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Limiting Noise Exposure Associated with Hearing Aid Use

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ABSTRACT

An abstract of the thesis of Alison Mary Gilbert for the Master of Science in Speech Communication: Speech and Hearing Science presented December 1, 1995.

Title: Limiting Noise Exposure Associated with Hearing Aid Use.

Industrial workers who have sustained hearing losses often wear hearing aids on the job in order to hear their co-worker's speech. However they risk damaging their hearing further by amplifying the high levels of background noise typical of such environments. The Occupational Safety and Health Administration (OSHA) has established guidelines to protect workers' hearing. A maximum allowable level of 90 dBA averaged over a period of eight hours is considered safe. Wearing hearing aids on the job may expose an individual to a considerably higher levels, however no guidelines as to maximum allowable levels of amplified noise exist at this time. This study evaluated the performance of four hearing aids in noise to determine which would provide appropriate amplification without exceeding the OSHA maximum.

The instruments were adjusted to provide 14 different frequency responses and placed on the Knowles Mannequin for Acoustic Research (KEMAR). A microphone in the position of KEMAR's eardrum recorded amplified levels of taped industrial noise. A sound level meter integrated the levels to give the OSHA Time Weighted Average (TWA), simulating the acoustic effect of an 8-hour noise exposure on an industrial worker.

Amplified noise remained below the OSHA maximum (90 dBA) in 2 of the 14 hearing aid conditions studied. Noise amplified by the Argosy Expander, an experimental noise-reducing hearing aid, remained below the OSHA maximum when the instrument was set to provide minimum gain and maximum noise reduction. The Argosy 3-Channel Clock also maintained amplified noise at a safe level when adjusted to provide gain only in a limited frequency region. Noise amplified by the Danavox Aura X programmed to provide a TILL response remained within one dB of the OSHA maximum.

This study demonstrated that it is possible to use amplification in environments with constant background noise without risking additional noise-induced hearing loss. Two hearing aids were proven effective in maintaining amplified industrial noise at safe levels, however determining their effect on speech intelligibility in noise is beyond the scope of this study. Further research is needed to address this issue.

LIMITING NOISE EXPOSURE ASSOCIATED WITH HEARING AID USE

by

ALISON MARY GILBERT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

In modern society noise exposure is a daily fact of life. In the home, during recreational activities, and especially in the workplace, it is virtually inescapable. Noise levels above 85 dBA are potentially damaging to the structures of the inner ear. Physiological effects of acoustic overstimulation of the inner ear include changes in vascular supply, causing damage to hair cells and dendrites (Spoendlin, 1971). Mechanical detachment of cochlear structures may occur if noise is sufficiently intense (Bohne, 1976). How much damage is done and whether it is temporary or permanent depends on the physical characteristics of the noise as well as the duration of the exposure (Melnick, 1985). Industrial workers are often exposed to these high levels of noise for extended periods of time. Changes in auditory sensitivity assessed before and after noise exposure are called threshold shifts (Melnick, 1984). If sensitivity returns to its pre-exposure level after a period of recovery it is known as temporary threshold shift (TTS). When physical changes caused by noise exposure do not reverse themselves with time and sensitivity does not return, the change is known as permanent threshold shift (PTS). Research suggests that noise exposure may hasten and/or intensify the loss of auditory sensitivity which naturally accompanies the aging process (Corso, 1980, Kryter, 1983).

The Walsh-Healy Public Contracts Act of 1969 was the first set of federal regulations aimed at protecting workers from excessive noise exposure (Teplitsky, 1984). In 1970 in response to the Williams-Steiger Act, the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) proposed a maximum allowable noise exposure of 90 dBA for an 8-hour exposure. The regulations were amended in 1974 to require audiometric monitoring of all workers exposed to 8 or more hours of noise levels equal to or exceeding 85 dBA. OSHA set specific guidelines in 1983 for the establishment of hearing conservation programs for workers in noisy industries (Department of Labor, 1983). Programs were to include monitoring of noise exposure in the workplace, engineering and administrative controls, a hearing protection program to include education of employees, and hearing evaluations.

Numerous studies have suggested that TTS and PTS may be associated with hearing aid use (Harford & Markle, 1955, Naunton, 1957, Ross & Truex, 1965, Ross & Lerman, 1967, Bellefleur & Van Dyke, 1968, Macrae, 1968a, Macrae 1968b, Macrae 1968c, Roberts, 1970, Jerger & Lewis, 1975, Markides, 1976, Rintelmann & Bess, 1977, Humes, 1978, Humes & Bess 1981, Macrae 1991, Macrae, 1993, Macrae 1994, Macrae, 1995). Many industrial workers have sustained hearing losses as a result of noise exposure on the job and during recreational activities (Kramer,1990). If these workers wear hearing aids on the job there are no guidelines aimed at preventing further deterioration of their hearing. In fact, no guidelines as to maximum amplified exposure exist.

A linear hearing aid amplifies speech as well as background noise until output reaches a pre-determined saturation level (Meyer, 1985). Dolan, et al (1992) demonstrated that industrial noise amplified even by mild gain linear hearing aids rose from supposedly safe levels to above levels allowable under OSHA guidelines. Hearing instruments whose outputs change as a function of amplitude and frequency distribution of the input signal are called Automatic Signal Processing (ASP) instruments. These instruments may reduce gain in one or more areas of the frequency response as input level increases (Revit, 1991). This reduction is called compression, and may be effected in a variety of ways. Some types of compression include input and output compression, Adaptive Compression, syllabic compression, and frequency-dependent compression

(Hickson, 1994). Compression may operate in one or several frequency bands of the output spectrum. No studies in the literature have addressed the effect of using ASP hearing aids in noisy industry. The present study addresses this issue.

The purpose of this study is to determine the effectiveness of ASP systems in reducing amplified sound exposure in industrial noise. Three ASP and one linear hearing aid, programmed with a total of 14 different frequency responses aimed at reducing harmful noise exposure were used. Each aid was placed on the Knowles Electronic Mannequin for Acoustic Research (KEMAR). For each condition the input to the aids was a 90 minute segment of taped industrial noise played in sound field at 74.5 dBA TWA. A microphone recorded the output of the aid in a Zwislocki coupler inside KEMAR's head, in order to simulate the sound pressure level at the tympanic membrane of a worker wearing hearing aids on the job. An integrating sound level meter recorded the Time Weighted Average (TWA) and Equivalent Continuous Sound Level (Leq), measures of noise exposure over time, of the amplified sound during the 90 minute exposure. This study explores whether it is possible to wear hearing aids on the job in noisy industry without risking additional hearing loss from noise exposure.

CHAPTER II

REVIEW OF THE LITERATURE

Physiological Effects of Noise Exposure

Noise may damage the auditory system in one of two ways. Acoustic trauma relates to the effect of one or more exposures to extremely high levels of noise (Melnick, 1984). Hearing loss which results from chronic exposure to noise over many years is called noise-induced hearing loss (NIHL),(Robinson, 1976). NIHL is less dramatic than acoustic trauma, but a far more common cause of hearing loss in adults. The most apparent effect of noise exposure on hearing is reflected in a change in thresholds relative to a normal hearing population (Riley, et al 1965). If these changes reverse themselves after a period of recovery they are known as temporary threshold shifts (TTS). If hearing sensitivity does not return to pre-exposure levels it is known as permanent threshold shift (PTS) (Melnick, 1984).

The physiological effects of noise on inner ear structures have been studied extensively using animal models. Spoendlin (1971) exposed guinea pigs to 100 to 138 dB broad band noise for periods of time ranging from one minute to one hour. The animals were sacrificed immediately following the exposure and their cochleas examined using electron microscopy. Structural changes were observed such as distortion of both outer hair cells and dendrites to the inner hair cells. With cessation of noise exposure and periods of rest these physiological changes seemed to have reversed themselves in similarly exposed animals and it might be expected that hearing levels had recovered. With continued high levels of exposure lasting for several weeks hair cells disintegrated, dendrites ruptured, and the Organ of Corti disappeared. At this point it might be assumed that the damage to the animals' hearing had been permanent.

An acoustic "toughening" effect has been demonstrated on the hearing thresholds of noise-exposed chinchillas (Hamernik, Ahroon, Davis, & Lei, 1991). An experimental group was exposed to broad band noise for 20 days on a schedule of 6 hours of exposure time each day. The control group received the same total exposure of sound energy but their exposure schedule was continuous for five days. It was found that permanent hearing loss was significantly less (up to 30 dB) for the "interrupted" group than for the "steady state" group. Based on morphological evidence the experimenters concluded that for the "interrupted" group the efferent auditory system, particularly the outer hair cells, had mediated a protective effect on the animals' hearing. The concept that pre-exposure to low level noise may reduce hearing loss from high level noise is persistent in the literature. Animals monaurally pre-exposed to very loud sounds have been found to be protected from permanent threshold shift (PTS) when compared to a control group of animals without the pre-exposure (Cody & Johnstone, 1982). In a 1988 a study conducted by Canlon, Borg and Flock, guinea pigs which had been pre-exposed to low level noise recovered from threshold shift produced by exposure to loud sounds, whereas threshold shifts in animals not pre-exposed were permanent. The physiological basis for this phenomenon is unknown. However the authors suggest that their findings might be relevant in the prevention of permanent hearing loss in noise-exposed workers.

The results of studies of TTS using human subjects (Melnick, 1976) have suggested that shifts will reach a maximum, or asymptotic level if noise is moderately intense and exposure is of an extended duration. Asymptote is reached on average after between 8 and 12 hours of noise exposure. If the asymptotic shift is 30 dB or less, the recovery time is significantly quicker than if the shift is greater than 30 dB. After such a shift hearing levels may not return to pre-exposure levels for several days. The magnitude of the threshold shift and the range of frequencies in which hearing is affected depends on the frequency distribution of the offending noise. For broadband noise typical of that found in industry the frequencies of 3000 to 6000 Hz are maximally affected (Salvi, 1993).

Permanent loss of auditory sensitivity also seems directly related to frequency, intensity and duration of the noise (Bohne, 1976, Melnick, 1984). The stereocilia of the inner and outer hair cells are particularly prone to damage from noise exposure. Damage to these structures is often an early predictor of PTS (Canlon, 1988). However no morphological changes can be said conclusively to indicate when threshold shift of a temporary nature might develop into a permanent one. Susceptibility to both TTS and PTS varies greatly between individuals and the physical correlates are not completely understood (Robinson, 1976, Mills, 1992).

Presbycusis and noise-induced hearing loss

Presbycusis is the gradual loss of hearing sensitivity which occurs as a result of normal aging (Zemlin, 1988). Much evidence suggests that noise exposure associated with modern society hastens and intensifies this process. In studies of noise induced hearing loss it is difficult to isolate the effects of presbycusis (hearing loss associated with aging) from sociocusis (hearing loss caused by non-occupational noise exposure), or from nosocusis, (hearing loss caused by otological disease). Kryter (1983) concluded that workers routinely exposed to intense noise have hearing sensitivity approximately 10 to 20 dB below that of the general population. In addition to their higher levels of noise exposure such workers also experience a disproportionately large amount of sociocusis and nosocusis, and these factors have an additive effect on hearing loss.

Corso (1980) proposed a mathematical formula with which to quantify the presbycusic component of occupational hearing loss. Corso's work assumes that aging and noise exposure are the major contributors to hearing loss. Over time the contribution of each factor becomes stable, or asymptotic. Therefore, for individuals of different ages the relative importance of noise versus aging differs. Corso derived a variable ratio by comparing the contribution of the two factors at different stages of life in order to determine a correction factor for computing occupational hearing loss.

When using human subjects it is especially difficult to isolate the effects of aging, noise exposure, and otological pathology on hearing loss. In an attempt to control these factors Mills, Schmiedt and Kulish (1990) conducted a study on the hearing of Mongolian gerbils. The animals were born and lived the remainder of their lives in an environment in which the ambient noise level never exceeded 40 dB. Their ears were examined in order to rule out the possibility of pathology which might affect hearing sensitivity, and their hearing was evaluated at regular intervals. The gerbils approaching the end of their natural lifespans, approximately 36 months, were found to have hearing sensitivity comparable to human males 60 to 65 years of age and females 70 years of age. The results suggested that gerbils also experience a loss of hearing sensitivity with advancing age regardless of noise exposure.

Noise Control Regulations

Occupational noise levels have been increasing dramatically since the industrial revolution, when machinery began to be the source of power for most industry and transportation. In 1981 the Environmental Protection Agency (EPA) initiated an investigation of noise in the workplace (EPA, 1981) which concluded that 9.27 million Americans are exposed to levels of 85 dBA on their jobs. According to the Occupational Safety and Health Administration 2.9 million American workers have daily exposures of 90 dBA and above. The most wide-reaching method for controlling occupational noise levels has been through standards, laws, and regulations. Standards are a set of rules or guidelines developed by a consensus group. Regulations are rules prescribed by an authority such as the government, and published in a document such as the Federal Register. Laws are prescribed by an authority and enacted by Congress.

Air Force Regulation 160-3 was the first standard aimed at protecting workers from excessive noise. It required the use of hearing protection devices (HPD) in ambient levels of greater than 95 dB in octave bands of 300 to 600 Hz, 600 to 1200 Hz, and 2400 to 4800 Hz (U.S. Air Force, 1956). The regulation recommended administrative monitoring as well as use of HPDs in levels exceeding 85 dB in the specified bands.

In 1961 the International Organization for Standardization (ISO) proposed the first standard to take into account the duration of noise exposure. A maximum limit of 85 dB in octave bands centered at 500, 1000, and 2000 Hz was to be allowed for exposures equal to or exceeding 5 hours. The Committee on Acoustics, Bioacoustics, and Biomechanics (CHABA) published a report (Kryter, Ward, Miller & Eldridge, 1966) with curves detailing tolerable exposure levels and duration times for noise levels from 85 to 135 dBA. Higher noise levels were considered safe if exposure times were decreased.

The first national legislation aimed at preventing hearing loss due to occupational noise exposure was the Walsh-Healey noise standard of 1969. It states that workers may be exposed to noise levels up to 90 dBA for a maximum of 8 hours. The level may increase by 5 dB for each halving of exposure time. This is known as the "exchange rate" between time and intensity. A more conservative exchange rate of 3 dB is the norm in most European countries (Suter, 1988). When levels exceed this maximum level employers must provide HPDs and employees must wear them. The Walsh-Healey noise standard also specifies that impulse noise (transient sounds having a duration of one second or less) may not exceed 140 dB. An ongoing hearing conservation program must exist at any site where noise levels exceed maximum allowable levels.

In 1970 Congress enacted the Occupational Safety and Health Act. It gave the responsibility for conducting research and developing standards relative to occupational safety to an organization called the National Institute for Occupational Safety and Health (NIOSH). OSHA was created as a section of the U. S. Labor Department to enact NIOSH recommendations. In 1971 OSHA adopted the Walsh-Healey noise standard and its provisions were extended to apply to not only employers with government contracts, but also the those involved in interstate commerce. Based on mounting evidence that 8-hour daily exposures of 90 dBA of noise posed an unreasonable risk of hearing loss, NIOSH sought to lower the allowable level to 85 dBA (NIOSH, 1972). An acoustical consulting firm (Bolt, Baranek & Newman, 1973) reported that the cost to American industry to comply with the proposed standard would be in the billions of dollars range. At the time the economic climate of the country was such that requiring industry to limit workers' daily exposure to 85 dBA was financially as well as politically untenable (Suter, 1988). As a compromise OSHA proposed to initiate hearing conservation programs in work sites with noise levels of 85 dBA or higher. This proposal in combination with more detailed requirements regarding noise monitoring and worker testing and education comprise the requirements in effect today (Department of Labor, 1983).

A worker's noise dose (Dn) is calculated by adding actual noise exposure times which have been divided by permissible noise levels. When Dn exceeds 100% hearing conservation measures must be employed (Oregon Occupational Safety and Health Code, 1983). A criterion sound level and a criterion sound duration in conjunction constitute noise dose. According to OSHA criterion sound level equals 90 dBA and criterion sound duration is 8 hours.

Time Weighted Average (TWA) sound level is that level which, if constant over an 8 hour period, would result in the same noise dose. OSHA defines TWA using a 5 dB exchange rate and an 80 dB threshold. A-weighting is used in sound measurement to de-emphasize the low frequency component of noise in order to simulate the action of the human auditory system (Ward, 1976).

Another measurement of sound level over time is the equivalent continuous sound level (Leq). Leq is defined as the continuous sound level which, integrated over a period of time, results in sound energy equal to a variable sound level integrated over the same period of time (Earshen, 1986).

Hearing aids and noise exposure

Those who wear hearing aids on the job, particularly in noisy industries, may be at further risk for noise-induced hearing loss. It has been demonstrated that hearing aid use on the job may expose workers to unsafe noise levels (Dolan et al, 1992). Time weighted average (TWA) and noise dose (Dn) specified by OSHA as safe for unaided ears may not be appropriate for workers who use hearing aids.

The subject of whether hearing aid use can damage users' residual hearing has been debated in the literature for over 50 years. Berry (1939) stated that hearing aid use posed no danger to a listener's residual hearing. According to Holmgren (1940) hearing aid use did not cause further harm to hearing. In fact, he suggested that amplification had had a beneficial effect on auditory sensitivity in several cases. A study conducted by Barr and Wedenberg (1965) reported similar findings. They divided subjects into experimental groups according to whether their hearing loss was "exogenous" (acquired) or "endogenous" (congenital). They found no evidence of further deterioration of hearing which they could attribute to use of amplification. Naunton (1957) also reported improved hearing thresholds in aided ears compared to those unaided, in his study of 120 adult users of the British Government-issued Medresco hearing aid. Subjects of this study were divided into groups according to age, rate of hearing aid use, and etiology of hearing loss. Although his findings failed to reach a level of significance, Naunton suggested that the improvement was found in long-term, frequent users but not in those who wore their hearing aids infrequently or for short periods of time. It was Naunton's contention that individuals with sensorineural hearing loss would refrain from using the aids at such a level as to be potentially damaging, due to their sensitivity to loud sounds. Therefore declines in residual hearing would necessarily be attributed to factors other than amplification. These findings were supported by Bellefleur and Van Dyke (1968) in their 10 year study of long-term effects of amplification on the residual hearing of 58 residents of the Clarke School for the Deaf in Massachusetts. They found no significant changes indicating that the childrens' hearing thresholds had deteriorated as a result of hearing aid use. The authors echoed Naunton's (1957) hypothesis that subjects who wore aids sufficiently powerful to damage their residual hearing were operating the instruments at comfortable, and therefore safe levels.

Ross and Lerman (1967) also failed to correlate progressive hearing loss with hearing aid use. Their study incorporated 18 subjects who used monaural amplification. The unaided ears of these subjects were used as a control. Relative threshold shifts of about 5 dB were found in both aided and unaided ears. Because information about the etiology of the hearing losses was unavailable for most of the subjects, the authors were unable to rule out spontaneous progressive loss as a variable. Although the authors failed to link the relative shifts with hearing aid use they advised that caution be used in fitting children with high gain aids by limiting the Maximum Power Output (MPO) and scheduling them for frequent audiological evaluations. Titche, Windrem & Starmer (1977) studied the hearing of 261 hearing aid users over a 10-year period. They found no evidence to suggest that hearing losses in aided ears had resulted from hearing aid use.

Markides (1976) also studied threshold shifts in childrens' aided and unaided ears and found hearing sensitivity improved in aided ears and worsened in those unaided. Results suggest that rather than due to a change of threshold, the disuse of the unaided ears contributed to the loss of acuity. The greater dependence on the ears with hearing aids may have encouraged improved acoustic awareness.

Many studies have documented individual case histories in which further hearing loss occurred in an aided but not in an unaided ear (Harford & Markle, (1955), Sataloff, (1961), Ross & Truex, (1965), Roberts, (1970), Hawkins, (1982). The first group study of this type to conclude that hearing aid use was potentially harmful to residual hearing was conducted by Kinney in 1961. Subjects were 178 children who wore hearing aids. They were divided into 2 groups based on the power of the hearing instrument used. However neither information regarding duration of use, nor volume settings were recorded. Results of Kinney's study suggested that use of powerful hearing aids by children with sensorineural hearing impairment may cause further decrements of hearing. Kinney advised against the use of instruments with greater than 40 dB of gain, even if speech awareness might improve with a higher level. He also advised against binaural hearing aid fittings for children, with the rationale that any threshold shifts resulting from amplification could recover if the instrument were periodically switched to the other ear. Macrae and Farrant (1965) studied threshold shifts in 87 children with sensorineural hearing impairment. The children were all aided monaurally and their unaided ears used as a control. The researchers found both temporary and permanent threshold shifts in both ears. However shifts recorded in subjects' aided ears were significantly greater than in unaided ears. Subjects with moderate initial losses suffered greater threshold shifts than those whose losses were more severe. Furthermore, the more hours a day amplification was used and the higher the gain, the greater the shift. Hearing losses of a congenital nature were found to be no more susceptible to further deterioration following hearing aid use than acquired losses. Macrae and Farrant suggested that Maximum Power Output (MPO) of the hearing aids be kept as low as practicable, that user's hearing be evaluated regularly, and that hearing aid use be avoided in high levels of ambient noise. Similar findings and recommendations were reported in subsequent studies (Macrae 1968a, Macrae 1968b, Macrae 1968c). Jerger and Lewis (1975) also advocated a cautious approach in fitting children with powerful binaural hearing aids. They acknowledged that while binaural amplification is educationally advantageous for children with binaural hearing loss, the danger of threshold shifts from hearing aid use must not be discounted. Noise exposure from classroom auditory trainers, particularly in schools for the hearing impaired has also been cited as a potential source of noise exposure (Rintelmann & Bess, 1977, Jerger & Lewis, 1975, Humes & Bess, 1981).

Macrae (1991) suggested that overamplification by hearing aids caused PTS in children with sensorineural hearing loss. The observed configuration of the hearing loss was flat across the frequencies, similar to other types of noise-induced hearing loss. It was hypothesized that hearing aid users with sensorineural hearing loss experience less damage from noise than normal hearing individuals, and that the time course of the loss progresses more slowly. To predict PTS from hearing aid use in individuals with sensorineural hearing loss Macrae applied Humes and Jesteadt's (1989) Modified Power Law (MPL) and Kraak's (1981) logarithmic equation for predicting hearing loss from noise exposure (Macrae 1991, Macrae 1993, Macrae 1995). The danger of TTS and

PTS from hearing aid use intensifies when the aids are worn consistently at higher than recommended use settings in noisy environments (Macrae, 1994). In severely hearing impaired hearing aid wearers asymptotic threshold shift could be expected after 8 to 10 hours of hearing aid use, although the shifts were far less than those considered capable of causing PTS (Melnick, 1976). The shifts were most common when amplification exceeded levels recommended by the National Acoustics Laboratory (NAL).

Macrae (1993) suggested that according to the MPL even with recommended levels of gain small temporary threshold shifts, on the order of 1 or 2 dB will occur for full-time users of powerful hearing aids. He recommended gain reduction to minimize asymptotic threshold shift. Like other forms of acoustic overstimulation, noise induced hearing loss resulting from hearing aid use is affected strongly by noise dose (Dn). Traditionally PTS has been predicted by determining TTS at frequencies at or above 1000 Hz at a predetermined interval following noise exposure (Humes & Bess, 1981). In order to consider the growth of and recovery from TTS an equation has been derived in which TTS is calculated at intervals throughout its growth and recovery stages (Kraak, Ertel, Fuder, & Kracht, 1974). The time integral of TTS or ITTS, may be a more useful predictor of PTS than is a measure of TTS obtained at one interval following noise exposure. This relates particularly to full-time users of powerful hearing aids (Humes & Bess, 1981) who are exposed routinely to impulsive or intermittent noise (Robinson, 1976). As with other types of noise exposure, the frequency of the stimulus, duration of exposure, and saturation sound pressure level (SSPL), or maximum output of the hearing aid (Humes, 1978) affect TTS associated with hearing aid use most significantly.

Noise Reduction Systems in Hearing Aids

Hearing aids are designed to amplify soft sounds as well as to prevent loud sounds from causing listener discomfort. Traditional hearing aids accomplish output limitation by "peak clipping" (Skinner, 1988). This occurs when output sound pressure level (SPL) surpasses a pre-determined maximum level. Beyond this point there is no significant increase in output, regardless of input level. When operating in saturation the instrument limits the amplitude of the sound waves comprising the output signal (Staab & Lybarger, 1994). Peak clipping distorts the output and detracts from sound quality (Skinner, 1988). This type of output limitation is termed linear because until reaching saturation, the input signal has a one-to one relationship with the output signal (Hickson, 1994).

Non linear, or Automatic Gain Control (AGC) hearing aids incorporate a monitoring circuit which reduces or intensifies the signal depending on its magnitude (Staab & Lybarger, 1994). It may be either input or output compression, depending on the location of the monitoring circuit relative to the user-operated volume control. With an output compression system the volume control affects gain only. For input AGC systems changing the volume control affects both gain and maximum output. Compression limits gain without the distortion caused by peak clipping by compressing the signal into the listener's dynamic range. Parameters such as compression kneepoint (or threshold) and compression ratio may be manipulated depending on the listening environment. The kneepoint refers to the level at which compression begins to operate. The compression ratio is the change in input level as compared to the corresponding change in output. One drawback of AGC hearing aids is that continuous low frequency background noise such as that typical of a noisy factory may cause the hearing aid to stay in compression for extended periods of time. The result may be inadequate amplification for high frequency signals, such as speech (Sammeth & Ochs, 1991). Multichannel compression systems have been developed to alleviate such problems. In an instrument with several channels corresponding to different frequency regions compression may operate only in the low band, or have a much lower compression threshold there than in the other bands. The goal of such a system is to attenuate low frequency sounds while preserving softer sounds such as the high frequency components of speech (Smriga, 1991). Some instruments, such as the Argosy 3-Channel Clock allow the location of the center band to move, in order to accommodate unusual hearing loss configurations. Circuits which modify gain and frequency response relative to the input signal are called Level Dependent Frequency Response (LDFR) circuits. Bass Increase at Low Levels (BILL) circuits amplify low frequency sounds to a greater degree when input levels are relatively low. Treble Increase at Low Level (TILL) instruments provide more high frequency emphasis when input is quiet. Programmable Increase at Low Level (PILL) circuitry allows the audiologist to make adjustments which provide either BILL or TILL responses depending on the listening environment (Killion, Staub, & Preves, 1990, Stypulkowski, 1993). It is also possible with (ASP circuitry) to account for changes in the temporal characteristics in different listening situations. Adaptive Compression developed by Telex in 1988 (U.S. Patent 4,718,099) varies compression release and attack times as a function of changes of the input signal. A hearing instrument with Adaptive Compression goes into compression and recovers quickly in response to brief, intense signals. When stimuli are of a longer duration, recovery is more gradual (Teder, 1993). Results of studies as to the advantages of linear over compression aids, or which type of compression reduces noise and/or enhances speech intelligibility most effectively have failed to reach a consensus (Hickson, 1994).

Word Understanding with Noise Reduction Systems in Hearing Aids

Fabry and Van Tasell (1990) conducted a study in which 12 subjects with sensorineural hearing impairment listened to connected, recorded discourse presented in speech-weighted noise with hearing aids employing the Argosy Manhattan circuit. This circuit is designed to increase levels of high frequency sound (the portion of the spectrum where consonant sounds are located) when levels of background noise (presumably low frequency) increase. With the Manhattan circuit activated, subjects demonstrated no increase in speech understanding compared to that shown when the hearing aids did not employ the selective filtering. Similar results had been reported by Van Tasell, Larsen, and Fabry (1988) and in a subsequent study by Fabry (1994). Consonant recognition in speech-babble and low frequency noise declined when subjects listened through "noise suppression" hearing aids employing both low frequency attenuation and compression (Tyler & Kuk, 1989). Results suggested that attenuating low frequency sounds in an attempt to separate background noise from speech sacrificed some useful low frequency speech sounds (vowels), and that compressing the speech signal introduced temporal distortion. The authors suggested that these hearing aids may provide greatest benefit by 1) increasing user comfort for high input levels and 2) decreasing distortion by increasing saturation levels (Tyler & Kuk, 1989, Sammeth & Ochs, 1991). According to Plomp (1988) individuals with sensorineural hearing impairment require strong amplitude contrasts in the speech signal for maximal understanding. He maintained that because compression with small time constraints (also called syllabic compression) reduces these peaks, natural amplitude variations are distorted. For this reason he advocated linear fittings for those with sensorineural hearing impairment for optimal word understanding in noise.

Moore (1991) presented an opposing view by asserting that recruitment (the abnormal growth of loudness) causes many individuals with sensorineural hearing impairment to process amplitude variations of input signals improperly. Therefore these variations provide no useful information for speech understanding, and it is desirable to minimize them. Positive effects on speech discrimination in noise were found when compression operated in up to 31 channels, with compression ratios adjusted in each channel individually to accommodate subjects' hearing loss (Crain & Yund, 1995). When the same compression ratio operated in each channel, performance decreased as 1) the number of channels increased and 2) the compression ratio increased. Yund and Buckles (1995a) found significantly improved word recognition when subjects listening to speech in noise through hearing aids employing multichannel compression (MCC) had a period of time in which to become accustomed to the processing. The same improvement did not occur after an adjustment period with linear amplification. MCC processing was found to provide the greatest benefit to individuals with mild to moderate hearing losses listening to speech in noise in low signal-to-noise ratio conditions (Yund & Buckles, 1995c).

CHAPTER III

METHODS

Stimulus and stimulus presentation

A 2-hour segment of industrial noise was recorded during a work shift at the Beaver Heat Treating Company in Milwaukie, Oregon. Noise measurements were made with a TEAC DA-P20 digital audiotape recorder held under the experimenter's left arm, connected by a shoulder strap attached to the carrying case. Recordings were made on a two hour digital Maxell audiotape. A Larson-Davis 812 precision sound level meter with a Larson-Davis 2560 one-half inch air condenser microphone was used to transduce the sound. A cable connected the recorder to the sound level meter. Sound was recorded on the left channel only, with the recording level set at 0 dB. The microphone of the sound level meter was held in the right hand at a 45 degree angle to the floor. Readings were taken while the experimenter walked through the plant, pausing within 1 to 2 feet from each sound source for approximately 5 to 10 minutes to simulate a worker's exposure to noise during a typical shift of work. The sound level meter was calibrated immediately prior to all sound measurements using a Larson Davis CA 250 calibrator according to procedures outlined in the user's manual.

Aided and unaided noise measurement

Figure 1 shows a diagram of the instrumentation used in determining aided and unaided exposures. In order to measure unaided noise exposure over a period of 90 minutes the Knowles Electronics Mannequin for Acoustic Research (KEMAR)[1] was

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[1] The Knowles Electronics Mannequin for Acoustic Research (KEMAR) is designed to have the dimensions and, therefore, to simulate acoustic properties of the average adult head and torso.

placed in a sound-isolated chamber (Industrial Acoustics Company Inc. model #SP 403), such that the vertex of its head was 32 inches from a Realistic Nova 15 loudspeaker. A microphone attached to a preamplifier was fastened 1.5 inches from the center of KEMAR's shoulder and 6 inches from the concha with cellulose tape. The recorded industrial noise was started one minute into the tape and played through the loudspeaker for 90 minutes. Equivalent continuous levels and Time Weighted Averages were measured in the coupler in the unaided condition.

To measure aided noise levels, each hearing aid was placed on KEMAR's right ear. The Danavox, a post-auricular style instrument, was coupled to a silicone earmold made for KEMAR's ear. The in-the-ear instruments were placed in the ear canal. The 90-minute noise tape was played for the 4 hearing aids configured in a total of 14 different conditions. Inside the sound isolated chamber, SPL was measured in the Zwislocki coupler[2] inside KEMAR's head. An ACO Pacific 4012 1/2 inch air condenser microphone in the position of KEMAR's eardrum was connected to an ACO Pacific preamplifier which was in turn connected to an ACO Pacific PS 9200 power supply. Output of the power supply was routed to a Rane PE 17 parametric equalizer. The equalizer was used in order to flatten the frequency response by attenuating high frequencies to compensate for resonance of the Zwislocki coupler. A flatter frequency response was desirable to make noise measurements compatible with OSHA measurements. Output of the equalizer was connected to a Larson-Davis sound level meter by means of a Larson-Davis AD005 adapter. The sound level meter was calibrated using a Larson-Davis CA 250 calibrator. During calibration the equalizer was

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[2] The Zwislocki coupler is designed to have the same impedance and resonating characteristics as an average adult ear canal. Therefore, in situ measurements using KEMAR and a Zwislocki coupler closely approximate sound reaching a median adult eardrum.

set on bypass. Calibration was checked and re-set with every battery change of the integrating sound level meter.

The noise was presented by the TEAC model DA-P20 DAT recorder, amplified by an NAD Stereo Power Amplifier, and attenuated by a Leader LAT-45 attenuator. A Realistic Nova 15 loudspeaker delivered sound to KEMAR. OSHA TWA and Leq were measured in the Zwislocki coupler first in the unaided condition and then for each aided condition.

Hearing Aids

Three different models of ASP hearing aids were used in this study. The hearing instruments are as follows: 1) the Telex 28 AC with Adaptive Compression, 2) the Argosy Expander, (an experimental instrument designed to reduce noise exposure) and 3) the Danavox 143X Aura. An Argosy 3-Channel Clock, a linear instrument was also used. Each instrument was placed on or in KEMAR's right ear. Output of each aid was measured by means of a Zwislocki coupler and an ACO Pacific 1134 1/2 inch microphone. The recorded noise was played at a distance of 32 inches measured from the vertex of KEMAR's head to the front edge of the loudspeaker and the output of each of the hearing aids recorded. Each hearing aid was programmed individually for a total of 14 different conditions in an attempt to determine which condition would reduce the level of the noise coming through the hearing aid most effectively. Instrumentation used for noise measurements is pictured in figure 2.

Prior to the noise measurements, the response of each aid was measured using a Fonix 6500 hearing aid test system and KEMAR. A loudspeaker was placed 12 inches from KEMAR's ear at a 45 degree angle. The sound source was a 70 dB broad-band composite signal. A probe tube connected to the microphone of the Fonix system was placed inside the Zwislocki coupler in KEMAR's head. A reference microphone was attached with a Velcro headband above KEMAR's ear and a "real ear" unaided curve was generated by presenting the 70 dB composite signal to KEMAR in the unaided condition. Real ear insertion gain was measured using KEMAR and the Zwislocki coupler. Insertion gain is a measurement made in the ear canal of the gain the hearing aid is providing (Skinner, 1988). Target gain was based on a hypothetical audiogram (fig. 1) using the National Acoustic Laboratories (NAL) procedure (Byrne & Tonisson, 1976). This audiogram represents a noise-induced hearing loss which might be expected in a chronically exposed worker. Each hearing aid was adjusted such that its insertion gain in KEMAR and the Zwislocki coupler approximated the target gain curve.

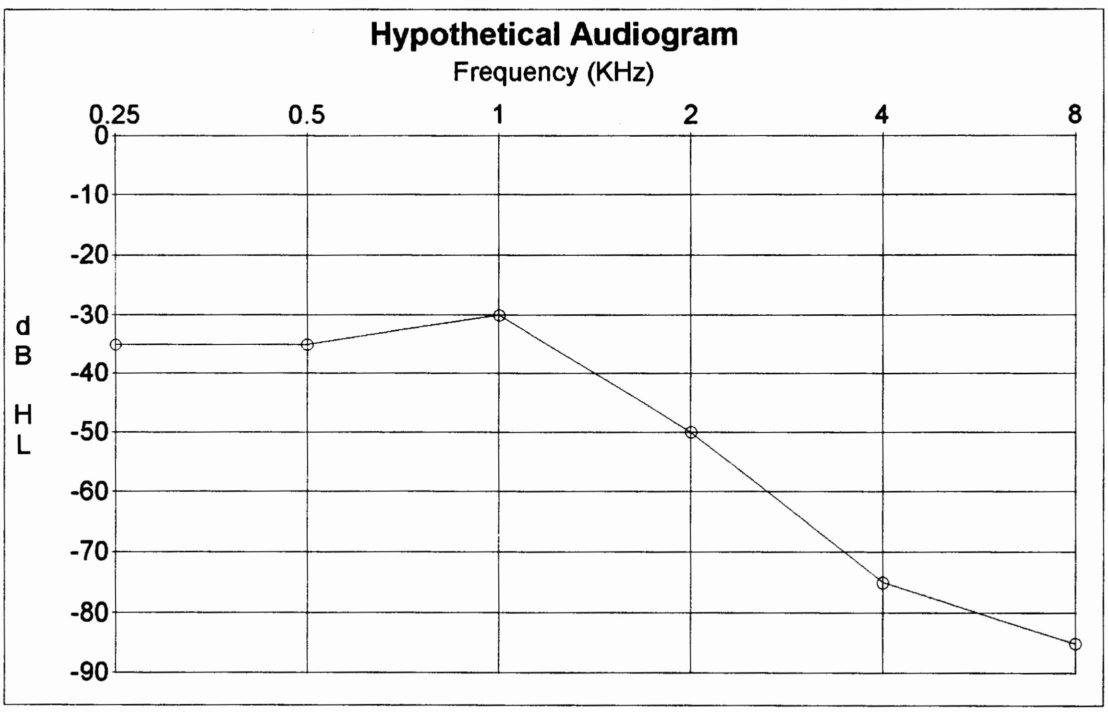

Fig. 1 Hypothetical audiogram of a noise exposed worker

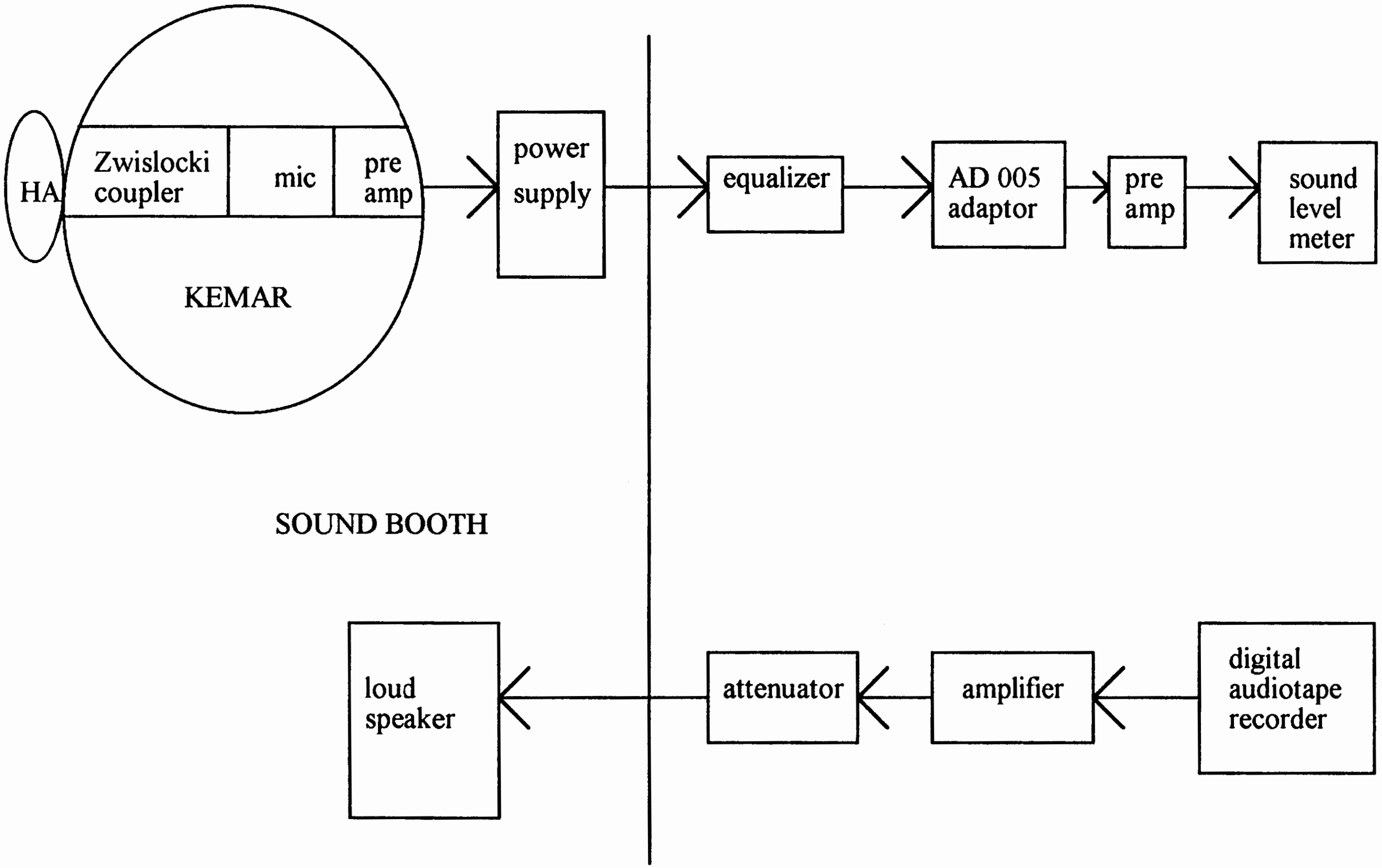

Fig. 2 Block diagram of instrumentation used in noise measurements.

Figure 3 is a real ear curve representing the Argosy Expander experimental hearing aid set to condition 1 (linear). Frequency in KHz is shown as a function of gain in dB. The curve which appears as a solid line represents target gain or, based on the individual's audiogram, the amount of gain the aid should be providing. The dashed line represents the insertion gain or the amount of gain measured in the ear canal that the instrument actually is providing (Skinner, 1988). For maximum user benefit in quiet the line representing insertion gain should match the line representing target gain as closely as possible. This is a typical match. Real ear curves of the remaining hearing aid conditions are shown in Appendix B.

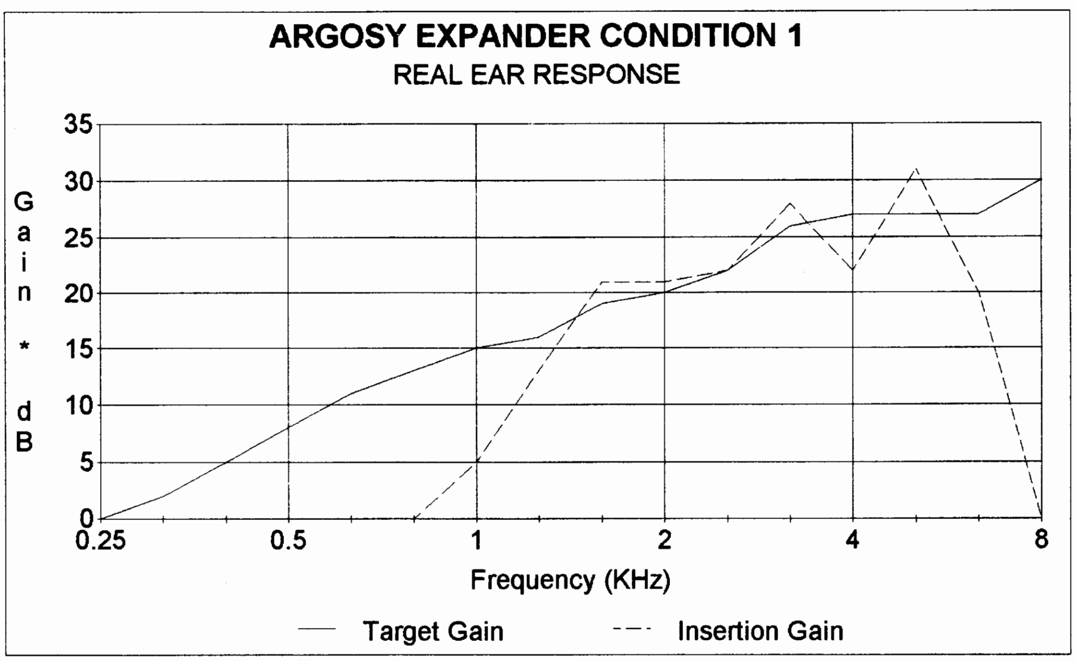

Fig. 3 Real ear curve representing insertion gain provided by the Argosy Expander in linear mode

CHAPTER IV

RESULTS

Figures 4 through 8 are graphs of equivalent continuous sound level (Leq) as a function of time for a 90 minute segment of industrial noise. Figure 4 shows Leq values for noise amplified by the Argosy Expander. The Expander is an experimental hearing aid for use in noise. It uses input compression with a 50 dB compression threshold and a 15 to 1 compression ratio when operating in maximum compression. The lowest curve represents the ambient or unaided condition, where levels range from 72 to 92 dBA, resulting in a TWA of 74.5 dBA. The highest curve shown in figure 4 represents Leq measured with the Expander set to condition 1, a linear mode. Levels vary only by 2 dB, suggesting that the instrument was saturating. The next curve shows levels recorded with the instrument set to condition 3, which utilizes maximum low cut and maximum compression. Resulting levels are between 90 and 97 dBA TWA. The final curve in the series represents Leq recorded with the Expander set to condition 2, in which gain and SSPL 90 (maximum output) were reduced and compression was set at maximum. Leq here ranges between 80 and 84 dBA, resulting in a TWA of 80.7, well below the OSHA maximum. The peaks of the exposure curve which were present in the unaided condition here are largely non-existent, indicating that the instrument was operating in full compression.

The lowest curve in figure 5 represents the ambient noise condition with no hearing aid used. Leq levels range from 75 to 92 dBA, resulting in a projected 8-hour TWA of 76.2 dBA. The top curve represents sound levels amplified by an Argosy 3-Channel Clock set to condition 1, a linear setting matching target gain at all frequencies. Leq in this condition ranges between 100 and 110 dBA. The projected 8-hour TWA for this condition was 93.2 dBA which was above the OSHA maximum of 90 dBA. The middle curve shows Leq of levels recorded through the 3-Channel Clock set to condition 2 which is a linear condition in which target gain is matched at 3 and 4 KHz, and low and middle frequency gain is reduced. Levels here were raised to between 85 and 95 dBA with a TWA of 88.8 dBA, which is below the OSHA maximum.

Figures 6 and 7 are graphs of Leq as a function of time for industrial noise levels recorded through the Danavox Aura 143X. The Danavox Aura utilizes multichannel input compression. AGC thresholds are set individually in the 3 channels, with a 5 to 1 compression ratio in each band. The lowest curve of figure 6 represents ambient, unaided noise levels. These ranged from 72 to 92 dB Leq, as in the unaided condition in figure 4. Noise recorded at the output of the Danavox Aura set to programs 1 and 2 resulted in nearly overlapping curves pictured at the top of figure 5. Program 1 was a linear setting. Amplified levels ranged between 95 and 115 dBA, resulting in a TWA of 103.4. Program 2 was a simulated BILL response(AGC thresholds of 60 dB in the low band, 70 dB in the middle band, and 80 dB in the high band with active low cut to 1000 Hz). This setting reduces amplification in the low frequencies at high input levels. Amplified levels here ranged between 94 and 112 dBA with a TWA of 101. The curve representing program 2 is almost identical to that representing the linear condition, suggesting that the BILL setting was not significantly more effective in reducing noise in this case than the linear setting. The next lower curve represents noise recorded through the Danavox Aura set to program 3, a simulated TILL response. AGC thresholds are 80 dB in the low band, 70 dB in the middle band, and 60 dB in the high band, with active low cut to 600 Hz.. Output levels in this case are between 85 and 95 dBA. Some peaks in the noise are preserved but the range of noise levels is reduced relative to the unaided condition, presumably due to the middle and high frequency compression. The relatively low compression threshold in the high band (60dB) and the active low cut to 600 Hz may have caused this to be the most effective of the Danavox Aura programs included in this study in reducing overall exposure levels. Using TILL processing, in which the high frequency portion of the noise spectrum is reduced at high input levels, it was possible to achieve an OSHA TWA of 90.7, which is within 1 dB of the OSHA maximum of 90 dB TWA.

Figure 7 shows exposure histories for 4 other settings of the Danavox Aura. The lowest curve on the graph on figure 7 represents ambient, unaided noise levels. Both programs 4 and 5 were linear with a high frequency emphasis. However program 5 also employs reduced gain in the low band. When the noise was amplified by the Danavox Aura set to programs 4 and 5, the curves overlapped and levels ranged between a 95 and 115 dBA Leq. OSHA TWAs are 102.6 and 102.5, respectively. Although levels are higher, the range of levels is comparable to that measured in the unaided condition, reflecting the linear processing. The next lower curves represent levels for programs 6 and 7, both providing broad band compression. The curves for these programs essentially overlap, occupying a range between 85 and 95 dBA, a more compressed range than that of the unaided condition. Program 6 employs low cut to 1200 Hz and AGC thresholds of 60 dB in the low band, 70 dB in the middle band, and 70 dB in the high band. The TWA for program 6 was 91 dBA. Program 7 also features active low cut to 1200 Hz, but AGC thresholds are 75, 75, and 85 dB in the low, middle and high bands. OSHA TWA was 91.3 dBA in this case, again slightly above the OSHA maximum.

Figure 8 represents levels of noise amplified by the Telex 28 AC with Adaptive Compression. Telex Adaptive Compression employs output compression which has a 1 to 1 (linear) compression ratio until limiting, at which point the ratio becomes 8 to 1. The lowest curve, with an Leq range of 72 to 92 dBA represents unaided levels. The highest curve in figure 7 represents continuous equivalent level of industrial noise between 102 and 109 dBA, as recorded through the hearing aid set to linear mode (condition 1). Saturation seems to occur in this condition, preventing amplified levels from exceeding 110 dBA. The middle curve pictured represents Leq of noise amplified by the Telex instrument set to maximum Adaptive Compression, (condition 2). Levels range between 101 and 105 dBA. The peaks of the noise are almost absent, presumably due to the action of the compression. Table 1 summarizes hearing aid settings and OSHA TWAs of noise amplified by each hearing aid in each condition.

Hearing Aid	Setting	TWA (OSHA) dBA
Argosy 3-Channel Clock		
Condition 1	linear, match target gain at all frequencies	93.2
Condition 2	linear, match target gain at 3 & 4 KHz, reduced gain in low & middle bands	88.8
Argosy Expander		
Condition 1	linear	108.7
Condition 2	reduced gain & SSPL 90, maximum compression	80.7
Condition 3	maximum low cut, maximum compression	93.7
Danavox Aura 143x		
Program 1	linear	103.4
Program 2	low cut to 1 KHz, AGC threshold of 60 dB in low band, 70 in middle band, 80 in high band	101
Program 3	low cut to 600 Hz, AGC threshold of 80 dB in low band, 70 in middle band, 60 in high band	90.7
Program 4	linear, high frequency emphasis	102.6
Program 5	linear, high frequency emphasis, reduced gain in low band	102.5
Program 6	low cut to 1200 Hz, AGC threshold of 60 dB in low band, 70 in middle band, 70 in high band	91
Program 7	low cut to 1200 Hz, AGC threshold of 75 dB in low band, 75 in middle band, 85 in high band	91.3
Telex 28 AC		
Condition 1	linear	106.8
Condition 2	maximum Adaptive Compression	102.8

Table 1

Figures 4 through 8 are graphs of Leq in dBA as a function of time in hours and minutes representing noise amplified by the hearing aids in each condition.

Argosy (Experimental Noise Reducer)

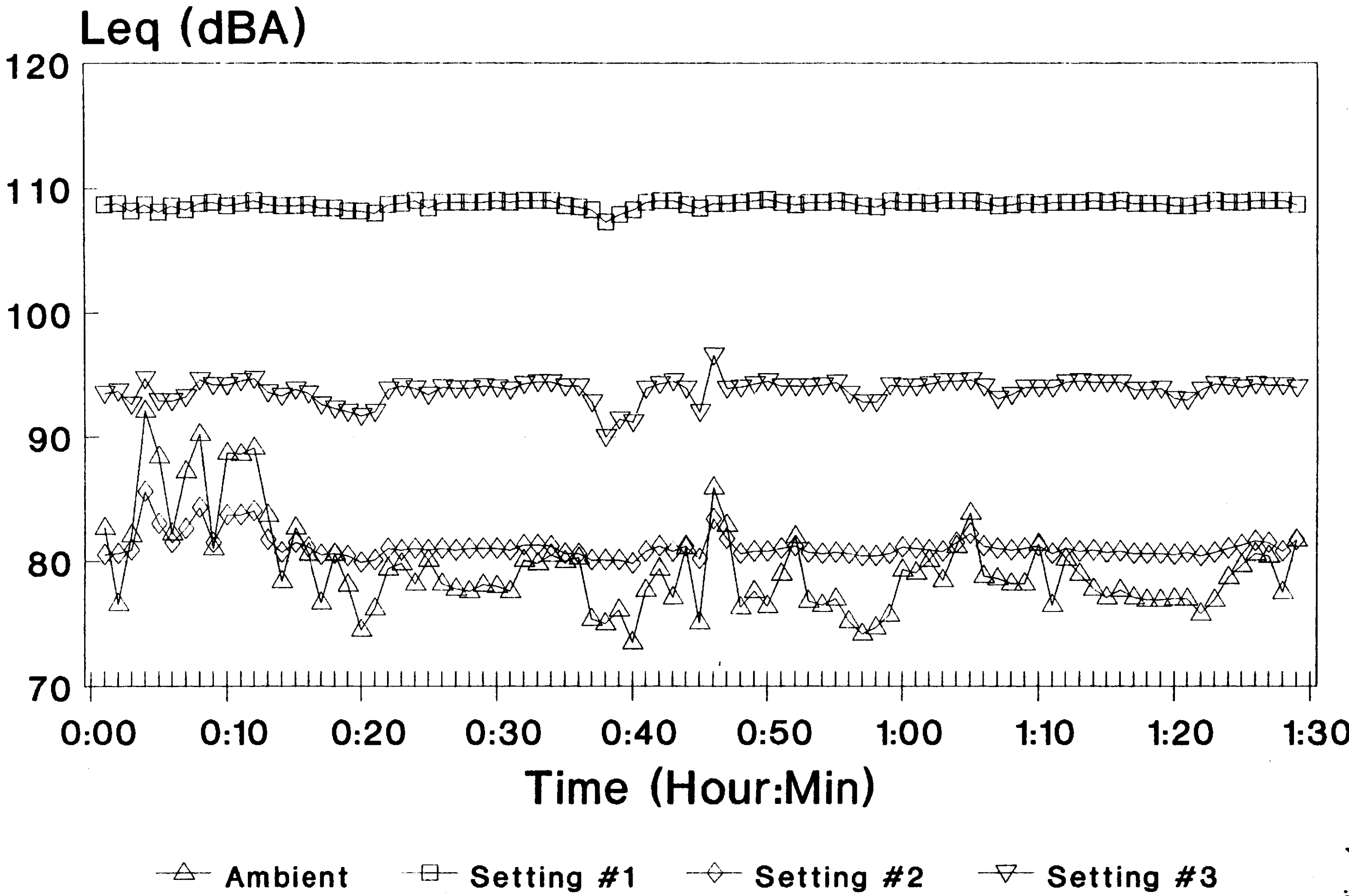

Fig. 4

Heat Treating Plant
Argosy Clock

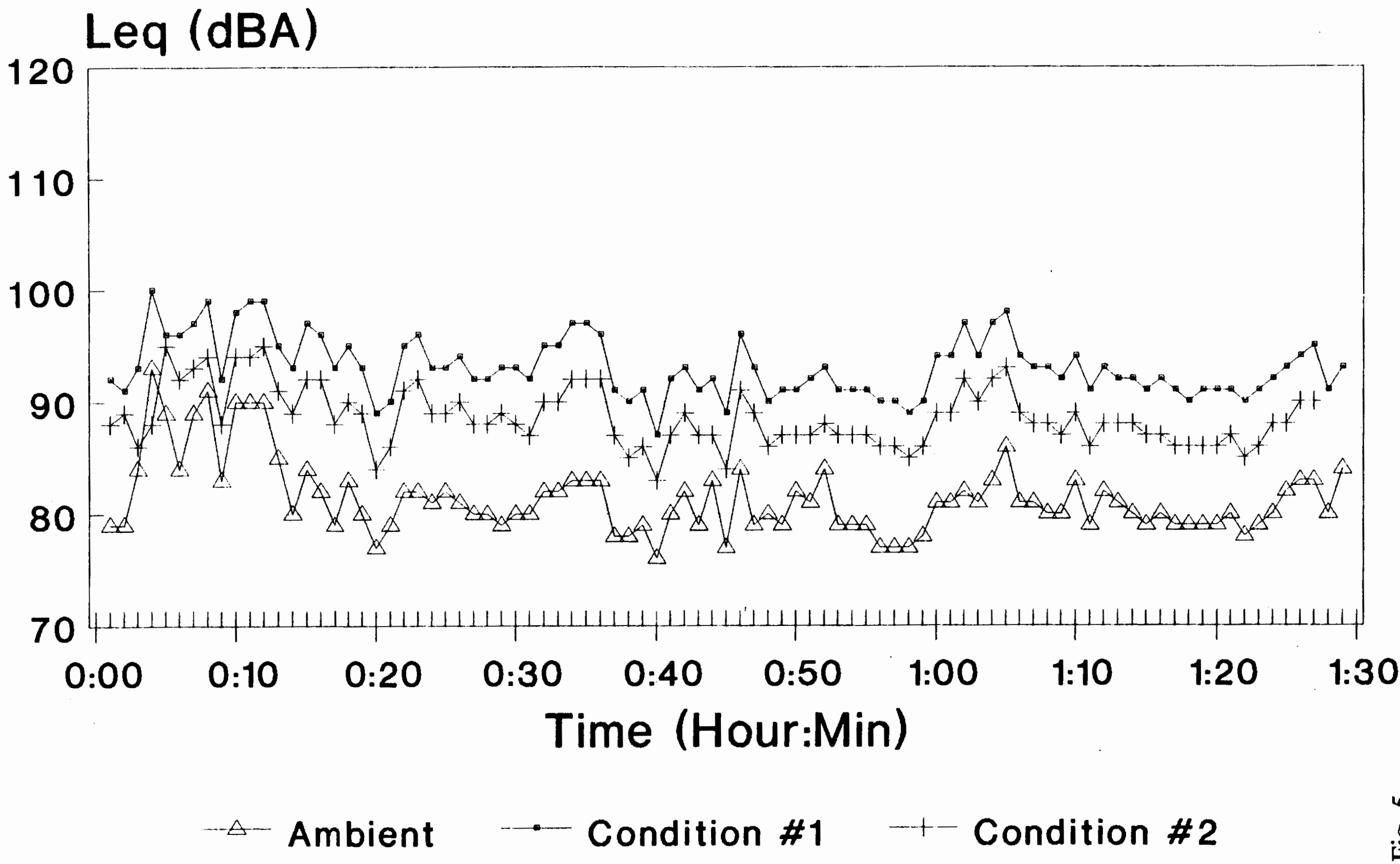

Fig. 5

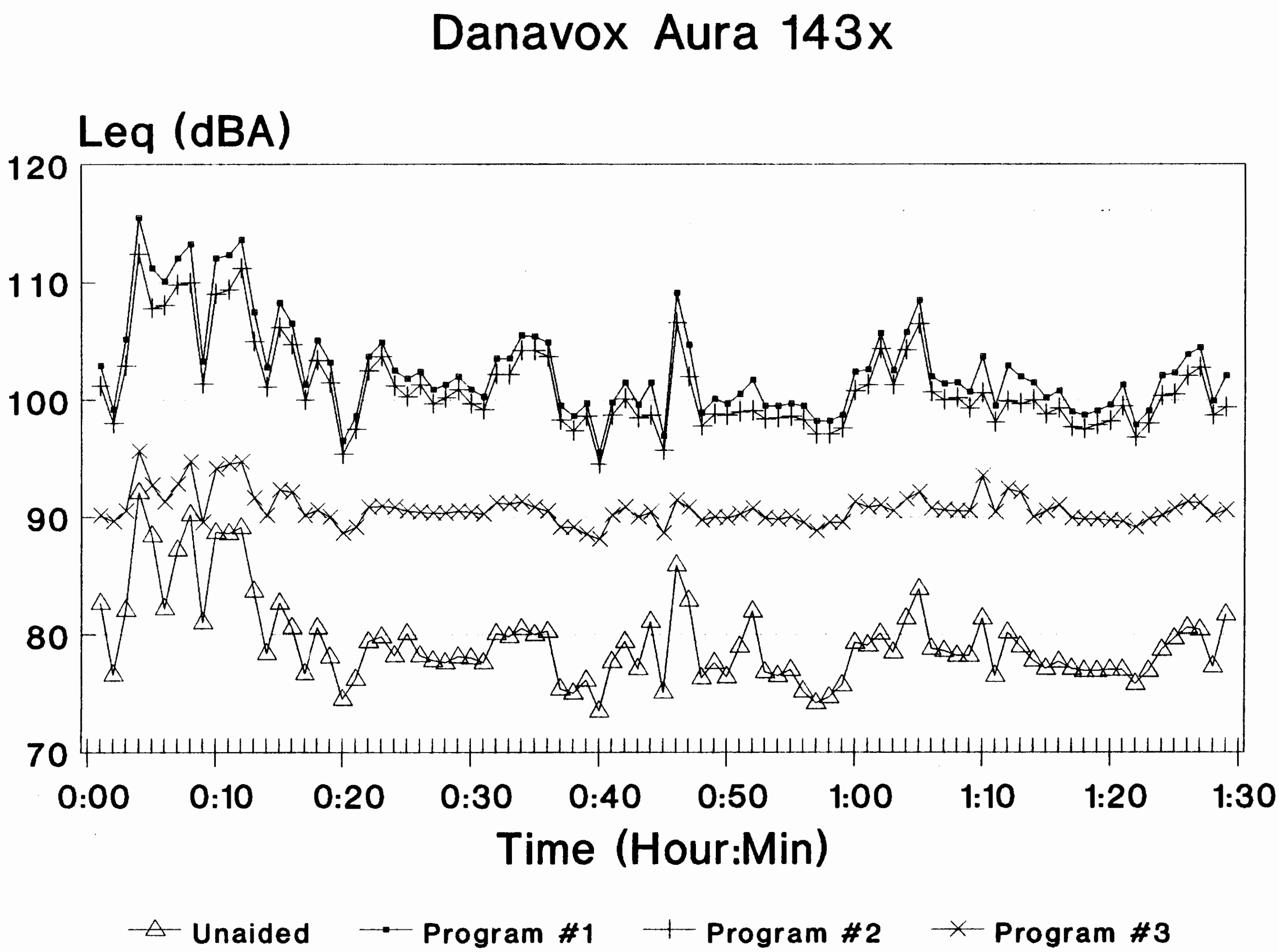
Danavox Aura 143x
Leq (dBA)
120
110
100
90
80
70
0:00
0:10
0:20
0:30
0:40
0:50
1:00
1:10
1:20
1:30
Time (Hour:Min)
Unaided
Program #1
Program #2
Program #3

Fig. 6

Danavox Aura 143x

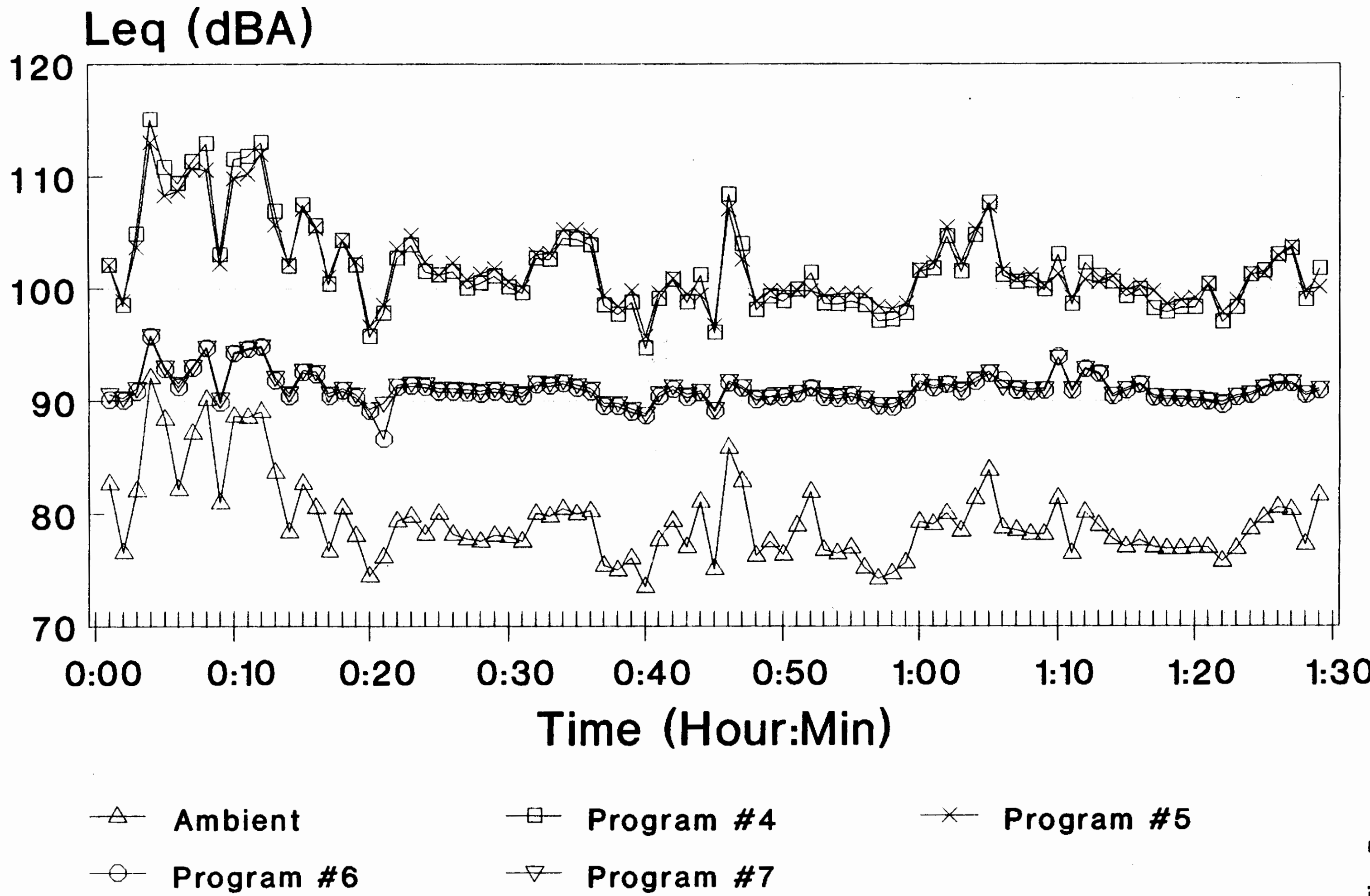

Fig. 7

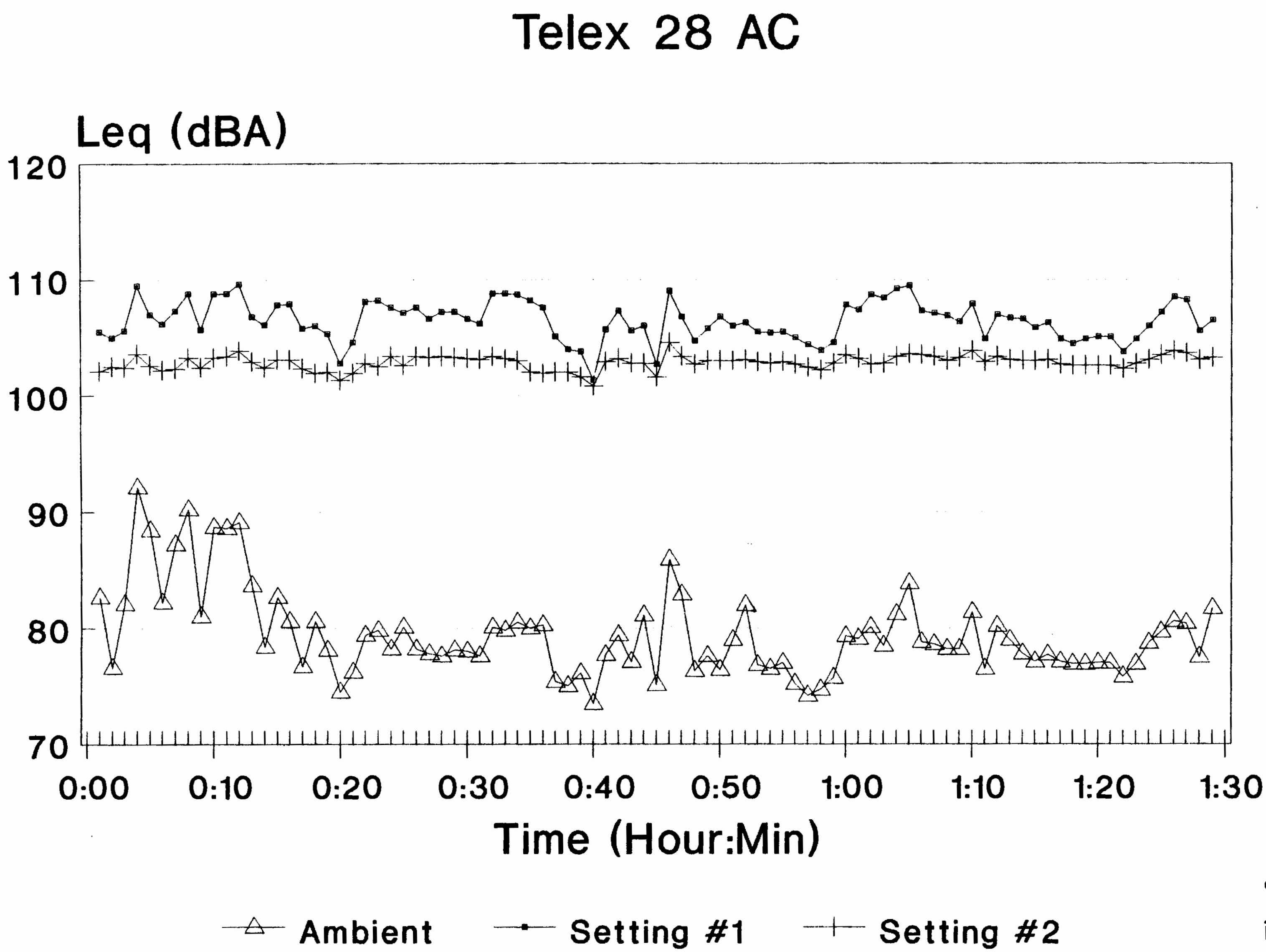
Telex 28 AC
Leq (dBA)
120
110
100
90
80
70
0:00
0:10
0:20
0:30
0:40
0:50
1:00
1:10
1:20
1:30
Time (Hour:Min)
Ambient
Setting #1
Setting #2

Fig. 8

CHAPTER V

DISCUSSION

The purpose of this study was to determine the effectiveness of noise limiting systems in reducing amplified exposure of industrial noise. Results suggested that in all but 2 of the 14 conditions measured, TWA exceeded the level specified by OSHA as being potentially harmful to the auditory system (90 dBA). Levels amplified by the Danavox Aura programmed with a TILL response achieved a level within 1 dB of the OSHA maximum. The TWA 80.7 dBA was recorded through the Argosy Expander set to minimum gain and maximum compression. This instrument utilizes Wide Dynamic Range Compression. With a sufficiently low compression ratio and threshold in steady background noise the instrument would operate in compression most, if not all, of the time the wearer was on the job in high levels of steady background noise. The wearer would not risk damaging his hearing at that level, however the results of studies of speech understanding in noise have suggested that a high compression ratio may cause speech comprehension to suffer (Van Tasell, Larsen, & Fabry, 1988, Tyler & Kuk, 1989, Plomp, 1988). If the hearing aid provided little or no benefit for speech understanding, the wearer would be better served by removing the aids in noise and wearing hearing protection devices.

A level of 88.8 dBA TWA was obtained through the Argosy 3-Channel Clock under condition 2 (high frequency emphasis). This is a linear instrument in that it does not use a compression circuit. However gain can be controlled independently in each frequency band (low, middle, and high) by means of potentiometers. In condition 2, gain was effectively eliminated for low and middle frequency regions of the frequency spectrum, such that there was little gain below 2000 Hz. For the range of 3000 to 4000 Hz insertion gain matched target gain. It is in this region that important high frequency speech cues, specifically consonant sounds are located. However eliminating gain in the middle and low bands may make low frequency speech sounds such as vowels inaudible, which also may compromise speech understanding. Because the Argosy 3-Channel Clock does not employ a compression circuit it limits output by peak clipping. A hearing instrument operating in saturation introduces distortion into the speech signal, compromising sound clarity and quality (Killion, 1993, Sweetow, 1994).

The TWA obtained with the Danavox Aura programmed to provide a TILL response was 90.7 dBA. TILL circuitry is designed to provide maximum high frequency gain at low levels. Gain decreases as input levels decrease. At high levels a hearing aid utilizing a TILL response provides no gain across the frequency spectrum (Mueller, Hawkins & Northern, 1992). Skinner (1980) found that optimal word identification at various presentation levels occurs when high frequency gain does not exceed the listener's uncomfortable listening level, and when low and high frequency speech cues fall within the listener's audible range. Skinner's results suggested that a hearing aid whose high frequency emphasis varied with input level might provide the listener with more audible speech sounds than an instrument with a fixed response. BILL circuitry also provides decreasing gain at increased input levels, however more high frequency amplification is present, even at high levels. Due to the action of the compression in the middle and high bands, the Danavox set to a TILL response was more effective than the BILL at reducing overall noise levels.

CONCLUSIONS

The purpose of wearing a hearing aid on the job is to hear warning signals, two-way radios, and speech of fellow workers. In high levels of background noise it is essential that this goal be achieved without further compromising the wearer's residual hearing. This study demonstrated that only 2 hearing aids worn in conditions simulating a typical working environment will not expose wearers to levels of noise deemed potentially damaging by OSHA. The instruments which registered OSHA TWAs below the maximum allowable level were the Argosy Expander and the Argosy 3-Channel Clock. Both instruments required adjustment of screw-set potentiometers to achieve the desired frequency response which would be inappropriate in other listening environments.

No single frequency response is appropriate for all listening situations. A *programmable hearing aid with user-operated multiple memories, and multichannel* compression such as the Danavox Aura 143X, has the advantage of being the most flexible of the instruments studied. Set to a simulated TILL response the Danavox instrument was very effective in reducing overall level, although the TWA of amplified noise was slightly above the OSHA maximum. Some advantages of programmable hearing aids are the ability to store several different user-controlled frequency responses in memory, all of which are potentially useful in different listening situations. With multiple channels, ASP and maximum output can be programmed individually as a function of frequency so as not to exceed the listener's loudness discomfort level (LDL) in any frequency region. With a single channel instrument a peak in the frequency response might exceed LDL in one area of the spectrum. Turning down the volume would reduce the entire spectrum and render some speech sounds inaudible. Three channel compression allows the AGC threshold to be lowered only in the band containing the peak. Volume in the other bands need not be affected, allowing more speech sounds to remain audible without loudness discomfort (Mueller, Hawkins, & Northern, 1992).

This study has demonstrated that amplified levels in a background of industrial noise can be kept below the OSHA TWA of 90 dB with output limiting systems in hearing aids. The effect of any of the instruments studied on speech intelligibility in noise is beyond the scope of this study. Further research is needed to address this issue.

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APPENDIX A

Hearing Aid Settings

Argosy 3-CHANNEL-CLOCK

Potentiometers:
1 controls gain in the low band
2 controls gain in the middle band
3 controls gain in the high band
gain is at minimum when potentiometers are rotated clockwise
C shifts frequency ranges of the bands to the right when rotated clockwise

Condition #1 (match target gain)
1 rotated 1/4 turn clockwise
2 rotated 1/4 turn clockwise
3 rotated 1/2 turn clockwise
C rotated maximum counter clockwise

Condition #2 (high frequency emphasis)
1 rotated maximum clockwise
2 rotated maximum clockwise
3 rotated 1/2 counter clockwise
C rotated maximum counter clockwise

Argosy Expander (Experimental Hearing Aid for use in Noise)

Potentiometers:
G regulates gain and SSPL 90
T moves compression knee
F tone control, gives maximum low cut in clockwise position

Condition #1
G rotated maximum clockwise, maximum gain and SSPL 90
T rotated maximum clockwise, minimum compression
F rotated 1/2 clockwise-some low cut on to match target gain curve for theoretical hearing loss

Condition #2
G rotated maximum counter clockwise, minimum SSPL 90
T rotated maximum counter clockwise, maximum compression
F rotated 1/2 clockwise-some low cut (same as #1)

Condition #3
G rotated maximum clockwise, maximum gain and SSPL 90
T rotated maximum counter clockwise, maximum compression
F rotated maximum clockwise-maximum low cut

Telex 28 AC

potentiometer marked with red dot controls compression

Condition #1
potentiometer rotated maximum clockwise, minimum compression

Condition #2
potentiometer rotated maximum counter clockwise, maximum compression

Danavox Aura 143X
default settings

#1 (basic)	#2 (noise)	#3 (noise)	#4 (wide band)
f1= 600 Hz	1000	600	600
f2= 3000 Hz	3000	2000	3000
gain 1= 2/12	1/12	2/12	4/12
2= 6/12	5/12	5/12	7/12
3= 10/12	10/12	7/12	10/12
prog -3	-3	-3	-3
AGC 1= 80	60	80	off
2= 80	70	70	off
3= 90	90	60	off
PCTC 0	0	0	0
VC 2	2	2	2

Danavox Aura 143X
experimental settings

#1 (basic)	#2 (noise)	#3 (wide band)
f1= 600 Hz	1200	1200
f2= 3000 Hz	3500	3000
gain 1= 2/12	1/12	1/12
gain 2= 6/12	5/12	5/12
gain 3= 10/12	11/12	10/12
prog -3	-3	-3
AGC 1 off	60	75
2 off	70	75
3 off	70	85
PCTC 0	0	0
VC 2	2	2

Figures 9 through 18 are graphs of gain in dB as a function of frequency in KHz. The graphs are real ear curves representing insertion gain provided by the hearing aids.

APPENDIX B

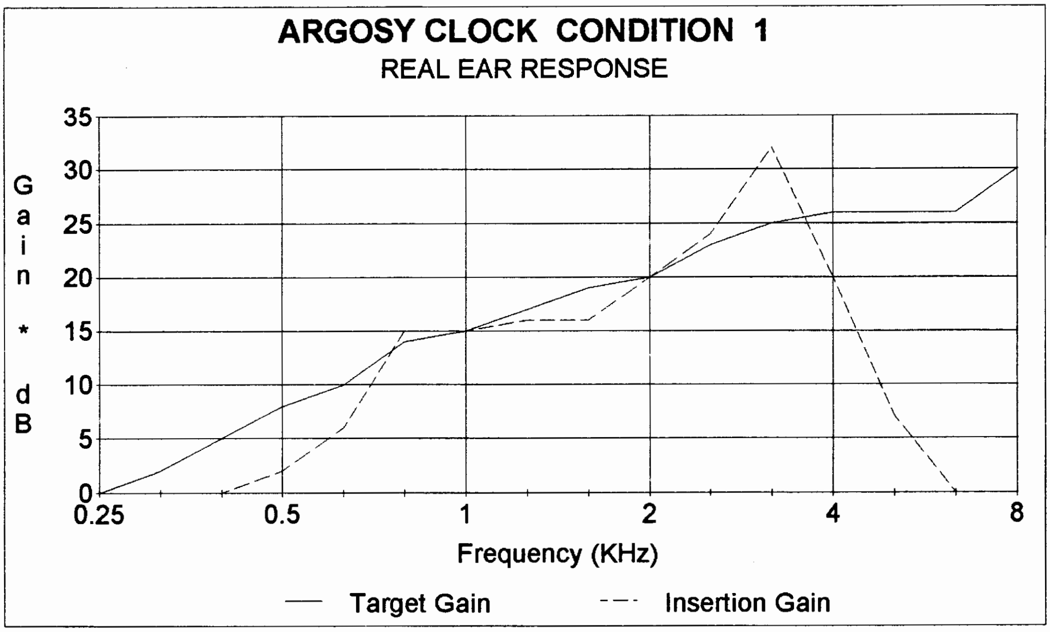

Fig. 9

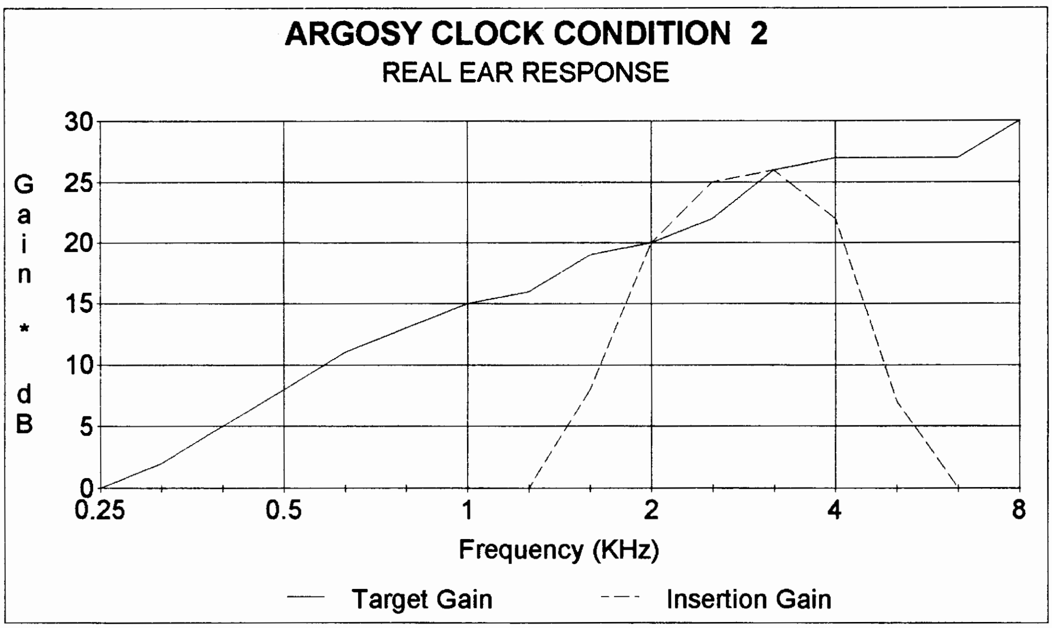

Fig. 10

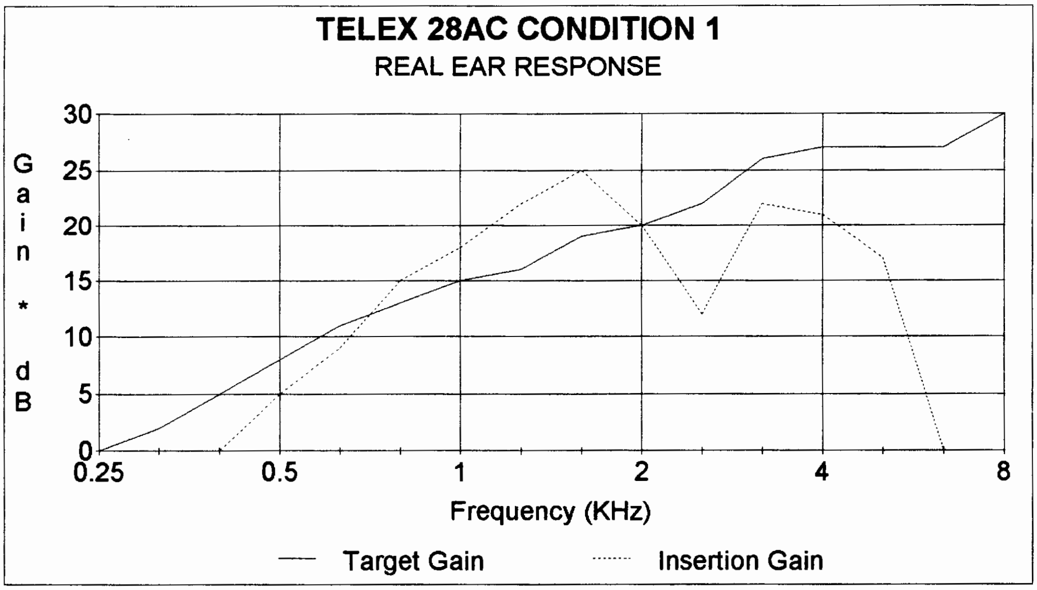
TELEX 28AC CONDITION 1
REAL EAR RESPONSE
Gain * dB
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 11

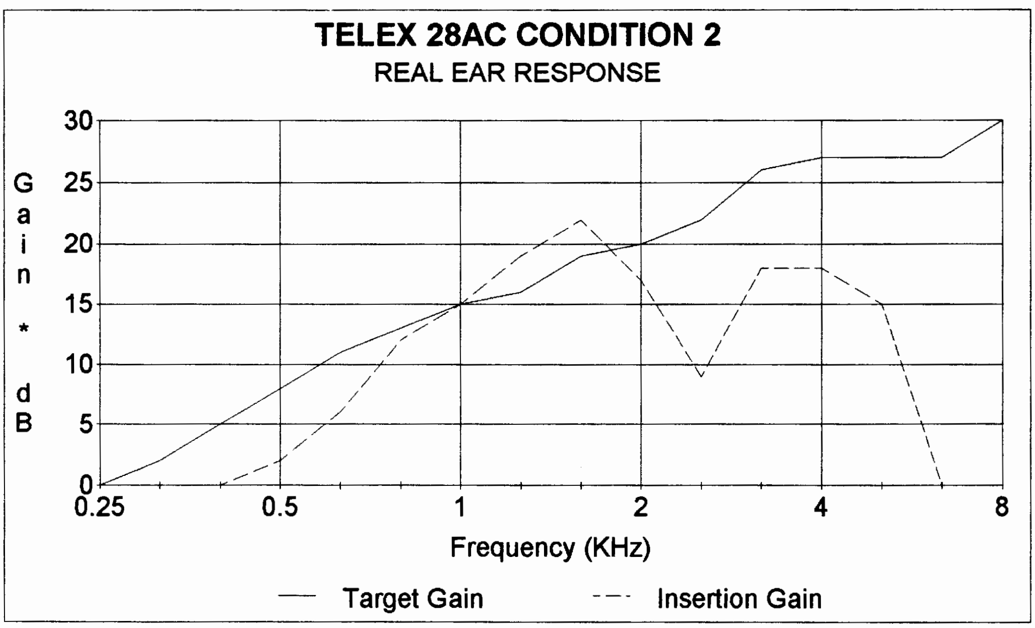
TELEX 28AC CONDITION 2
REAL EAR RESPONSE
Gain * dB
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 12

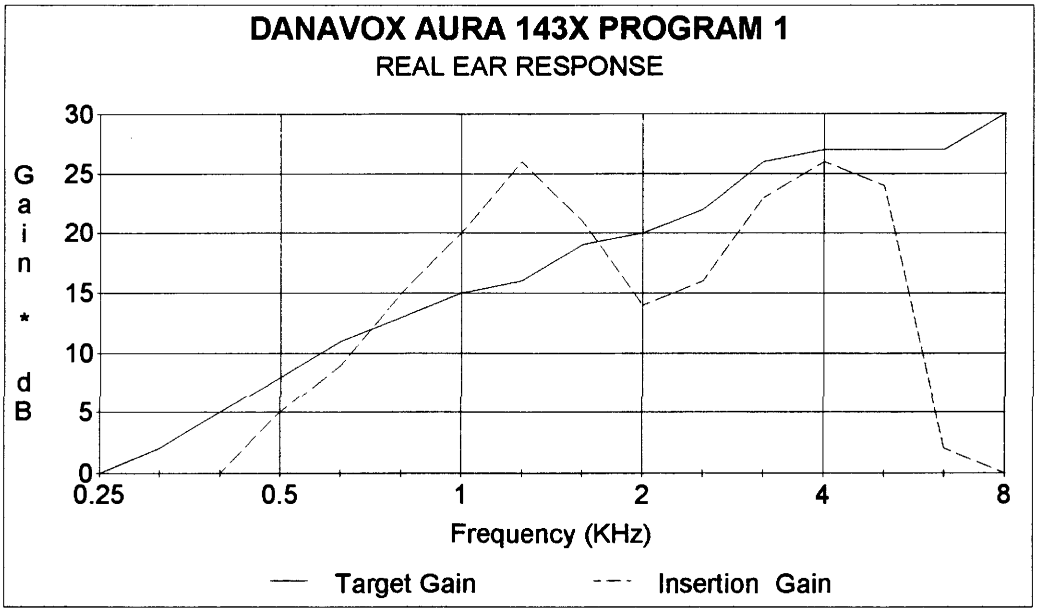
DANAVOX AURA 143X PROGRAM 1
REAL EAR RESPONSE
Gain * dB
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 13

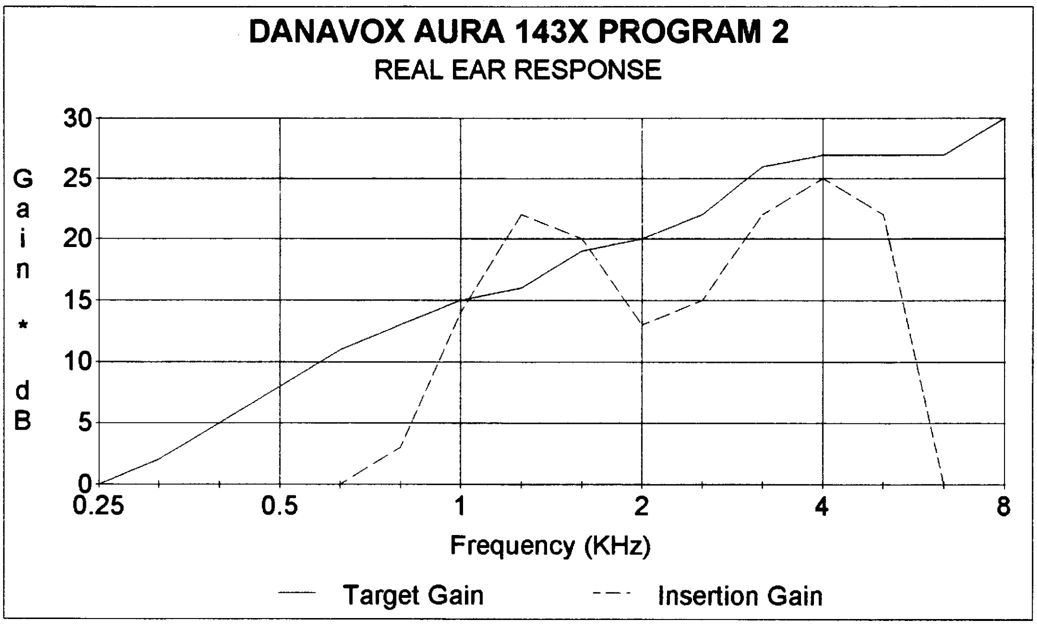
DANAVOX AURA 143X PROGRAM 2
REAL EAR RESPONSE
Gain * dB
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 14

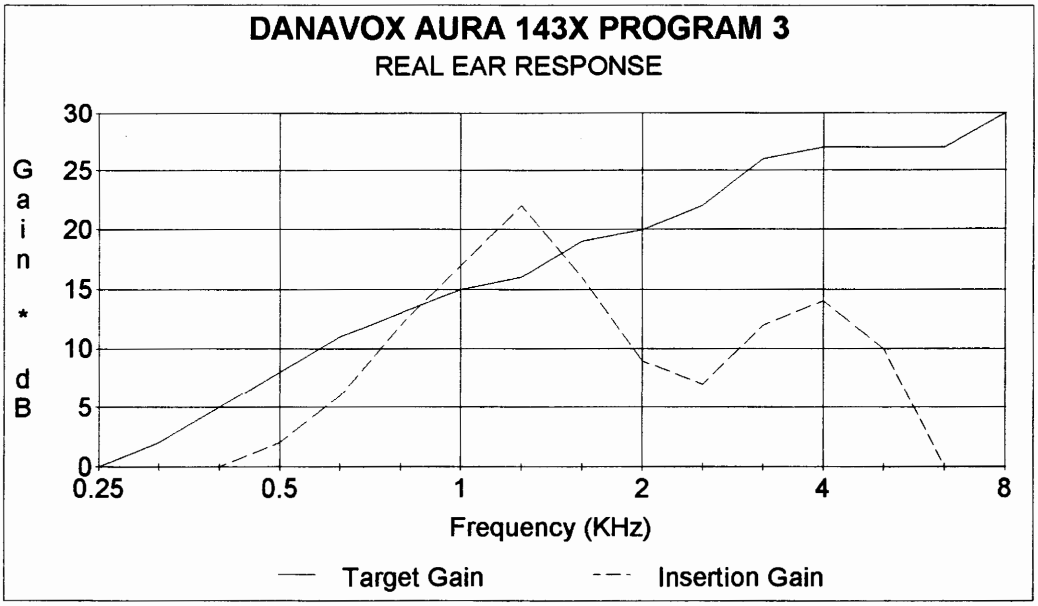
DANAVOX AURA 143X PROGRAM 3
REAL EAR RESPONSE
G a i n * d B
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 15

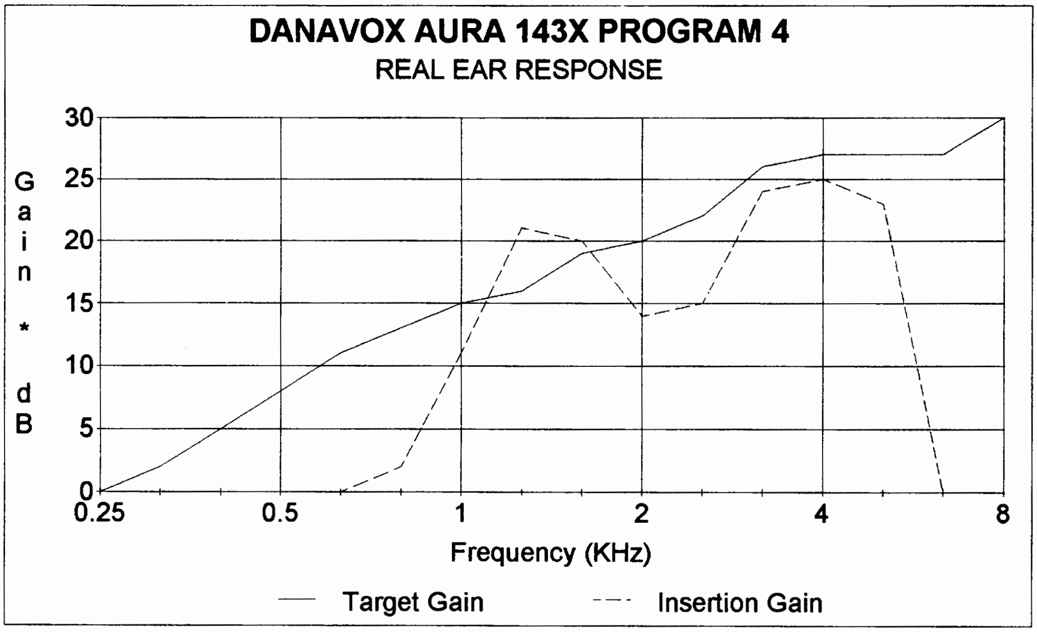
DANAVOX AURA 143X PROGRAM 4
REAL EAR RESPONSE
G a i n * d B
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 16

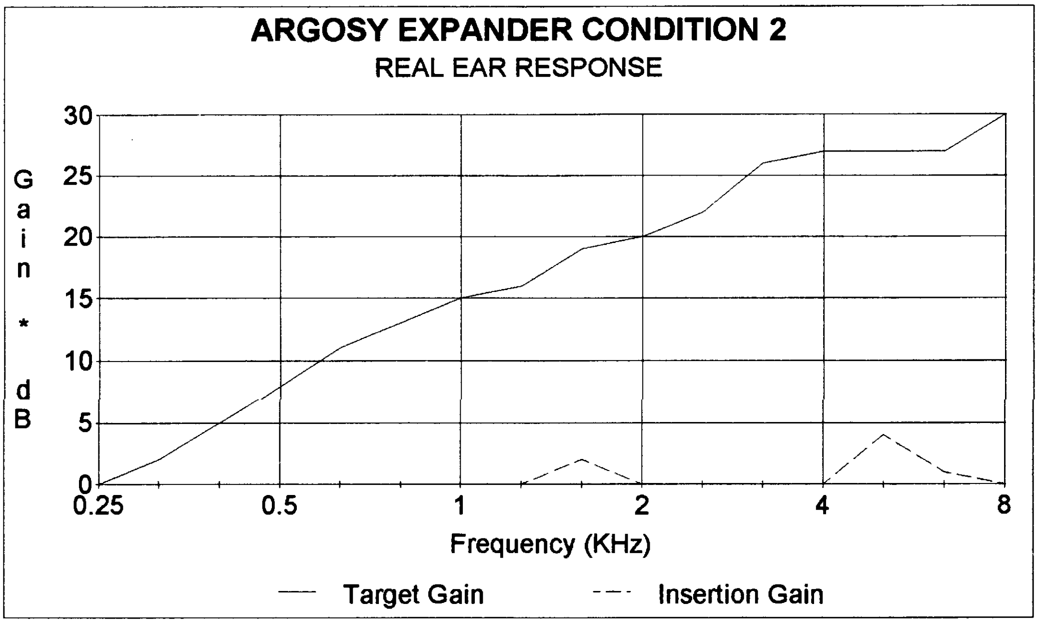
ARGOSY EXPANDER CONDITION 2
REAL EAR RESPONSE
Gain * dB
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 17

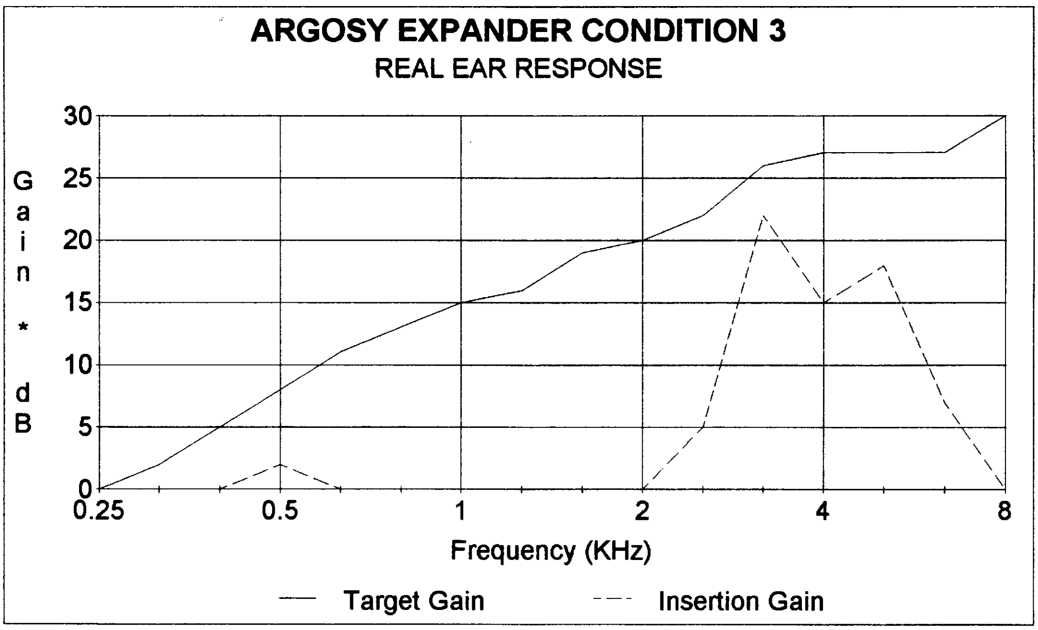
ARGOSY EXPANDER CONDITION 3
REAL EAR RESPONSE
Gain * dB
30
25
20
15
10
5
0
0.25
0.5
1
2
4
8
Frequency (KHz)
Target Gain
Insertion Gain

Fig. 18