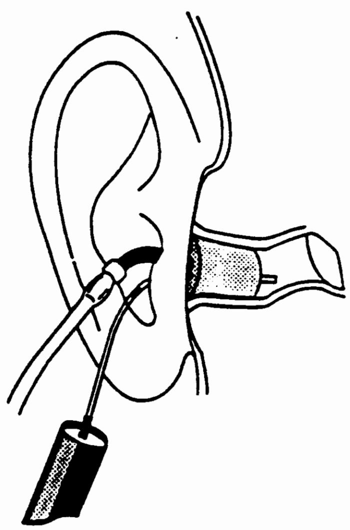


Figure 3. Eartip/probe assembly when inserted in child's ear canal. Reference marks are aligned at intertragal notch.

the plug of the insert phones could be connected. The impedance difference between the Fonix and the insert phones was effectively reduced. The real ear response of the eartip was obtained for the same stimulus conditions in which previous measurements were made.

To obtain the RECD, a standard measurement of the foam eartip/probe assembly on an HA-1 coupler is also necessary. This measurement was obtained once and used for all subjects. The set-up involves threading a probe tube through the bottom of the 14 mm calibrator adapter allowing it to extend approximately 3 mm from the edge. The tube is connected to the probe microphone body and then inserted into the HA-1 coupler, as illustrated in Figure 4. A coupler response of the eartip was obtained and stored. The RECD for each subject is derived by subtracting the coupler response of the eartip from the real ear response of the eartip.

Calculating the Hearing Aid Microphone Location Effect

Most of the studies measuring microphone location effects have used a direct method (Fikret-Pasa & Revit, 1992; Kuhn, 1979). While a direct method is convenient and reliable, it may not be the most theoretically valid approach (Shaw, 1974). This study involved an indirect method of determining hearing aid microphone location effect.

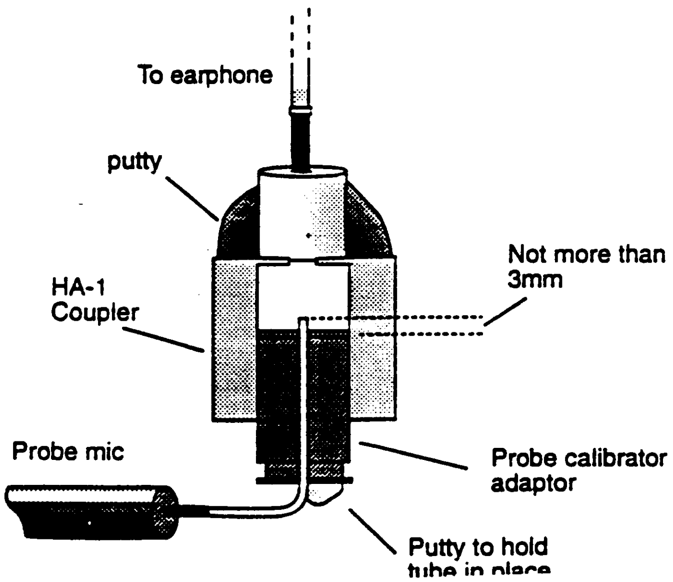


Figure 4. HA-1 coupler measurement of eartip connected to ER-3A insert phone.

(Illustrations from Fry Electronics Hearing Aid Test System Operators Manual. Sections 8-59 to 8-61, with permission.)

According to Revit (1992), the following formula defines the relationship between the real ear insertion response and 2 cc coupler response of a hearing aid:

(1) Predicted REIR = Measured 2ccr + (RECD + Aid microphone effect - REUR), Killion & Revit, (1993).

Permutating the equation as shown below, allows for deriving the microphone location effect using data obtained from previously defined procedures.

(2) Aid microphone effect = Measured REIR - Measured 2ccr - RECD + REUR.

Chapter IV

Results

The primary purpose of this study was to quantify the difference in decibels between the output of an insert earphone in real ears versus the HA-1 2 cc coupler. In addition, the hearing aid microphone location effect for behind-the-ear hearing aids was derived using a formula developed by Killion and Revit (1993).

Results

Field to drum transfer function. The field to drum function was calculated for 16 ears. Figure 5 displays the average field to drum transfer function for this study as well as data from Shaw (1974). An SPL increase relative to the 70 dB SPL composite signal occurred at all frequencies with the largest increase (19 dB) observed at approximately 3000 Hz. These values compare favorably to certain data reported in the literature (Shaw, 1974).

Real ear to coupler difference. Due to time constraints of one test session, the probe microphone measurements necessary for calculating the RECD and aid mic effect could not be completed with one child. Therefore, RECD and hearing aid microphone location effect results were calculated for 14 ears.

The mean RECD's and standard deviations between 250 and 8000 Hz are shown in Table 1. Also shown are means and standard deviations for five studies involving children and one adult study. (The RECD's for this study, present a value at 200 Hz as opposed to 250 Hz because the probe microphone equipment

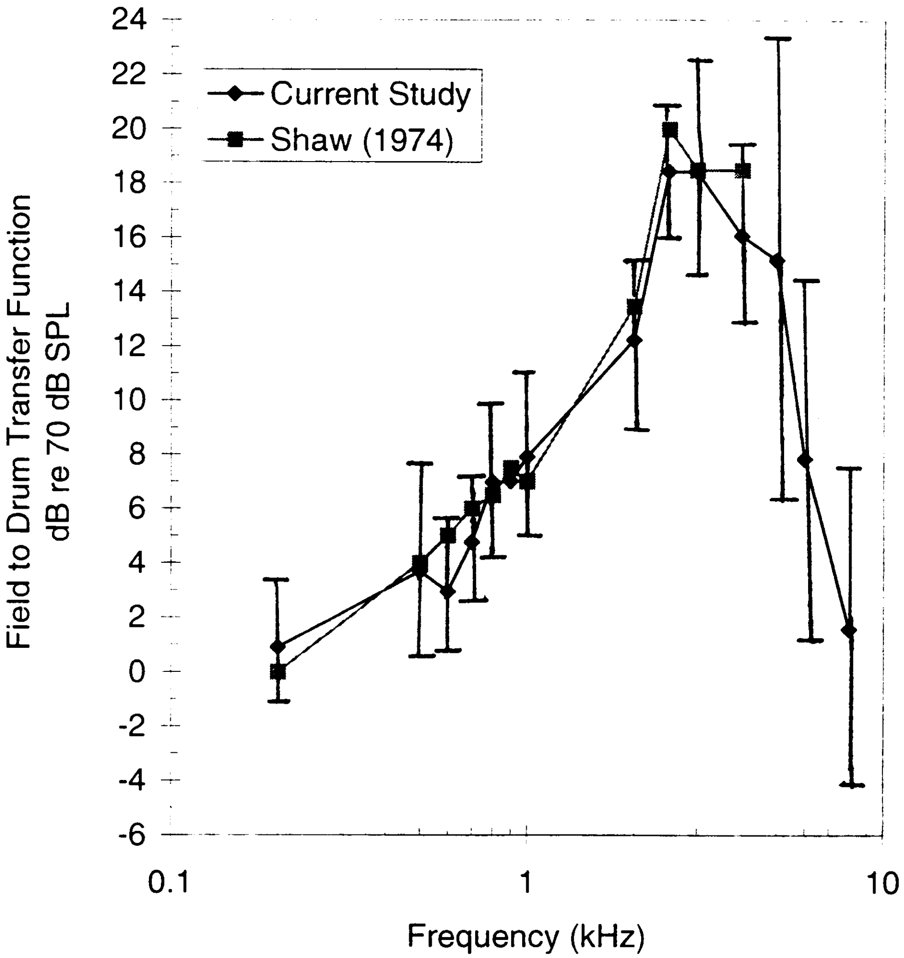


Figure 5. Mean field to eardrum transfer function for 16 ears. Error bars indicate one standard deviation from the mean. Also shown is the mean field to eardrum transfer function for 5 adults (Shaw, 1974).

Table 1

Mean Real ear to Coupler Difference (dB)

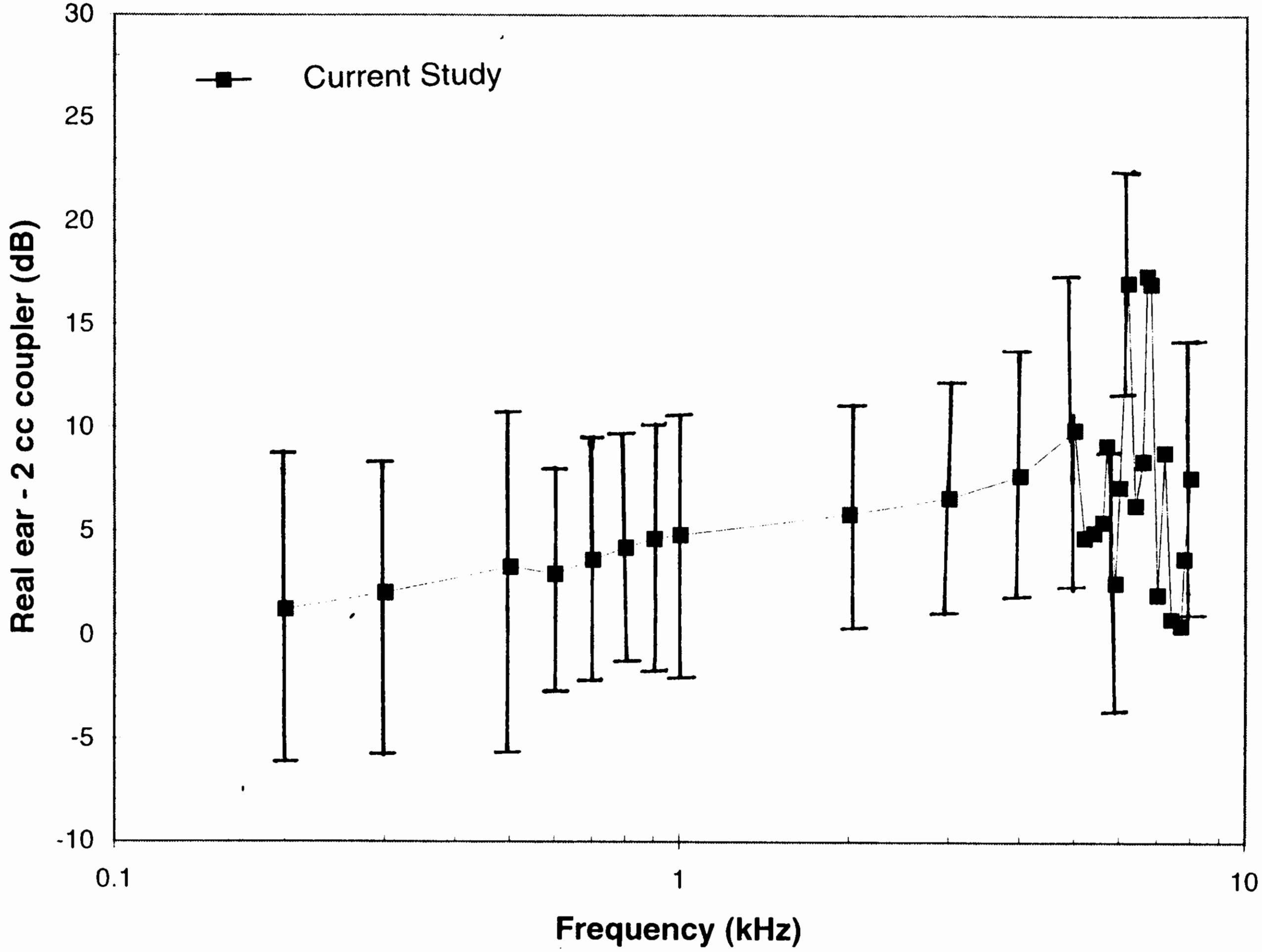
Primary Investigator	Frequency (kHz) 0.25	0.5	1	2	3	4	5	6	8
1. Present study n =14 Age 3 to 8	**1**	**3**	**5**	**6**	**7**	**8**	**10**	**7**	**8**
	(7)	(6)	(8)	(6)	(7)	(8)		(7)	(8)
2. Feigin, et. al (1989) n = 22 Age < 5	0	6	10	8	9	13		19	25
	(6)	(6)	(6)		(6)	(11)		(11)	(16)
3. Harris, et. al (1989) n = 30 Age 4 to 16	2	0	1	3	3	3	14		
	(11)	(10)	(10)	(11)		(12)	(13)		
4. Nelson-Barlow, et.al (1988) n = 15 Age 3 to 15		3	2	8	5	7			
		(4)	(4)	(4)	(8)	(8)			
5. Martin, et. al (1996) n = 14 Age 4.6 to 7.6	4	5	8	11	12	13	15	17	0
	(5)	(3)	(2)	(3)	(3)	(3)	(4)	(4)	(8)
6. Feigin, et. al (1989) n = 21 adults	-3	1	5	4	5	8	11	15	20
	(9)	(9)	(5)	(5)	(2)	(2)	(5)	(5)	(9)

Note. n = sample size of study
Bold values are those for the present study
Values in parentheses indicate 1 standard deviation from the mean.
Values in this table have been rounded to the nearest whole number.

used for measuring the RECD displayed numeric data only at 100 Hz intervals.) Results showed that the output in real ears was greater than the output in the 2 cc coupler for all frequencies between 200 and 8000 Hz, reflecting the limitations of the 2 cc coupler in predicting the real ear responses of children. The mean RECD increased as a function of frequency and ranged from 1.28 dB at 200 Hz to 18 dB at approximately 7000 Hz. A plot of the mean RECD's in dB as a function of frequency is shown in Figure 6. Figure 7 shows mean RECD's of 21 adults and 22 children from Feigin et. al. (1989) for comparison. Consistent increases in the RECD are observed up to 4000 Hz. Above 4000 Hz, the data show large fluctations.

The mean RECD's for this study, are within +/- 5 dB of values reported in other studies, at least through 3000 Hz. In the higher frequencies however, the mean RECD's for this study are smaller in comparison to most other studies (Feigin, 1989; Martin, & Westwood, 1995).

Hearing aid microphone location effect. Table 2 displays the means and standard deviations for the hearing aid microphone location effect for 14 behind-the-ear hearing aids. Figure 8 shows a plot of the average hearing aid microphone location effect in dB as a function of frequency. The aid mic effect results from Kuhn & Burnett (1977) are also shown for comparison. At nearly all frequencies, with the exception of 1.5, 2, and above 7 kHz, the values are negative. In addition, the results show large standard deviations at all frequencies. Inspection of these



<u>Figure 6</u>. Mean real ear to coupler difference (dB) for 14 ears. Error bars indicate one standard deviation from the mean.

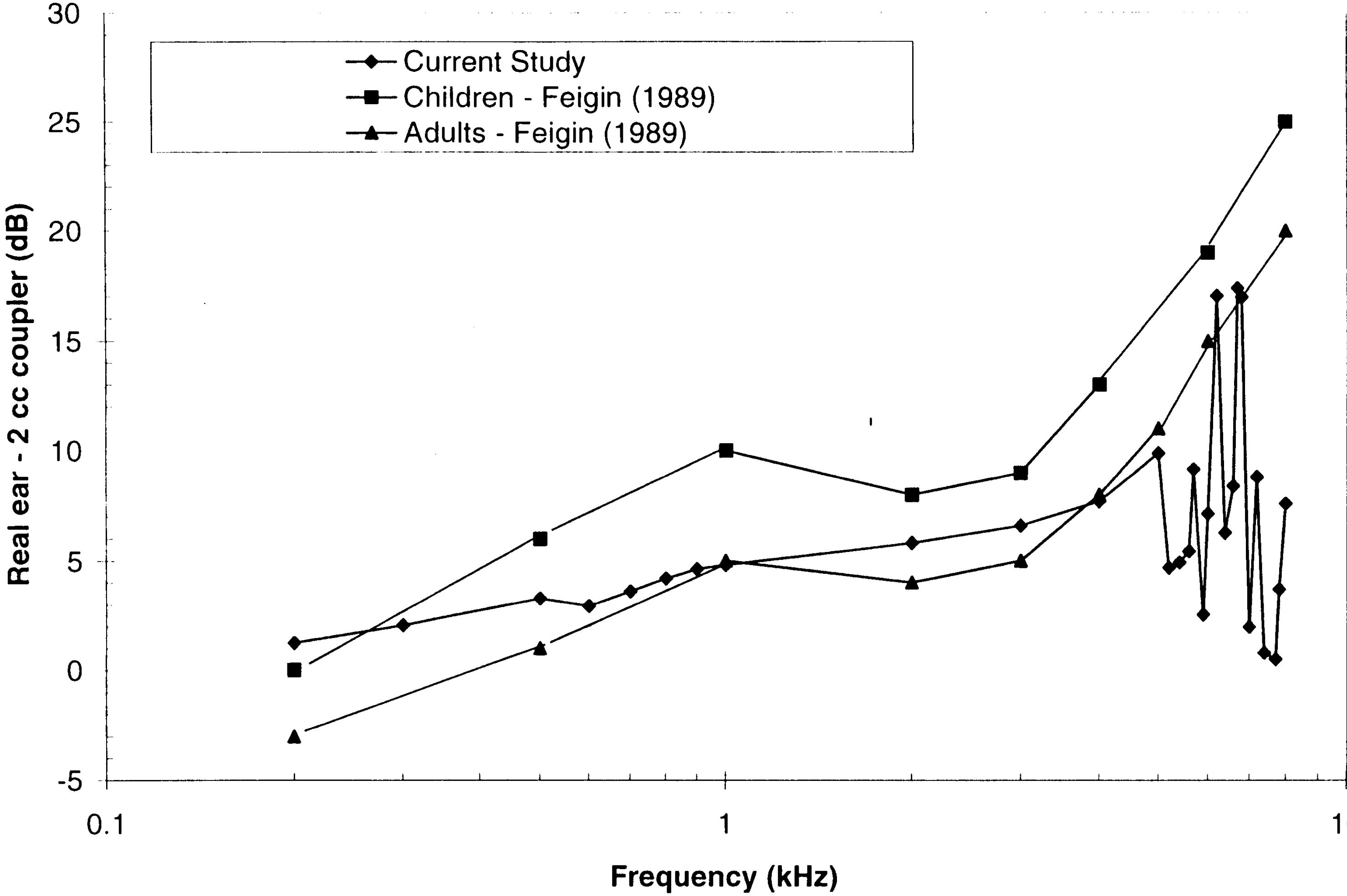


Figure 7. Mean real ear to coupler difference for 14 ears. Also shown are mean RECD's for 21 adults and 22 children (Feigin, 1989).

Table 2

Hearing Aid Microphone Location Effect

Frequency (Hz)	Aid mic effect	SD
200	-10	21
500	-8	18
1000	-7	17
1500	2.0	20
2000	1.0	17
3000	-2.0	17
4000	-9.0	19
6000	- .1	16
8000	6.0	18

Note: column 2 indicates mean aid mic effect (dB)
SD = one standard deviation (dB)
Values have been rounded to the nearest whole number

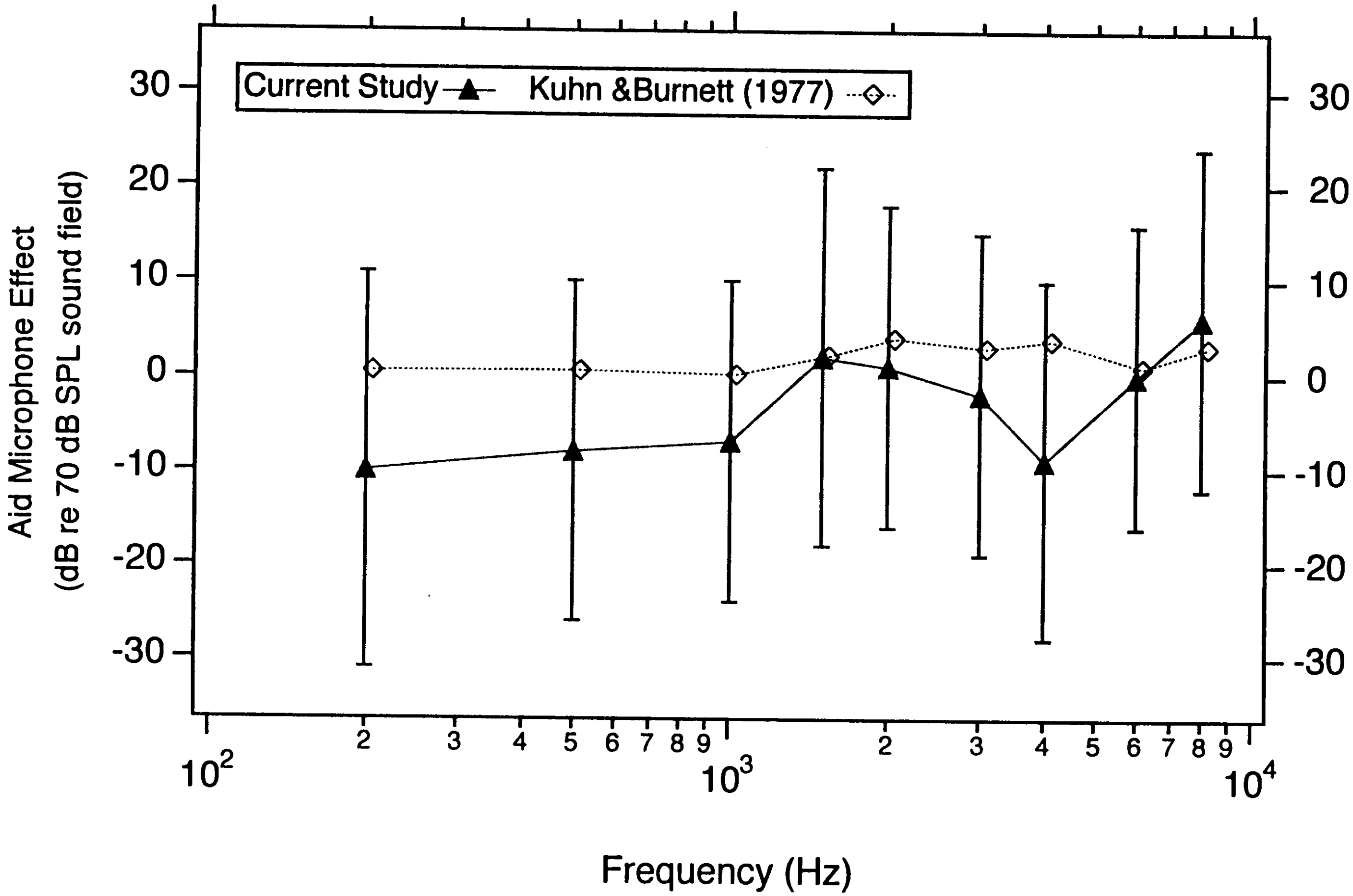


Figure 8. Mean hearing aid microphone location effect for 14 behind-the-ear hearing aids. Error bars indicate one standard deviation from the mean. Also shown are hearing aid microphone location effect results from Kuhn & Burnett (1977).

data suggest very little consistency in comparison to previously published microphone location effect data.

Chapter V

Discussion

The primary goal of this study was to quantify real ear to coupler differences in children and investigate the clinical feasibility of measuring individual real ear to coupler differences (RECD)'s in a pediatric population. The theoretical basis for measuring the RECD is to determine the acoustic differences between the real ear and the coupler. Once the RECD has been measured, the application of individual RECD corrections in the hearing aid selection process may increase the likelihood that a hearing aid will provide accurate amplification.

The RECD was measured for ten children. In addition, the hearing aid microphone location effect was calculated for fourteen behind-the-ear hearing aids utilizing an indirect technique. Real ear to coupler difference data were examined as a function of frequency to determine if there was a difference between output in a real ear versus the 2 cc coupler.

Real ear to coupler difference.

The results showed that the output in real ears was greater than output in a 2 cc coupler at all frequencies between 200 and 8000 Hz. The RECD's for this study were compared to the RECD's of five other studies involving children and one adult study. The mean RECD's obtained in this study, were within +/- 5 dB of values reported by Feigin (1989), Martin (1996), and Westwood (1995) at most frequencies. However, these data appeared to more closely approximate adult values as opposed to reported children's values. There are several possible explanations for this.

One reason for lower RECD's may be that the children who participated in this study genuinely had external and middle ear characteristics similar to adults which lowered the mean RECD. Based on a study by Feigin (1989), it is predicted that the RECD's of children should approximate adult values by 7.7 years of age. The average age of children in this study was six years old. According to Feigin's prediction, the mean RECD of our subjects should still be higher than the average adult RECD. This did not appear to be the case. Another reason Feigin et. al. and Martin (1996) may have obtained higher RECD's is because the average age of subjects in their studies was younger than children in this study. It is important to note that other investigators have not found significant differences between the RECD of older children and adults (Nelson-Barlow, Auslander, Rines, & Stelmachowicz, 1988; Harris, 1989).

Another possible explanation for lower RECD's in this study may be that probe tube insertion was not deep enough in the canal to yield an accurate high frequency response. The discrepencies between the present study and studies by Feigin et. al.(1989), Martin (1996), and Westwood et. al.(1995) occurred mainly in the high frequencies. (See Table 2). Dirks & Kincaid (1987) reported that the sound pressure level (SPL) measured at the tip of a probe tube may vary by as much as 14 dB depending upon probe placement within the canal. Shallow probe tube insertion causes a reduced high frequency response. In addition, there may have been the presence of standing waves in the ear canals of these children. The possibility of standing waves is greater at the higher frequencies due to smaller frequency wavelength (Dirks, Ahlstrom, & Eisenberg, 1996). This could also explain large fluctuations observed in the high frequencies.

Hearing Aid Microphone Location Effect

The hearing aid microphone location effect was derived indirectly, by solving the formula proposed by Killion & Revit (1993). At present, there are no other studies which have utilized a formula for deriving the aid microphone effect. The results showed an increase in sound pressure level at 1500 and 2000 Hz, and at frequencies above 7000 Hz , with large standard deviations at all frequencies. However, the results of this study show large inconsistencies with previous studies (Bentler, & Pavlovic, 1989; Madaffari, 1974; Kuhn & Burnett, 1977). There are several possible explanations for the inconsistencies.

The present study utilized a soundfield substitution method for determining the hearing aid microphone location effect. This method, is theoretically, the most valid means of measuring hearing aid microphone location effect (Shaw, 1974). However, the accuracy of the aid microphone effect results may have been severely compromised for several reasons. First, several researchers have reported that the substitution method is subject to a high degree of error when even slight movements of the subject's head and/or body occur (Gulick, Gesheider, & Frisina, 1989; Mueller, 1992; Sivian, & White, 1933). In this study, every attempt was made to avoid movement by the child when soundfield measurements were made. However, even with the most cooperative child, small movements were unavoidable.

A second reason for large errors may have been the environment where testing was performed. Shaw (1974) stated that the substitution method is best performed in an anechoic chamber due to the risk of standing waves and sound shadows in a soundfield. Measurements for this study were made in soundbooths at two local elementary schools and the university clinic as opposed to an anechoic chamber. Therefore, the possibility for standing waves and sound shadows was higher. In addition, because three different soundbooths were used, this increased variability and the potential for errors.

A final cause for large errors in the aid mic effect data, may have been because the values used to solve the formula to determine hearing aid microphone location effect included error. In this study, the hearing aid microphone location effect was calculated after obtaining the real ear unaided response (REUR), real ear aided response REAR), real ear to coupler difference (RECD), real ear insertion response (REIR), and the response of the hearing aid on the coupler (2ccr). There is some amount of error inherent in each of these measurements, and, therefore, the aid mic effect results may include an accumulation of errors from the REUR, REAR, RECD, and the REIR measurements.

Conclusions

The results of this study showed that the output in real ears was greater than in a 2 cc coupler for ten children between three and eight years of age. Results are consistent with previous RECD studies with a pediatric population.

The primary implication of these results involves the manner in which the real ear to coupler difference should be corrected. Failing to correct for the RECD, or applying inappropriate corrections, may result in the selection of a hearing instrument with gain and output characteristics which are less accurate, according to values specified by prescription formulas. Excessive amplification will occur at whatever frequencies the real ear output exceeds the 2 cc coupler output. When children receive over-amplification from their hearing aids, there is the possibilty of damage to residual hearing.

At present, it is not clear what hearing aid output sound pressure level can cause additional hearing loss (Hawkins, 1992). However, numerous large-scale investigations and single case studies have documented threshold shifts in children with hearing impairment who use amplification (Kinney, 1953; Kinney, 1961; Harford, & Markle, 1955; Heffernan & Simons, 1979; Jerger & Lewis, 1975; Kasten & Braunlin, 1970; Macrae, 1968; Macrae & Farrat, 1965; Roberts, 1970).

A second possible effect of inappropriate RECD corrections is the selection of a hearing aid with output which exceeds the child's loudness discomfort level (LDL). Ideally, the saturation sound pressure level of a hearing aid should be reduced by the amount of the real ear to coupler difference. This is particularly important for children, since loudness discomfort levels may be unreliable (Hawkins & Northern, 1992), or impossible to measure with a pediatric patient. While hearing aids can be ordered with potentiometers to adjust the maximum output of hearing aids, it is ideal if an appropriate saturation sound pressure level can be specified during the initial selection of a hearing aid. Correctly accounting for the child's real ear to coupler difference may assist in the selection of an appropriate saturation sound pressure level.

It may be argued that individual measurement of the real ear to coupler difference prior to hearing aid selection is unnecessary, since real ear measurement is readily available for confirming the real ear response of the hearing aid. Real ear measurement is undoubtably a valuable fitting technique. However, it behooves audiologists to accurately correct for the RECD and hearing aid microphone location effect so that the initial hearing aid selection will offer the most accurate electroaoustic characteristics as prescribed by a formula. Selection of accurate gain and output characteristics may help reduce the number of hearing aids which are returned to the manufacturer due to poor agreement of the real ear response with the prescribed target.

Another compelling argument for measuring the real ear to coupler difference with children, is that it is ideal to fit hearing aids with as much potentiometer adjustment as possible. Providing an individual real ear to coupler difference measurement with the hearing aid order, may reduce the amount of time spent adjusting potentiometers during the fitting. In addition, the hearing aid potentiometers may provide a greater range of adjustment at future visits, for example, if the child experiences a change in hearing or requires earmold size changes with external ear growth.

The hearing aid microphone location effect results from this study revealed large negative values and large intersubject variability. These results indicate that standardized corrections for the hearing aid microphone location effect should be used in the selection process of hearing aids. This being the case, it is important to utilize standardized corrections for the type of hearing aid being selected. Bentler & Pavlovic (1989), and Sullivan (1989) have published hearing aid microphone location effect results for behind-the-ear, in-the-ear, and in-the-canal hearing aids.

Corrections for the hearing aid microphone location effect and real ear to coupler difference are necessary for pediatric hearing aid selections to increase the likelihood that appropriate amplification will be fit. The results of this study indicate that individualized real ear to coupler difference corrections are feasible with a pediatric population. However, large inconsistencies in the hearing aid microphone location effect data, indicate that standardized corrections would be more accurate than individual corrections. Additional studies are needed to support this premise.

Study Limitations

There are several limitations to the present study. One limitation is the age of children who participated in this study. The average age of children in this study was six years old. A younger mean subject age would have been preferred since most research indicates that external and middle ear characteristics of children reach adult values by two to three years of age (Okabe, Tanaka, Hamada, Miura, & Funai, 1988; Keefe, Bulen, Hoberg-Arehart, & Burns, 1993; Upfold & Byrne, 1988; Westwood & Bamford, 1995). Additional studies of the real ear to coupler difference with infants are needed as audiologists are becoming more aggressive in pursuing hearing aid fittings at a younger age (Harrison & Roush, 1996).

A second limitation is the method which was used for determining probe tube placement in the ear canal. There are presently three methods for determining probe tube placement. These include the acoustic method, the constant insertion depth method, and earmold plus 5-mm method. For this study, an earmold plus 5-mm method was used. A study by Dirks, Ahlstrom, & Eisenberg (1996) compared the accuracy of these three types of probe insertion methods. They found that the acoustic method was the most accurate and the constant probe insertion depth and earmold plus 5 mm method were equally accurate. However, Dirks et al. used earmolds which extended at least 8 to 10 mm into the ear canal. Most of the earmolds used in this study had very short canal lengths, therefore insertion depth was probably more shallow than was used by Dirks et. al. While it is most accurate to use an acoustic method of probe tube placement, this method is time-consuming and, therefore, inappropriate with a pediatric population in a clinical setting. For this study, it may have been more accurate to use a constant insertion depth method of probe tube placement.

Clinical Implications

The primary clinical implication of this study concerns the feasibility of individualized real ear to coupler difference corrections during the hearing aid selection process. A number of researchers have proposed that applying individual correction factors instead of using averaged corrections would result in a more accurate hearing aid fittings for both children and adults, at least through 4 kHz (Egolf, Kennedy, & Larson, 1992; Fikret-Pasa & Revit, 1992; Killion & Revit, 1993; Moodie, Seewald, & Sinclair, 1994). However, corrections for the RECD in the high frequencies has not been recommended (Killion & Revit, 1993). Killion & Revit stated that "due to the number of sources of error above 4 kHz, the dispenser is likely to cause additional errors by attempting to correct for the RECD in the high frequencies" (p. 77). Furthermore, they stated that the test room conditions and equipment must be ideal to keep the standard deviation below 3 to 5 dB and recommended that *any* corrections for the RECD above 4 kHz, should be a smooth extension of any curve corrections below 4 kHz.

Assuming that individual corrections are more accurate, two logical questions arise. First, is it feasible to reliably obtain individual real ear to coupler difference measurements in a clinical audiology setting? This question is of particular concern with young children and infants since excessive movement during probe measurements will compromise the reliability of the test.

To address this issue, Sinclair, Beauchaine, Moodie, Feigin, Seewald, & Stelmachowicz (1996) studied the reliability of individual RECD's. They measured the RECD in 90 children ages birth to seven years and in ten adults. The results indicated that test-retest reliability of these measurements was acceptable for all age subjects. They noted that for preschool age children, the variability in the RECD was slightly greater than in older children or adults, but the differences in reliability were not significant.

A second question concerns the time required to measure individual real ear to coupler differences. Would clinical audiologists have the time to measure individual

RECD's in a busy pediatric setting? Sinclair et al. (1996) reported that the time required for measuring RECD's involved no more than five minutes with each child.

The session time required of each child for this study was approximately 20 to 30 minutes. This included otoscopy, tympanometric screen, a free field measurement without the child present, real ear unaided response, real ear aided response, insert phone measurement, and coupler measurement with the hearing aid. Each measurement was completed for both ears. If only the RECD measurement was necessary, the estimated session time would be less than five minutes, consistent with the values reported by Sinclair et al.

The primary clinical implication of the hearing aid microphone location effect concerns whether corrections during the hearing aid selection process be from individual measurements or from standardized data. The results of this study indicate that individual measurement of the hearing aid microphone location effect results in large errors. Thus, the use of standardized corrections is recommended.

Implications for Future Research

A primary focus of future research should be to conduct additional real ear to coupler difference studies with children. At the present time, there are only six published studies of RECD's involving children.

It is particularly important to understand how the RECD changes with age. A longitudinal study in which infants are followed from birth through early childhood would be beneficial. This type of study might involve measuring the RECD of infants at routine intervals throughout early childhood to observe changes in the RECD with external and middle ear growth.

A second implication for future research concerns the study of the RECD in individuals with various middle ear pathologies. The prevalence of otitis media in the pediatric population is high. At the present time, there is only one study of the RECD in children with otitis media (Martin, Westwood, & Bamford, 1996).

It is also important to conduct studies comparing the efficacy of average versus individual corrections in the hearing aid fitting. A number of researchers have proposed that applying individual corrections to prescriptive hearing aid fitting formulas, would yield more accurate fittings (Egolf, Kennedy, & Larson, 1992; Fikret-Pasa, & Revit, 1992; Moodie, Seewald, & Sinclair, 1994). However, there have been no studies to document this.

Finally, it is essential that real ear to coupler difference studies be conducted for children of all ages so that age appropriate standardized corrections can be established. While individual RECD mesurements are recommended, in certain cases measurement of the RECD may not be possible. When the RECD cannot be reliably measured, the use of standardized corrections is warranted (Moodie, Seewald, Sinclair, 1994).

There are several implications for future research concerning the effects of hearing aid microphone location. At the present time, there is disagreement as to the most accurate method of measuring microphone location effect. Additional studies of hearing aid microphone location are needed in order to determine the procedure which yields the most accurate results. Future research should also include the studies of microphone location effect for behind-the-ear, in-the-ear, and in-the-canal hearing aids to establish standardized corrections. At the present time, there is only one published study of the microphone location effect for in-the-canal hearing aids (Sullivan, 1989).

Summary

The present study investigated the real ear to coupler difference in ten hearing impaired children between four and eight years of age. Results showed that output was greater in the real ear than coupler for all standard audiometric frequencies. Large intersubject variabilty was noted, particularly in the high frequencies. A secondary goal of this research involved the measurement of the hearing aid microphone location effect for fourteen behind-the-ear hearing aids. Results showed very large standard deviations and inconsistency with previous data, therefore, the accuracy of this data is questioned.

The implications of the real ear to coupler difference and hearing aid microphone location effect results concern the possibility that inaccurate amplification may be selected for a hearing impaired child, if these factors are not accounted for, or are inappropriately accounted for. The primary effect of failing to correct for, or inappropriately correct for the RECD, is the selection of a hearing instrument which provides inaccurate amplification as specified by prescriptive formulas. It is beneficial to audiologists, particularly when selecting amplification for children, to select as accurate an electroacoustic response as possible to avoid hearing aid returns and allow maximum adjustment of hearing aid potentiometers when changes in amplification are needed.

Implications for future research include additional studies of the real ear to coupler difference for the pediatric population, studies in individuals with various middle ear pathologies, as well as observing changes in the RECD as a function of age. Development of age appropriate standardized corrections are also important when individual RECD measurements cannot be performed. Additional studies of hearing aid microphone location effect are recommended to assist in the development of a more precise method for measuring microphone location effects and to establish standardized corrections.

References

American National Standards Institute (1973). Method for coupler calibration of earphones-ANSI S3.7-1973. New York: American National Standards Institute, Inc.

American National Standards Institute (1987). Specification of hearing aid characteristics-ANSI S3.22-1987. New York: American National Standards Institute, Inc.

Balow, B., Fultin, H., & Peploe, E. (1971). Reading comprehension skills among heairng impaired adolescents. Volta Review, 73, 113-119.

Bateman, H., & Mason, R. (1984). Applied anatomy and physiology of the speech and hearing mechanism. (pp. 426-451). Springfield, IL: Charles C. Thomas.

Bentler, R. (1989). External ear resonance characteristics in children. Journal of Speech and Hearing Disorders, 54, 264-268.

Bentler, R., & Pavlovic, C. (1989). Transfer functions and correction factors used in hearing aid evaluation and research. Ear and Hearing, 10, 58-63.

Berger, K. (1980). The search for a master hearing aid. In M. Pollack (Ed.), Amplification for the hearing impaired (2nd ed., pp. 325-380). New York: Grune & Stratton.

Bergman, B., & Bentler (1991). Relationship of acoustic immittance measures to hearing aid output. (Unpublished Master's thesis, Iowa). In T. A. Ricketts & R. A. Bentler (1995) American Journal of Audiology, March, 43-45.

Berninger, E., Ovegard, A., & Svard, I. (1992). Coupler-related real ear gain: Interaction between subject and hearing aid type. Scandinavian Audiology, 21, 15-22.

Boothe, L., Lasky, E., & Kricos, P. (1982). Comparison of language abilities of deaf children and young deaf adults. Journal of Rehabilitation for the Deaf, 15, 10-15.

Brammer, A., & Percy, J. (1977). Monitoring sound pressures within the ear: Application to noise exposure. Journal of the Acoustical Society of America, 61, 731-738.

Bratt, G. (1980). Hearing aid receiver output in occluded ear canals in children. Unpublished doctoral dissertation, Vanderbilt University, Nashville, TN.

Burkhard, R., & Sachs, M. (1975). Anthropometric manikin for acoustic research. Journal of the Acoustical Society of America, 58, 214-222.

Burnett, E. (1989). Handbook of hearing aid measurement. Washington, D.C.: VA Medical Center.

Burnett, E., & Beck, L. (1987). A correction for converting 2 cm^3 coupler responses to insertion responses for custom in-the-ear nondirectional hearing aids. Ear and Hearing, 8 (Suppl. 5), 89-94.

Byrne, D., & Dillion, H. (1986). The National Acoustic Laboratories (NAL) new procedure for selecting the gain and frequency response of a hearing aid. Ear and Hearing, 7, 257-265.

Carhart, R. (1946). Selection of hearing aids. Archives of Otolaryngology, 14, 1-18.

Clark, B. & Leslie, P. (1971). Visual-motor skills and reading ability of deaf children. Perceptual and Motor Skills, 33, 263-268.

Cox, R., & Risberg, D. (1986). Comparison of in-the-ear and over-the-ear hearing aid fittings. Journal of Speech and Hearing Disorders, 51, 362-369.

Dempster, J., & Mackenzie, K. (1990). The resonant frequency of the external auditory canal in University children. Ear and Hearing, 11, 269-298.

Dillion, H. (1991). Allowing for real ear venting effects when selecting the coupler gain of hearing aids. Ear and Hearing, 12 (6), 406-416.

Dillion, H., & Murray, N. (1987). Accuracy of twelve methods for estimating the real ear gain of hearing aids. Ear and Hearing, 8, 2-11.

Dirks, D., Ahlstrom, J., & Eisenberg, L. (1996). Comparison of probe insertion methods on estimates of ear canal SPL. Journal of the American Academy of Audiology, 7, 31-38.

Dirks, D., & Kincaid, G. (1987). Basic acoustic considerations of ear canal probe measurements. Ear and Hearing, 8 (Suppl. 5), 60-67.

Egolf, D., Feth, L., Cooper, W., & Franks, J. (1995). Effects of normal and pathologic eardrum impedance on sound pressure in the aided ear canal: A computer simulation. Journal of the Acoustical Society of America, 78 (4), 1281-1285.

Egolf, D., Kennedy, W., & Larson,V. (1992). Occluded-ear simulator with variable acoustic properties. Journal of the Acoustical Society of America, 91, 2813-2823.

Feagans, L. (1992). Effects of hearing loss on development: Speech and language development. In R. Eavey & J. Klein (Eds.), Report of the 102nd Ross Conference on Pediatric Research: Hearing loss in childhood (pp. 82-87). Columbus, OH: Ross Laboratories.

Feagans, L., Blood, I, Tubman, J. (1988). Otitis media: Models of effects and implications for intervention. In F. H. Bess (Ed.), Hearing impairment in children (pp. 347-374). Parkton, MD: York Press

Feigin, J., Kopun, J., Stelmacholwicz, P., & Gorga, M. (1989). Probe-tube microphone measures of ear-canal sound pressure levels in infants and children. Ear and Hearing, 10, 254-258.

Fikret-Pasa, S., & Revit, L. (1992). Individualized correction factors in the preselection of hearing aids. Journal of Speech and Hearing Research, 35(2), 384-400.

Fry Electronics, Inc. (1992). Computer controlled real-time analyzer: Operators Manual. (Section 8-1 to 8-67). Tigard, Oregon.

Furth, H. (1966). A comparison of reading test norms for deaf and hearing children. American Annals of the Deaf, 111, 461-462.

Gartrell, L., & Church, G. (1990). Effect of microphone location in ITE versus BTE hearing aids. Journal of the American Academy of Audiolology, 1, 151-153.

Geddes, N. (1987). Tympanometry and the stapedial reflexes in the first five days of life. International Journal of Pediatric Otorhinolaryngology, 13, 293-297.

Gilmer, K. (1995). Comparison of actual versus prescribed gain for children with profound hearing impairments. Unpublished master's thesis. Portland State University, Portland, Oregon.

Green, R. (1988). The relative accuracy of coupler and behavioral estimates of the real ear gain of a hearing aid. British Journal of Audiology, 22, 35-44.

Gulick, W., Gescheider, G., & Frisina, R. (1989). Hearing: Physiological Acoustics, Neural Coding, and Psychoacoustics. (pp. 227-243). New York: Oxford University Press.

Hall, J. (1979). Effects of age and sex on static compliance. Archives of Otolarynogology, 105, 601-605.

Harford, E. (1982). Real ear measurements for prescribing a hearing aid. In M. Paparella & M. Goycoolea (Eds.), Ear Clinics International (pp. 171-. 181). Baltimore, MD: Williams & Wilkins.

Harford, E., & Markle, D. (1955). The atypical effect of a hearing aid on one patient with congenital deafness. Laryngoscope, 65, 970-972.

Harris, W., & Adams, D. (1989). A comparison between coupler gain and insertion gain of hearing aids as used in partially hearing units in five schools in Belfast. British Journal of Audiology, 23, 255-260.

Harrison, M., & Roush, J. (1996). Age of suspicion, identification, and intervention for infants and young children with hearing loss: A National Study. Ear and Hearing, 17 (1), 55-61.

Hawkins, (1992). Selecting SSPL90 using probe microphone measurements. In G. H. Mueller, D. B. Hawkins, & J. L. Northern (Eds.), Probe microphone measurements: Hearing aid selection and assessment (pp. 145-158). San Diego, CA: Singular Publishing Group

Hawkins, D., Cooper, W., & Thompson, D. (1990). Comparisons among SPL's in real ears, 2 cm^3, and 6 cm^3 couplers. Journal of the American Academy of Audiology, 1, 151-153.

Hawkins, D., Montgomery, A., & Prosek, R., & Walden, B. (1987). Examination of two issues concerning functional gain measurements. Journal of Speech and Hearing Disorders, 52, 56-63.

Hawkins, D., & Northern, J., (1992). Probe microphone measurements with children. In G. H. Mueller, D. B. Hawkins, & J. L. Northern (Eds.), Probe microphone measurements: Hearing aid selection and assessment (pp. 159-181). San Diego, CA: Singular Publishing Group.

Hayes, D. (1993). Acoustic resonators in the coupler and in the ear. Scandinavian Audiology, 22, 187-191.

Heffernan, H., & Simons, M. (1979). Temporary increase in sensorineural hearing loss with hearing aid use. Annals of Otology, Rhinology, and Laryngology, 88, 86-91.

Holte L. (1989). Longitudinal tympanometry and pneumatic otoscopy in healthy newborn infants (Doctoral Dissertation, Syracuse University). In D. H. Keefe, J. C. Bulen, K. Hoberg-Arehart, & E. M. Burns, Journal of the Acoustical Society of America, 94 (5) (pp. 2617-2637).

Humes, L., & Kirn, E. (1990). The reliability of functional gain. Journal of Speech and Hearing Disorders, 55, 56-63.

Jerger, J., & Lewis, N. (1975). Binaural hearing aids: Are they dangerous for children? Archives of Otolaryngology, 101, 480-483.

Joswig, M. (1993). Impulse response and impedances of ears. Acustica, 77, 271-282.

Kasten, R., & Braunlin, R. (1970). Traumatic hearing aid usage: A case study. Paper presented at the meeting of the American Speech and Hearing Association. In W. F. Rintelman, & F. H. Bess, High level amplification and potential hearing loss in children. (pp. 278-307). Parkton, MD: York Press.

Keefe, D., Bulen, J., Hoberg-Arehart, K., & Burns, E. (1993). Ear canal impedance and reflection coefficient in human infants and adults. Journal of the Acoustical Society of America, 94, (5), 2617-2638.

Keefe, D., Ling, R., & Bulen, J. (1992). Method to measure acoustic impedance and reflectance coefficient, 91, 470-485.

Kiessling, J. (1982). Hearing aid selection by brainstem response audiometry. Scandinavian Audiology, 11, 269-275.

Killion, M., & Monser, E. (1980). CORFIG: Coupler response for flat insertion gain. In Studebaker & Hochberg (Eds.), Acoustical Factors Affecting Hearing Aid Performance. Baltimore: University Park Press.

Killion, M., & Revit, L. (1993). CORFIG: Real ear to coupler and back. In G. A. Studebaker & I. Hochberg (Eds.): Acoustical factors for affecting hearing aid performance. 2nd ed. Boston: Allyn and Bacon.

Kinney, C. (1953). Hearing impairments in children. Laryngoscope, 63, 220-226.

Kinney, C. (1961). The further destruction of partially deafened children's hearing by the use of powerful hearing aids. Annals of Otology, Rhinology, and Laryngology, 70, 828-835.

Kruger, B., & Ruben, R. (1987). The acoustic properties of the infant ear. Acta Otolaryngologica, 103, 578-585.

Kuk, F. (1994). Use of paired comparisons in hearing aid fittings. In M. Valente (Ed.), Strategies for selecting and verifying hearing aid fittings. (pp. 108-135). New York: Thieme Medical Publishers, Inc.

Kuhn, G. (1979). The pressure transformation from a diffuse sound field to the external ear and to the body and head surface. Journal of the Acoustical Society of America, 65, 991-1000.

Kuhn, G., & Burnett, E. (1977). Acoustic pressure field alongside a manikin's head with a view towards in situ hearing aid tests. Journal of the Acoustical Society of America, 62, 416-423.

Libby, E. (1986). The 1/3-2/3 insertion gain hearing aid selection guide. Hearing Instruments, 37, 27-28.

Lybarger, S.,& Teder, H. (1986). 2 cc coupler curves to insertion gain curves: Calculated and experimental results. Hearing Instruments, 37, 36-40.

Macrae, J. (1968). Deterioration of the residual hearing of children with sensorineural deafness. Acta Otolaryngologica, 66, 33-39.

Macrae, J., & Farrant, F. (1965). The effect of hearing aid use on the residual hearing of children with sensorineural deafness. Annals of Otology, Rhinology, and Laryngology, 74, 409-419.

Madaffari, P. (1974). Pressure response about the ear. Paper presented at the 88th meeting of the Acoustical Society of America, St. Louis, MO.

Madsen, P. (1986). Insertion gain optimization. Hearing Instruments, 37(1), 28-32.

Margolis, R., & Heller, J. (1987). Screening tympanometry: Criteria for medical referral. Audiology, 26, 197-208.

Marshall, H. (1970). Effect of training on visual perception skills and reading achievement in deaf children. Experimental Publication System, 8, 281-283.

Martin, H., Westwood, G., & Bamford, J. (1996). Real ear to coupler differences in children having otitis media with effusion. British Journal of Audiology, 30, 71-78.

Mason, D., & Popelka, G. (1986). Comparison of hearing aid gain using functional coupler and probe-tube measurements. Journal of Speech and Hearing Research, 29, 218-226.

McCaffrey, H., & Sussman, H. (1994). An investigation of vowel organization in speakers with severe and profound hearing loss. Journal of Speech and Hearing Research, 37 (4), 938-951.

McCandless, G. (1994). Overview and rationale of threshold-based hearing aid selection procedures. In M. Valente, Strategies for selecting and verifying hearing aids. (pp. 1-18). New York: Thieme Medical Publishers, Inc.

McCandless, G., & Lyregaard, P. (1983). Prescription of gain/output (POGO) for hearing aids. Hearing Instruments, 35 (1) 16-21.

Meadow, K. (1976). The development of deaf children. In E. Hetherington (Ed.), Review of Child Development Research, Vol. 5. Chicago: University of Chicago Press.

Moodie, S., Seewald, R., & Sinclair, S. (1994). Procedure for predicting real-ear hearing aid performance in young children. American Journal of Audiology, March, 23-29.

Moller, A. (1983). Auditory Physiology. New York: Academic.

Mueller, G. (1992). Terminology and procedures. In H. G. Mueller, D. B. Hawkins, & J. L. Nothern (Eds.), Probe Microphone Measurements: Hearing aid selection and assessment (pp. 41-66). San Diego, CA: Singular Publishing Group.

Myklebust, H. (1960). The psychology of deafness. New York: Grune & Stratton.

Nelson-Barlow, N., Auslander, M.C., Rines, D., & Stelmachowicz, P. (1988). Probe tube microphone measurements in hearing-impaired children and adults. Ear and Hearing, 9, 243-247.

Northern, J., & Downs, M. (1978). Hearing in Children (pp. 149-191). Baltimore: Williams & Wilkins.

Northern, J., & Downs, M. (1991). Hearing in Children (4rth Ed.). Baltimore: Williams & Wilkins.

Okabe, K., Tanaka, S., Hamada, H., Miura, T., & Funai, H. (1988). Acoustic impedance measurement on normal ears of children. Journal of the Acoustical Society of Japan, 9 (6), 287-294.

Revit, L. (1994). Using coupler tests in the fitting of hearing aids. In M. Valente (Ed.), Strategies for selecting and verifying hearing aid fittings. New York: Thieme Medical Publishers, Inc.

Ricketts, T., & Bentler, R. (1995). Impact of a "standard" earmold on the RECD. American Journal of Audiology, March, 4, 43-45.

Roberts, C. (1970). Can hearing aids damage hearing? Acta Otolaryngologica, 69, 123-125.

Romanow, F. (1942). Methods for measuring the performance of hearing aids. Journal of the Acoustical Society of America, 13, 294-304.

Ross, M. Brackett, D., & Maxon, A. (1982). Hard of hearing children in regular schools. Englewood Cliffs, NJ: Prentice-Hall.

Ross, M., Brackett, D., & Maxon, A. (1991). Assessment and management of main-streamed hearing impaired children: Principles and practices. Austin: Pro-ed.

Ross, M., & Seewald, R. (1988). Hearing aid selection and evaluation with young children. In F. H. Bess (Ed.) Hearing impairment in children. (pp. 190-213). Parkton, MD: York Press.

Sachs, R., & Burkhard, M. (1972). Zwislocki coupler evaluation with insert earphones. Rep. 20022-1, Industrial Research Products, Inc. Elk Grove Village, IL (pp. 1-11).

Seewald, R. (1990). Probe-tube microphone measurements with children. Paper presented at the Fourth Hearing Aid Conference. In D. B. Hawkins, & J. L. Northern. Probe microphone measurements with children. (pp. 67-89).

Seewald, R., Ross, M., Spiro, M. (1985). Selecting amplification characteristics for young hearing impaired children. Ear and Hearing, 6, 48-53.

Seewald, R., Ross, M., & Stelmachowicz, P. (1987). Selecting and verifying hearing aid performance characteristics for children. Journal of the Academy of Rehabilitative Audiology, 20, 25-37.

Seyfried, D., Hutchinson, J., & Smith, L. (1989). Language and speech of the hearing impaired. In R.L. Schow & M.A. Nerbonne, (Eds.), Introduction to aural rehabilitation (2nd. Ed., pp. 181-239). Boston: Allyn and Bacon.

Shore, I., Bilger, R., & Hirsch, I. (1960). Hearing aid evaluation: Reliability of repeated measurements. In J. Katz (Ed.), Handbook of Clinical Audiology. (pp. 723-735). Baltimore: Williams & Wilkins.

Shanks, J., & Lilly, D. (1981). An evaluation of tympanometric estimates of ear canal volume. Journal of Speech and Hearing Research, 24, 557-566.

Shaw, E. (1974). Transformation of sound pressure levels from the free field to the ear drum in the horizontal plane. Journal of the Acoustical Society of America, 13, 1848-1861.

Sinclair, S., Beauchaine, K., Moodie, S., Feigin, J., Seewald, R., & Stelmachowicz, P. (1996). Repeatability of a real ear to coupler difference measurement as a function of age. American Journal of Audiology, 5(3), 52-56.

Sivian, L., & White, S. (1933). On minimum audible sound fields. Journal of the Acoustical Society of America, 4, 288-321.

Skarakis, E., & Prutting, C. (1977). Early communication: Semantic functions of communicative intentions in the communication of the preschool child with impaired hearing. American Annals for the Deaf, 122, 382-391.

Snik, A., & Stollman, M. (1995). Measured and calculated insertion gains in young children. British Journal of Audiology, 29, 7-11.

Stach, B. (1997). Comprehensive Dictionary of Audiology. Baltimore, Maryland: Williams & Wilkins.

Steffens, M., Eilers, R., Fishman, L. Oller, K., & Urbano, R. (1994). Early vocal development in tactually aided children with severe-profound hearing loss. Journal of Speech & Hearing Research, 37, 700-711.

Stinson, M., Shaw, E., & Lawton, B. (1982). Estimation of acoustical energy reflectance at the eardrum from measurements of pressure distribution in the human ear canal. Journal of the Acoustical Society of America, 18, 401-408.

Sullivan, R. (1989). Custom canal and concha hearing instruments: A real ear comparison: Part 1. Hearing Instruments, 40, 23-29.

Tecca, J. (1994). Use of real-ear measurements to verify hearing aid fittings. In M. Valente (Ed.), Strategies for selecting and verifying hearing aid fittings. (pp. 89-107). New York: Thieme Medical Publishers, Inc.

Trybus, R., & Karchmer, M. (1977). School achievement scores of hearing-impaired children: National data on achievement status and growth patterns. American Annals Deaf Directory of Programs and Services, 122, 62-69.

Upfold, G., & Byrne, D. (1988). Variability of ear canal resonance and it's implications for the design of hearing aids and earplugs. Austrailian Journal of Audiology, 10, 97-102.

Valente, M. (1994). Strategies for selecting and verifying hearing aids. New York: Thieme Publishers, Inc.

Valente, M., Valente, M., Meister, M., & Macauley, K. & Vass, W. (1994). Strategies for selecting and verifying hearing aid fittings. In M. Valente, Strategies Selecting and Verifying Hearing Aids. New York: Thieme Medical Publishers, Inc.

Vernon, M. (1972). Language development's relationship to cognition, affectivity, and intelligence. Canadian Psychologist, 13, 360-374.

Watson, N., & Knudson, V. (1940). Selective amplification in hearing aids. In R.L. Schow & M.A. Nerbonne, Introduction to aural rehabilitation (2nd. Ed. pp. 31-80).

Waldstein, R., & Baum, S. (1994). Perception of co-articulatory cues in the speech of children with profound hearing loss and children with normal hearing. Journal of Speech & Hearing Research, 37(3), 938-951.

Webster, A., & Ellwood, J. (1985). The hearing impaired child in the ordinary school. London: Croom Helm.

Westwood, G., & Bamford, J. (1995). Probe tube microphone measures with very young infants: Real ear to coupler differences and longitudinal changes in the real ear unaided response. Ear and Hearing, 16, 263-273.

Wetzell, C., & Harford, E. (1983). Predictability of real ear hearing aid performance from coupler measurements. Ear and Hearing, 4 (5), 237-242.

Zemplenyi, J., Dirks, D., & Gilman, S. (1985). Probe determined hearing aid gain compared to functional and coupler gains. Journal of Speech and Hearing Research, 28, 394-404.

Zwislocki, J. (1970). An acoustic coupler for earphone calibration. Report LSC-S-7 Laboratory of Sensory Communication. Syracuse University, Syracuse, New York.