Journal of
Rehabilitation Research and Development

VOL. 30 NO. 3 1993

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Library of Congress Catalog Card No. 6.60273
ISSN 0907-506X

The *Journal of Rehabilitation Research and Development* is a quarterly publication of the Rehabilitation Research and Development Service, Department of Veterans Affairs. The opinions of contributors are their own and are not necessarily those of the Department of Veterans Affairs. Address correspondence to: Editor, *Journal of Rehabilitation Research and Development*, Scientific and Technical Publications Section, VA Rehabilitation Research and Development Service, 103 South Gay Street, Baltimore, MD 21202-4051.

The *Journal of Rehabilitation Research and Development* and its supplements are printed on acid-free paper, as of Vol. 25 No. 2 (Spring 1988).

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Editor
Tamara T. Sowell

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We hope to open up an ongoing dialogue between professionals as a means of exchanging information and sharing diverse opinions among disciplines.

Editor
Tamara T. Sowell

Journal of Rehabilitation Research and Development

NOTICE TO CONTRIBUTORS

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The *Journal of Rehabilitation Research and Development*, published quarterly, is a scientific rehabilitation engineering, research and development publication in the multidisciplinary field of disability rehabilitation. General priority areas are: Prosthetics and Orthotics; Spinal Cord Injury and Related Neurological Disorders; Communication, Sensory and Cognitive Aids; and, Gerontology. The *Journal* receives submissions from sources within the United States and throughout the world.

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Department of Veterans Affairs

Journal of Rehabilitation Research and Development

Volume 30, Number 3, 1993

The *Journal of Rehabilitation Research and Development* is a publication of the Rehabilitation Research and Development Service, Scientific and Technical Publications Section, Veterans Health Administration, Department of Veterans Affairs, Baltimore, MD

Department of Veterans Affairs

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CONTENTS

GUEST EDITORIAL

This issue of the *Journal of Rehabilitation Research and Development* focuses on the evaluation of modern hearing aids, related devices and other technological developments. Recent technological advances have brought about substantial changes in the design of these instruments. Many modern hearing aids use digital techniques for controlling and processing the signals being amplified. These instruments have significant new capabilities in terms of both their signal-processing capabilities and the flexibility with which they can be prescribed and fitted. Similarly, the test instruments used for hearing-aid evaluation and audiological testing, in general, have improved substantially over the past few years with the increasing use of digital signal processing technology. The scope of these technological advances and their potential for providing improved amplification for veterans with hearing loss were addressed in Vol. 30, No. 1, 1993, of the *Journal*, a special issue entitled *Part I: Advanced Hearing Aid Technology*. This issue, *Part II: Clinical Evaluation of New Generation Hearing Aids* is concerned with the evaluation of modern hearing aids embodying this new technology as well as with related issues involving hearing aids and modern test instruments.

The first paper in this collection, by R.M. Cox, addresses a growing problem in the prescriptive fitting of modern hearing aids. Traditional evaluation and fitting procedures are not adequate for many modern hearing aids because of differences in the way signals are amplified and concomitant differences in the way these instruments need to be adjusted. This paper reviews the issues involved and identifies new techniques which can be used to make full use of the new capabilities of such devices.

Increasing use is being made of more than one channel of amplification in the new generation of hearing aids. This basic change in hearing-aid design results in instruments of considerably greater flexibility which can be prescribed more accurately and which can deal more effectively with unfriendly acoustic environments, such as speech produced in a noisy room. The increased flexibility and the many different adjustments that are needed, however, also add to the audiologist's task in evaluating and fitting these devices. The second paper, by D. Dirks, J. Ahlstrom, and P.D. Noffsinger, is concerned with the specific problem of determining the preferred frequency-gain response of a hearing aid with two or three channels of amplification, this being the most common form of multichannel amplification being used in modern hearing aids. The results of this investigation provide a scientific basis for the development of practical prescriptive fitting strategies for hearing aids of this type.

One of the most common complaints of hearing-aid users is that speech is particularly difficult to understand in the presence of background noise. Reducing the effects of background noise is a major problem in many scientific fields and a variety of techniques have been developed for this purpose, many of which require extensive signal processing. There are, however, inherent limitations on how much noise can be eliminated even with the most advanced signal processing techniques. The third paper, by D.A. Fabry, M.R. Leek, B.E. Walden, and M. Cord, evaluates a form of noise reduction that has been incorporated in several modern hearing aids. The method employed is to filter out low-frequency components of the signals being amplified when intense low-frequency noise is present. Since this filtering operation also eliminates low-frequency components of the speech signal, it is only used when low-frequency noise is present. The results of the investigation showed that for hearing losses that increase rapidly above 1,000 Hz, some improvement in speech recognition was obtained when intense (85dB SPL) rather than moderate (70dB SPL) low-frequency noise was present.

Although hearing aids are among the most widely used forms of assistive technology, only a small proportion of people (including veterans) who would benefit from acoustic amplification actually use hearing aids. The fourth paper by S. Silman, C.A. Silverman, M.B. Emmer, and S.A. Gelfand, shows that for an impaired ear, lack of amplification over prolonged periods of time can result in a deterioration in speech recognition ability when amplification is finally provided. There is also evidence that speech recognition ability improves to some extent with long-term use of a

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hearing aid. This is a particularly important finding with significant implications for veterans who have a hearing loss but do not use hearing aids.

There have been many dramatic advances in modern medicine; these include the development of potent antibiotic drugs and new methods of intervention such as chemotherapy, which have saved many lives. Unfortunately, some of these therapeutic drugs and chemotherapeutic agents can have adverse side effects, such as ototoxicity resulting in severe hearing damage. It is thus crucial to develop efficient techniques for the early detection of hearing loss resulting from medication of this type. The fifth paper, by S.A. Fausti, R.H. Frey, J.A. Henry, D.J. Olson, and H.I. Schaffer, describes the use of high-frequency audiometry and computerized measurement of the auditory brainstem response as a means of monitoring hearing in patients at risk for hearing loss. Hearing thresholds were measured over a wide frequency range and the predictive power of these measurements in detecting possible hearing damage was evaluated. Efficient procedures for monitoring the hearing of patients receiving potentially ototoxic medication were then developed based on the results of this study.

The field of automatic speech recognition has made dramatic advances in the past few years and it is hoped that the technology developed for this purpose will also be of benefit to veterans and others with severe hearing losses.

The last paper in this issue falls in the Clinical Report section of the *Journal* dedicated to recent clinical advances. The clinical report, by R.H. Wilson, describes the development of a set of test materials on compact disc designed for use in VA Audiology Clinics. Two sets of test materials have been prepared, one for basic auditory evaluations and one for a more detailed assessment of central auditory processing. The compact disc is perhaps the most well-known product resulting from the application of digital techniques to audio engineering. The quality of a digital audio recording on compact disc is far superior to a traditional analog recording (e.g., a long-playing record), in terms of bandwidth, low distortion, and wide dynamic range. In addition, a large number of recordings can be stored on a single compact disc and individual recordings can be retrieved for playback efficiently, conveniently and, if necessary, automatically.

The papers in this collection provide substantive new information that will do much to improve the quality of life of veterans with hearing loss, or at risk for hearing loss. These research results will also fill important gaps in our knowledge and be of value to the field of acoustic amplification in general. It is with some pride that we note that five of the six papers in this important collection were supported by funds from the Rehabilitation Research and Development Service of the Department of Veterans Affairs.

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Guest Editors

Clinical Relevance for the Veteran

SUMMARY OF SCIENTIFIC/TECHNICAL PAPERS IN THIS ISSUE

by Harry Levitt, PhD, Guest Editor

On the Evaluation of a New Generation of Hearing Aids. Robyn M. Cox, PhD *(p. 297)*

Purpose of the Work. A new generation of hearing aids is being developed which offer the promise of novel speech processing capabilities and methods of automatic loudness control. Fitting and evaluation strategies for these new instruments are likely to differ from those currently used for traditional linear hearing aids. This paper reviews the issues involved in order to develop fitting and evaluation procedures appropriate for use with this new generation of hearing aids. **Procedures.** The problems inherent in hearing aid evaluation are reviewed and specific ways of addressing these problems are described. Procedures appropriate for hearing aids that have advanced signal processing capabilities are identified. These include several new tests developed by the authors. Of particular concern are performance evaluations in the field; the relative merits of different approaches to this problem are discussed. **Results.** Techniques have been identified which will avoid the pitfalls of traditional methods of hearing aid fitting and evaluation. These include several new techniques developed by the authors for evaluating hearing aid benefit in everyday environments and for measuring relevant audiological characteristics of the listener. **Relevance to Veteran Population.** Modern hearing aids with new technological features are being fitted to veterans on a substantial scale. It is important that clinicians use fitting and evaluation procedures appropriate for these new instruments.

Preferred Frequency Response for Two- and Three-Channel Amplification Systems. Donald Dirks, PhD; Jayne Ahlstrom, MS; P. Douglas Noffsinger, PhD *(p. 305)*

Purpose of the Work. Hearing aids have recently been developed that provide more than one channel of amplification, each channel amplifying a different band of frequencies. The purpose of this investigation was to compare the preferred frequency-gain responses of hearing aids with two and three channels of amplification. **Subjects and Procedures.** Nine subjects with mild to moderately-severe sensorineural hearing loss participated. Three subjects had hearing loss that increased gradually with frequency, four subjects had hearing loss that increased rapidly with frequency, and two subjects had hearing loss that did not vary significantly with frequency. Each subject listened to continuous speech through a computer-simulated hearing aid and provided judgments of relative preference as the hearing aid was adjusted. A statistically efficient adjustment procedure was used under computer control. **Results.** The three-channel system provided greater flexibility in the choice of bandwidths for amplification, but no significant differences were observed between the preferred frequency-gain responses that were obtained, on the average, for the two- and three-channel systems. Both systems, however, showed a range of preferred frequency-gain responses depending on the bandwidths selected for each channel. The three-channel system showed a greater spread in the choice of preferred frequency-gain characteristics. **Relevance to Veteran Population.** Many technologically advanced hearing aids use more than one channel of amplification. This paper provides information on the relative differences between two- and three-channel systems in determining preferred frequency-gain responses. Information of this type is needed in order to develop more effective multichannel hearing aids and improved methods of prescribing these hearing aids.

Do Adaptive Frequency Response (AFR) Hearing Aids Reduce 'Upward Spread' of Masking? David A. Fabry, PhD; Marjorie R. Leek, PhD; Brian E. Walden, PhD; Mary Cord, MA *(p. 318)*

Purpose of the Work. One approach to the problem of background noise in acoustic amplification is to reduce the gain at low frequencies when intense low-

frequency noise is present. This technique has been used in several modern hearing aids with mixed results. This paper investigated whether a high quality hearing aid of this type (e.g., noise and distortion generated internally by the instrument itself were negligible) could produce significant improvements in speech recognition at high noise levels and whether such improvements could be related to upward spread of masking, an effect in which intense low-frequency sound reduces the audibility of high-frequency sounds. **Subjects and Procedures.** Eight adults with sensorineural hearing losses that increased rapidly with frequency in the region between 1,000 and 2,000 Hz participated. Four adults with normal hearing also participated. The masking effect of low-frequency noise at two levels (moderate and intense) was measured in each subject. Speech recognition scores were obtained for each noise level under two conditions of amplification, with and without attenuation of the low frequencies. This attenuation was applied equally to both speech and noise, as would occur in a hearing aid of this type. **Results.** The more intense low-frequency noise produced more masking in the high frequencies than the less intense noise. For five of the eight test subjects, attenuation of the low frequencies reduced this upward spread of masking substantially. This reduction in high-frequency masking was reflected in the speech recognition scores. Attenuation of the low frequencies produced a small increase in speech recognition for the low-intensity noise but a relatively large increase in intelligibility for the high-intensity noise. **Relevance to Veteran Population.** Amplification of background noise is a particularly troublesome problem for hearing-aid users. Given the large number of veterans who wear hearing aids, this is a problem of great concern. The method of noise reduction investigated in this study provides some alleviation of this problem under certain conditions (steep high-frequency hearing loss, intense low-frequency noise, and a hearing aid that does not produce significant internal noise or distortion).

Effects of Prolonged Lack of Amplification on Speech-Recognition Performance: Preliminary Findings. Shlomo Silman, PhD; Carol A. Silverman, PhD; Michele B. Emmer, MS; Stanley A. Gelfand, PhD *(p. 326)*

Purpose of the Work. Several recent studies have shown that lack of amplification in an impaired ear over a prolonged period of time can result in decreased speech recognition ability for that ear. The purpose of this study was to investigate the effects of lack of amplification to the unaided ear in adults with a symmetric binaural hearing loss who have been fitted with a monaural hearing aid. A second objective was to investigate the effect of amplification on speech recognition performance in the aided ears of persons fitted with either monaural or binaural hearing aids. **Subjects and Procedures.** Forty-seven adults with symmetric binaural hearing loss were fitted with hearing aids; 19 were fitted monaurally and 28 binaurally. An additional 19 normal-hearing adults served as controls. Three speech recognition tests were administered to each subject 6–12 weeks after hearing aid fitting and again approximately one year later. **Results.** For the subjects fitted with a monaural hearing aid, the difference in speech recognition test scores between the aided and unaided ears was found to change significantly after one year of hearing-aid use. The unaided ear showed a small reduction in test score while the aided ear showed some evidence of an increase in test score. No significant differences were observed over the same time period for either the binaurally aided subjects or the normal-hearing controls. **Relevance to Veteran Population.** The data obtained in this study indicate that lack of amplification in one ear can lead to poorer speech recognition over time for that ear while the ear that is amplified might also show a small improvement in speech recognition over time. An important implication of this finding is that veterans with hearing losses requiring amplification should be fitted with hearing aids as soon as possible so as to avoid further deterioration in speech reception skills resulting from prolonged lack of amplification.

High-Frequency (8-20 kHz) Testing Techniques and Instrumentation for Early Detection of Ototoxicity. Stephen A. Fausti, PhD; Richard H. Frey, BS; James A. Henry, MS; Deanna J. Olson, MS; Heidi I. Schaffer, MA *(p. 333)*

Purpose of the Work. Veteran patients with certain types of serious illnesses are often treated with therapeutic drugs which have the potential of causing hearing loss. Since many of these patients

already have some degree of hearing impairment, it is necessary to develop sensitive tests that would indicate if there is likely to be any significant increase in hearing loss resulting from the use of these drugs. A sensitive early indicator is a reduction in auditory sensitivity at high frequencies. The purpose of this study was to compare the relative efficiency of measuring hearing thresholds in the low- and high-frequency ranges for the purpose of early detection of hearing loss. **Subjects and Procedures.** Eighty-three patients receiving aminoglycoside antibiotics or medication for chemotherapy participated in the study. Baseline audiological data, including hearing thresholds, were obtained prior to treatment. Hearing thresholds were then obtained at regular intervals during treatment, immediately after termination of treatment, and at 1- and 6-months post-treatment. Auditory brainstem responses were also obtained on a subset of subjects. **Results.** Increased hearing loss was observed in about 70% of the patients. About half of these hearing losses were first detected by changes in the high-frequency range only, a third by changes in the low-frequency range only, and the remainder by changes in both frequency ranges concurrently. Measurement of auditory brainstem responses to high-frequency tone bursts showed a 90% success rate in detecting significant changes in auditory thresholds. **Relevance to Veteran Population.** The survival rate of critically ill patients is increasing with the ongoing development of powerful new therapeutic drugs, but there is the danger of consequent damage to the patient's hearing as a result of using these new drugs. Early detection of possible hearing damage is of vital importance in these circumstances. With early detection leading to subsequent changes in the drug regimen, it should be possible to avoid serious damage to the auditory system. The results of this study will pave the way to the development of effective protocols for monitoring the hearing of patients receiving treatment of this kind including objective techniques, such as measurement of the auditory brainstem response, which can be used with seriously ill patients who are unable to respond to conventional behavioral methods of measuring auditory thresholds.

Development and Use of Auditory Compact Discs in Auditory Evaluation: A Clinical Report.
Richard H. Wilson, PhD *(p. 342)*

Purpose of the Work. An essential component of auditory evaluation, including hearing-aid evaluation, involves measurement of speech reception ability. Recent advances in audio technology allow for the development of improved test materials using compact discs in which high quality recordings are stored digitally and can be accessed rapidly and conveniently in a clinical setting. The purpose of this investigation was to develop test materials for auditory evaluation using this new technology. **Procedures and Results.** Ninety-seven VA Audiology Clinics were surveyed to determine which speech recognition/identification materials were needed by VA audiologists. A set of test materials, based on the results of this survey, was chosen and digital recordings were made of these materials and transferred to two compact discs. The first disc contains speech recognition/identification test materials for basic auditory evaluations. The second disc was developed for assessing central auditory perceptual abilities and includes both speech and tonal materials. **Relevance to Veteran Population.** The two sets of auditory test materials in compact disc form have been designed specifically for use in VA Audiology Clinics. These digitized test materials are superior to test recordings currently in use in several respects. These include improved sound quality, greater ease of use, and access to test materials that previously were not readily available.

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On the evaluation of a new generation of hearing aids

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Abstract—Hearing aids with new technological features offer the promise of novel speech-processing and loudness-control capabilities. Full exploitation and assessment of these capabilities will call for the acceptance of fitting and evaluation strategies different from those currently used for traditional linear hearing aids. Until an appropriate set of procedures comes into relatively widespread use, it will be difficult to draw definitive conclusions about the desirability and effectiveness of the new options in amplification systems. This paper reviews some of the issues that should be considered as new evaluation procedures are explored.

Key words: *amplification systems, evaluation strategies, hearing aids, speech processing.*

INTRODUCTION

Technological advances have made it possible to build practical hearing aids with features never before available. For example, they may process the incoming signal in several independent bands; have flexible, adjustable compression capabilities; employ special algorithms and/or microphone arrays to improve signal-to-noise ratio; or contain different amplification characteristics (programs) for use in different listening environments. As instruments with these new and unproven capabilities become available, it is inevitable that we begin to ask how we can demonstrate the effectiveness of the new features. Clinicians and researchers need to know how these instruments compare with traditional single-band linear, single-microphone, single-program hearing aids. If these more capable but more costly devices are to be recommended for a large number of hearing aid wearers, it must be possible to demonstrate their advantages.

There is widespread recognition that appropriate evaluation and fitting procedures for the new generation of high-technology hearing aids will require an approach different from that considered satisfactory for traditional instruments. Changes are called for in many aspects of the fitting and evaluation protocol. This article will review some of the issues that should be considered in developing these procedures.

FITTING THE HEARING AID

It seems likely that full exploitation of the capabilities of many of the new hearing aid designs will require a more complete exploration of the auditory capabilities and disabilities of the hearing aid candidate than is found in current practice. New instruments offer potential for at least two features that could be valuable to the hearing-impaired: processing the entire range of input signal levels so that they are perceived with normal loudness relationships by the hearing aid wearer, and algorithms or microphone arrays to improve the signal-to-noise ratio in unfavorable listening situations. Appropri-

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This evaluation of a new generation of hearing aids was supported by the Department of Veterans Affairs Rehabilitation Research and Development Service, Washington, DC.

ate application of these capabilities may call for an expanded fitting protocol.

Restoring Normal Loudness Relationships

Most well-known procedures for the prescriptive fitting of hearing aids were developed with linear, single-program instruments in mind. With this type of hearing aid, changes in gain can be achieved only by manual adjustment, and the instrument can have only one set of characteristics (frequency-response and maximum output). Given these limitations, it is expedient to choose the amplification characteristics to optimize performance under a limited set of conditions, usually assumed to be face-to-face communication in quiet or only moderately noisy backgrounds. The characteristics are typically chosen solely on the basis of auditory thresholds. To validate the fitting, measurements of real-ear gain are widely employed. Because the fitting is optimized for one set of conditions, measurement for a single input level is all that is needed. Usually, the data are obtained from insertion gain measurements for a swept pure tone input of 70 dB SPL.

This general approach, while practical and reasonably appropriate for linear instruments, does not take advantage of the capabilities of newly developed hearing aids that automatically adjust gain and/or frequency response as a function of input characteristics. Instruments that allow adjustment of compression thresholds or compression ratios in each of several frequency bands open up the possibility of remapping the whole range of likely inputs onto the dynamic range of the hearing-impaired listener. Thus, sounds that are soft, comfortable, or loud for normal-hearing listeners theoretically can be produced at levels that are correspondingly soft, comfortable, and loud for the hearing-impaired individual. It is no longer necessary to settle for optimizing amplification for a limited set of input conditions: new amplification devices potentially can deal appropriately with a large proportion of the input conditions experienced by the normal hearer.

To fit these hearing aids, two types of data are needed that are frequently not included in currently popular prescriptive fitting methods. First, data are needed to describe the auditory area or long-term listening range of the hearing aid candidate. In other words, the ear canal sound-pressure levels required to elicit judgments of soft, comfortable, somewhat loud, very loud, etc., must be determined. There are at least three fairly well-known measurement procedures that can be used to describe the long-term listening range of a hearing-impaired person as a function of frequency (1,2,3). Second, validation of the fitting calls for real-ear measurement and adjustment of hearing aid characteristics until input levels with a given loudness for normal-hearing listeners are delivered to the ear canal at the corresponding loudness for the hearing-impaired individual. This aspect of the fitting procedure has not been fully investigated. In contrast to currently popular validation procedures that focus on insertion gain for a single input level, this type of validation involves consideration of the real-ear-aided response (REAR) for a series of input levels. Cox and Alexander (4) reported implementation of this type of validation system. The most significant problem they encountered was achieving precise control of the spectrum of a speech-shaped broad-band input signal. Further research is needed to describe workable REAR-based validation systems, and development of commercial instrumentation to facilitate this approach would be a valuable contribution.

Improving Signal-to-Noise Ratio

New technology has been employed to develop hearing aids with adaptive frequency responses that are intended to improve speech intelligibility in unfavorable listening conditions. The approach is grounded in the assumption that reduction of low-frequency gain under high-noise conditions will produce the dual benefits of removing a substantial proportion of the noise components (because background noise is often low-frequency) and reducing upward spread-of-masking effects. Some studies have supported the efficacy of this approach (5), while others have suggested that it is largely ineffective (6). Those employing hearing-impaired listeners have tended to indicate that some individuals appear to benefit from an adaptive frequency response while others do not (7,8). The explanation for the lack of consistent results among hearing-impaired listeners may lie in the differing auditory resolution capabilities of these individuals. For instance, it is clear that there is considerable variation in auditory filter shapes across hearing-impaired listeners (9) as well as a wide range of temporal processing abilities (10). Clinically practical approaches to the measure-

ment of auditory resolution abilities have been explored by several investigators (11,12,13,14). Future developments in this arena may provide evaluation tools that will permit prospective selection of appropriate candidates for hearing aid features such as adaptive frequency response and syllabic compression.

The ultimate goal in hearing aid fitting should be to develop prefitting psychoacoustical tests and postfitting acoustic validation methods that can be used with confidence to select an appropriate amplification system for each hearing-impaired individual. This goal probably will not be achieved in the near future. In the meantime, the efficacy of features such as putative loudness normalization, adaptive frequency responses, and signal-to-noise ratio improvement through multimicrophone arrangements will often need to be evaluated using performance testing after the fitting. Performance tests can be conducted in either laboratory or field settings, or both, as described below.

PERFORMANCE EVALUATION IN THE LABORATORY OR CLINIC

In the short history of hearing aids, it has been customary to fall back on speech intelligibility testing to evaluate instruments with previously untried capabilities. The practice of using speech understanding as the ultimate standard of efficacy is easily justified because improved speech communication is the main goal of most hearing aid wearers (15,16). As attempts are made to describe applicability and refine new features of hearing aids employing technological advances, a resurgence of interest in speech intelligibility testing seems likely. The clearest applications for such tests at present are to evaluate the effectiveness of technology that attempts to improve signal-to-noise ratio, and to establish program parameter values for multiprogram hearing aids.

Although monosyllabic word tests have been widely used to evaluate hearing aids, their basic unsuitability for this task has been recognized for many years. Monosyllabic words (and nonsense syllables) do not resemble natural speech, and the relationship between understanding of these types of stimuli and understanding of everyday conversational speech is not known. Many newly introduced hearing aids are adaptive in their performance, adjusting their characteristics with varying attack and release times, on the basis of the ongoing input. Because of this, it is especially important that they be evaluated and compared using speech that is as natural as possible. Ideally, the speech test material would be long enough to include contextual cues and would develop a familiar topic over several sentences, as normal conversations do. It would be delivered with natural inflection in a conversational manner and be produced by several different normal talkers. Competing noises and other environmental influences would resemble those encountered under everyday conditions. Finally, the results would be highly reliable and there would be a large number of equivalent forms to allow testing of many conditions.

Unfortunately, the ideal speech intelligibility test does not exist. However, several tests have been developed that incorporate some of the required features. For example, the Connected Speech Test, or CST (17,18,19) employs 10-sentence passages of speech about familiar topics, produced with fairly natural rate and inflection. The intelligibility of the talker was found to be average among a group of normal talkers (20). The competing noise is a six-talker babble similar to the murmur of voices in a crowded room. The 48 passages may be combined into empirically equated sets of 2, 4, 6, or more. This test is scored objectively in terms of the proportion of scoring words correctly repeated from each sentence. Benefit from linear hearing aids, measured using the CST, has been consistent with subjective reports of hearing aid wearers indicating that benefit is dependent on acoustic environment (21). The speech intelligibility demands produced by the test in three different environmental configurations have been rated by hearing aid wearers as quite similar, though not identical, to those of daily life (22). The principal disadvantages of the CST are the relatively long administration time and a number of equivalent forms that may be fewer than desired. Because substantial learning occurs for natural speech with a single exposure, there are limitations on the reuse of passages with the same subjects.

Administration time of connected speech tests can be substantially shortened if subjective ratings of intelligibility are used instead of objective scoring. Early work on this approach to intelligibility testing with fairly natural speech samples was

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reported by Speaks, et al. (23). The Speech Intelligibility Rating (SIR) test, based on subjective intelligibility ratings, was developed by Cox and McDaniel (24,25). For the SIR test, the subject listens to a 35-second passage of connected speech about a familiar topic and then estimates the proportion of words understood on a percentage type of scale. The final score for a given listening condition is based on the ratings for from three to five passages. Several investigators have reported the use of this test with hearing-impaired subjects to evaluate and compare both traditional hearing aids and instruments with novel processing abilities (26,27,28). Because it employs continuous, reasonably natural speech, and can be administered in a short period of time, the SIR test is well-suited to clinical comparisons of hearing aids or hearing aid features. Furthermore, Cox, Alexander, and Rivera (29) found that, although subjective intelligibility estimates similar to those generated by the SIR test were somewhat less reliable than objective intelligibility scores such as those obtained using the CST, the overall ranking of hearing aid conditions produced by the two types of tests was similar. The major drawback of the SIR test is that its set of equivalent passages is limited to 20. Because of the essentially instantaneous learning that occurs for natural speech, the effects of passage repetition are difficult to predict. As a result, the SIR test is best suited to applications with comparisons of four or fewer conditions so that passage repetition will not be necessary.

It is well-known that traditional linear hearing aids deliver the least benefit for listening conditions where they are most needed—the unfavorable conditions produced by the degradations of background noise and reverberation. Perhaps the most eagerly anticipated advantage of new technology in hearing aids is an improvement in the benefit obtained in unfavorable conditions, either through adaptive frequency response algorithms, multiprogram instruments, or other approaches. Simulation of unfavorable listening environments will be an integral part of speech intelligibility test evaluations with hearing aids employing these technologies. Given the considerable importance of environmental acoustics in the evaluation of technologically advanced instruments, it is essential to consider the validity of the acoustic environment used for clinic and laboratory testing. The degradations employed in the test setting should have a known relationship to those encountered in daily life. Simulations that are both traditional and intuitively reasonable may not be as satisfactory as anticipated. For example, Cox and Alexander (22) reported that a multitalker babble used to simulate the competing noise in a "cocktail party" situation was rated as less disturbing than noises encountered at real cocktail parties, despite the use of an appropriate signal-to-babble ratio. Similarly, in an investigation of the accuracy with which a reverberant environment could be simulated in an audiometric test room, Cox, Alexander, and Rivera (30) reported that although the results for two normal talkers indicated that the simulation was quite accurate, the results for a third normal talker indicated that the simulated reverberant environment was different in some respects from the real reverberant environment. These types of data reveal that more research is needed to explore methods of accurately simulating everyday noisy and reverberant environments under controlled conditions. Successful simulations may make an important contribution to valid and useful comparisons of noise-reduction hearing aids as well as providing a suitable milieu for establishing parameter values in multiprogram instruments.

Even assuming that an appropriate speech intelligibility test is used and accurate environment simulations are developed, at least one other variable will play an important role in laboratory evaluations of hearing aids with new technological features. Two recent investigations have shown that a substantial period of normal use is required before the benefit available from a newly fitted hearing aid is fully mature. Cox and Alexander (22) assessed laboratory-measured hearing aid benefit immediately following the fitting and again after 10 weeks of normal daily hearing aid use. The results indicated that over the 10-week adjustment period, benefit improved significantly in certain listening environments but not in other environments. Furthermore, the amount of improvement was more predictable in some listening conditions than in others. The results were consistent with a hypothesis that full utilization of newly audible speech cues cannot be achieved by many individuals without considerable practice. Gatehouse (31) also reported that laboratory-measured hearing aid benefit increased over the 12 weeks following a new hearing aid fitting. This study also clearly supports the existence of a substantial adjustment period before hearing aid benefit stabilizes.

Both of these investigations employed traditional linear hearing aids which do not substantially alter the cues available in natural speech. It is possible that the adjustment period would be even longer for hearing aids that recode speech cues by compressing or enhancing them. In addition, the interaction between the benefit maturation process and the employment of multiprogram hearing aids has yet to be investigated. Because multiprogram instruments may provide different speech cues depending on the program being accessed, it is possible that maturation of benefit for one program may interfere with maturation of benefit for another program (for example, if one program compresses speech and the other does not). Clearly, more research is needed to delineate the process of benefit maturation and to determine whether, and to what extent, the amount of improvement in benefit is predictable. Unless long-term benefit can be predicted with reasonable accuracy from initial measurements, the validity of benefit data obtained very soon after hearing aid fitting must be seriously questioned.

PERFORMANCE EVALUATION IN THE FIELD

Questionnaire-based approaches have a long history in the evaluation of hearing aids and the verification of their effectiveness. Typically, the instrument under investigation is fitted to each of a group of hearing-impaired listeners and they use the device in their daily lives for a period of days or weeks. Following this, each subject responds to a series of questionnaire items concerning his/her experiences with the amplification system. This type of evaluation has already been employed by several investigators to quantify the benefits of hearing aids employing technologically advanced features (32,33,34). Acquisition of data through the process of asking the hearing aid wearer about the help provided by the instrument has an appealing simplicity and relevance to the issues in question. Nevertheless, field types of evaluations have their own set of limitations.

One especially troublesome problem is the lack of comparable results across studies. Investigators have tended to develop their own inventories, relying on the content validity of the items to address the issues of interest, and employing measurement scales varying from estimated percentages to binary choices. In addition, psychometric data describing means, variability, reliability, and item interrelationships are generally not reported for these single-use inventories. Because of differences in data structures and a lack of reference data, it is often difficult to compare the results of studies evaluating different instruments or opposing technologies. The utility of field evaluations would be enhanced considerably if a standard inventory with established psychometric properties could be used by the various investigative teams as well as by clinicians.

The fundamental property of most innovative hearing aids at this time is their ability to adapt their performance to accommodate a range of inputs or acoustic environments. To assess the effectiveness of these types of instruments, an inventory that quantifies benefit in several subscales relating to different environments or input conditions is appropriate. Several inventories that might be suitable have been reported. The Hearing Aid Performance Inventory (HAPI), developed by Walden, Demorest, and Hepler (35) quantifies the magnitude of hearing aid benefit in four subscales. The Profile of Hearing Aid Benefit, or PHAB (36) quantifies the frequency of benefit in seven subscales. The Profile of Hearing Aid Performance, or PHAP (37) is similar to the PHAB but reports performance with the hearing aid in terms of frequency of problems in various situations. Mean subscale scores, variability, and interitem relationships are available for all three inventories for subjects using traditional hearing aids. In addition, test-retest data and subscale critical differences have been reported for the PHAB (38) and the PHAP (37). These data applying to traditional hearing aids could provide a basis for evaluation of the effectiveness of new technological features.

One of the most attractive applications of self-assessment inventories is the potential for evaluating opposing technologies or fitting strategies on the same individual. In this type of investigation, the subject is furnished first with one proposed amplification system, and then with the other. Responses to self-report inventories are obtained to evaluate each system. However, several investigators have reported the test-retest reliability of self-assessment inventories used with hearing-impaired listeners (37,38,39,40), and these studies are consistent in

suggesting that data from existing self-assessment inventories do not have high inherent reliability for individual subjects. For example, 95 percent critical differences for subscales of the PHAB range from 25 percent to 38 percent (38). This result is not very surprising, given the myriad uncontrolled experiences that might affect responses on any given day. Nevertheless, the practical implication is that when data are evaluated on an individual basis, self-assessment inventories may be sensitive only to relatively large differences between conditions. Thus, to gain sensitivity sufficient to detect smaller differences between hearing aids with different technologies, field evaluations should be conducted using groups of subjects.

Because the data from self-assessment inventories is necessarily subjective, the possible influence of extraneous factors such as memory, personality, education, age, health, and mood should be a matter of concern. If these factors significantly influence the responses given to inventory items about hearing aid benefit, experimental control must be exercised over the influential variables when composing matched groups of subjects for field evaluations. While it seems plausible that at least some nonauditory variables could affect inventory data, relatively little research interest has been directed at this problem to date, despite the widespread interest in, and use of, self-assessment inventories.

In a study relevant to this issue, Gatehouse (41) reported that age has a significant effect on the amount of self-assessed hearing disability: older individuals routinely report less disability than younger individuals with the same audiograms. Based on this result, it would not be surprising to discover that older individuals typically report less hearing aid benefit than younger persons. If so, field evaluations made by groups with different ages may not be comparable. In the same study, Gatehouse also noted a strong relationship between personality and self-assessed hearing disability and a weaker relationship between IQ and self-assessed hearing disability. His data suggest clearly that it would be important to control for these variables if valid comparisons are to be made across groups assessing different hearing aid technologies.

Cox and Rivera (38) noted a significant relationship between an individual's willingness to make negative self-appraisals and the negativeness of his/her responses to items that query the loudness discomfort associated with amplified environmental sounds. This result is interesting because the loudness discomfort occasioned by hearing aid use is a variable that many technologically advanced hearing aids attempt to minimize. Clearly, field evaluations comparing these devices will need to control variables that influence rated discomfort.

These studies indicate that certain nonauditory variables can be expected to have significant influences on data derived from field evaluation research as well as from clinical uses of this technique. More research is indicated to determine which variables are important, how they may parsimoniously be quantified, and the extent and direction of their influence on self-assessment data.

Experience with hearing aids appears to be another factor that can affect responses to self-report inventories. Cox and Alexander (22) reported that self-assessed hearing aid benefit increased during the postfitting adjustment period in a manner similar to the improvement in laboratory-assessed benefit. In addition to the effect of benefit maturation on inventory scores, subjects who were previously experienced hearing aid users reported significantly more benefit than the group of previously naive subjects. This result might be attributed to a self-selection process, whereby only those individuals who consider themselves to be receiving adequate benefit continue wearing hearing aids long enough to become experienced users. This self-selection effect would operate whenever previously successful hearing aid users are employed as subjects. It is probably also reasonable to assume that previous experience with traditional linear hearing aids would have an effect on inventory responses evaluating an instrument that processes sound in a different way.

The recent upsurge of interest in inventories to quantify hearing aid benefit suggests that field evaluations of new technology in hearing aids will probably be employed increasingly in the near future, perhaps because of the lack of a generally accepted approach to laboratory evaluation and/or lingering doubts about the validity of any such evaluation. Laboratory measurements of performance with hearing aids are valuable only if they are predictive of performance in daily life. However, it is not simple to devise laboratory measures that are demonstrably predictive of daily life experiences. For example, Cox and Alexander (22) were able to establish a significant relationship between labora-

tory measurements of hearing aid benefit in two simulated environments and subscales of the PHAB assessing the same two environments. However, in a third and especially troublesome environment, the "cocktail party," no relationship was found between laboratory measurements and field assessments. Field evaluations will continue to be a necessary adjunct to laboratory testing until both types of measurements are sufficiently refined that a clear relationship can be established between the two types of data.

SUMMARY

The application of new technological developments has brought sophisticated sound processing of various types within the grasp of professionals who fit and evaluate hearing aids on hearing-impaired listeners. These advances bring with them the challenge of developing techniques that will promote appropriate choices among available device features and valid evaluation of their benefits. Full exploitation of the capabilities of the new generation of hearing aids will call for substantial changes in fitting and evaluation protocols. We can anticipate a need for a more thorough evaluation of the auditory processing capabilities of the hearing aid candidate, both in terms of loudness perception and in auditory resolution. Furthermore, verification of an appropriate fitting will require a more extensive REAR-based measurement protocol, assessing a variety of input conditions.

One of the most intriguing features of the new types of hearing aids is their ability to adapt their performance to changing input conditions. The effects of these adaptations on speech intelligibility should be determined. Because of the complex and somewhat unpredictable nature of new amplification devices, evaluation of their effects and comparisons of different strategies calls for the use of intelligibility tests employing speech material, competing stimuli, and environmental influences that are as natural as possible. It seems unlikely that the traditional approach of measuring the intelligibility of monosyllabic words in a noise-free, sound-treated audiometric test room will yield data that can elicit important distinctions among systems. In addition, before valid conclusions can be drawn about the benefit accruing to a particular amplification system, the potential for maturation of benefit should be considered.

Field evaluations using self-report inventories are an attractive option for appraisal of innovative hearing aids when the validity of laboratory tests is in question. The generalizability of self-report data would be increased if standardized inventories were used in field evaluations. A few inventories have been developed that quantify performance with hearing aids in several subscales, each relating to a different type of input condition. These could be useful in evaluating instruments that adapt their performance on the basis of input. However, enthusiasm for field evaluations should be tempered by data that have shown a number of variables to affect self-assessed hearing aid benefit, including age, aspects of personality and adjustment, and previous experience with hearing aids. Furthermore, the test-retest reliability of self-report data is generally poorer than that of objective data obtained in a laboratory setting.

Because the applicability and effectiveness of hearing aids employing new technological features are still uncertain, a diversified approach to performance evaluation, employing a combination of laboratory and field strategies, seems advisable. Ultimately, the data will indicate which processing approaches are successful and for whom they are appropriate.

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Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 30 No. 3, 1993
Pages 306-317

Preferred frequency response for two- and three-channel amplification systems

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Abstract—The purpose of these investigations was to compare the preferred frequency-gain responses obtained from two- and three-channel amplification systems. The current experiments were limited to a linear system in which the crossover frequency dividing the channels was systematically varied. The subjects for the experiment were nine individuals with mild to moderately severe sensorineural hearing loss with various audiometric configurations. The subjects listened to continuous discourse, in noise, via a computer-controlled digital master hearing aid containing two real-time data acquisition processors. Initially, a modified simplex procedure was used to obtain preferred frequency-gain responses using several different crossover frequencies. A round-robin procedure was then conducted in which each preferred response from the simplex was compared with every other preferred response. The frequency-gain responses chosen most often for the two- and three-channel systems were compared. The results showed no significant differences between the preferred frequency-gain response for the two- versus the three-channel system. In addition, the preferred response chosen most often was not consistently observed at the same crossover frequency for all subjects, with the exception of those with steeply sloping hearing loss who chose 1,120 Hz as the first or second preference for the two-channel system. The round-robin results were rank-ordered according to the number of times each frequency-gain response was chosen. In general, subjects chose several frequency-gain responses at various crossover frequencies, which were not significantly different from each other statistically. The results of a final experiment suggested that physical similarities in the preferred responses chosen at the various crossover frequencies played a role in the rank-ordering of the preference judgments obtained in the original investigation.

Key words: *amplification systems, digital hearing aids, hearing aids, preferred frequency-gain response, sensorineural hearing loss, two- and three-channel amplification systems.*

INTRODUCTION

The goal of most hearing aid selection procedures is to provide adequate gain so that speech cues important for intelligibility are audible. This general goal is not easily achieved for many patients with cochlear impairment who have elevated thresholds together with recruitment, which reduces the dynamic range. There is evidence (1,2) that an appropriate amplification system for such patients should restore the speech cues to normal loudness levels at each frequency and amplitude. For most hearing-impaired individuals, however, the loudness function and dynamic range of hearing varies over the frequency spectrum. Theoretically, the ideal amplification system would contain a sufficient number of frequency bands or channels, each acting independently, to accommodate the variations in dynamic range that exist at frequencies within the speech spectrum. In practice, several investigators (3,4) have advocated the use of two-channel amplification

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systems, in which the channels operate independently, and often contain some form of compression.

Currently, several digitally controlled, programmable hearing aids are available incorporating two or three independent channels. Often, the signals are split into a high- and low- frequency channel, allowing for relatively independent processing of consonant and vowel cues, respectively. A third channel, which allows for increased bandwidth flexibility, is also available in at least one digitally programmable hearing aid. This might be especially useful for individuals with large variations in both audiometric configuration and dynamic range across the frequency spectrum (e.g., patients with steeply sloping high-frequency loss). There is, however, no strong evidence that demonstrates the superiority of having three versus two independent channels. This paper contains results of our initial efforts to develop and test a digital master hearing aid with two and three independent, adjustable channels. Specifically, the digital master hearing aid was used to compare the preferred frequency-gain responses obtained from hearing-impaired individuals utilizing the two-channel versus three-channel systems.

An important characteristic of two- and three-channel systems is the flexibility to adjust the crossover frequency(ies) that divide the channels according to the preferences or requirements of the listener. No rules or recommendations for choosing the desired bandwidth of each channel have, as yet, been studied systematically. It is possible that the choice of bandwidths preferred by the individual hearing-impaired listener may interact with the preferred frequency-gain responses. In fact, an individual listener may potentially find more than one frequency-gain response acceptable as the crossover frequency is varied. Because of this potential interaction between the preferred frequency-gain response and the crossover frequency(ies), the current investigation incorporated two measurement techniques (one dependent on the other) to determine a final frequency-gain/crossover frequency combination that was preferred for the two- and three-channel systems. The first, a modified simplex adaptive strategy (5) was used to determine a preferred frequency-gain response for each of several predetermined crossover frequencies. This procedure resulted in a set of preferred frequency-gain responses, each obtained with a different crossover frequency. These responses were stored in a database for subsequent comparison with each other, using a second measurement technique, a round-robin paired comparison strategy. Since in that strategy, each preferred response was compared with each other response, it was possible to rank-order the number of times each frequency-gain/crossover frequency combination was preferred, as well as to determine the ultimate "winner(s)." From these results, comparisons could then be made between the preferred frequency-gain/crossover frequency combination for the two- and three-channel systems.

METHOD

Instrumentation

Figure 1 contains a block diagram of the basic components of the experimental system. The speech (continuous discourse) and noise signals used in this experiment were recorded on digital audio tape (DAT) recorders. These same recorders were then used to deliver the stimuli to the digital master hearing aid. The output of the recorders were attenuated (fixed attenuator, FATT) to achieve the desired signal-to-noise ratio (S/N), mixed, and then delivered to a compression/limiter device (having an attack time of 2 msec and release time of 45 msec) to reduce the effects of any spurious peaks that might have occurred in the speech or noise stimuli. The threshold of the compression/limiter was set at 85 dB sound pressure level (SPL). Following preamplification, the stimuli were delivered to an anti-aliasing filter to prepare the stimuli for digital processing. The stimuli were then converted from analog to digital form using 16 bit resolution with a sampling rate of 19.84 kHz. The digital processing system incorporated two real-time data acquisition processors (Ariel DSP-16+) operating in parallel under PC-AT control. The computer also controlled a programmable attenuator (PATT) to establish the overall SPL. The signals from the two Ariel boards were mixed and delivered to a reconstruction or anti-imaging filter to smooth the output of the digital-to-analog conversion. Both the anti-aliasing and reconstruction filters were programmed to low-pass filter the signals with a cutoff frequency at 7.0 kHz. The attenuation was 51.5 dB at the Nyquist frequency of 9.9 kHz.

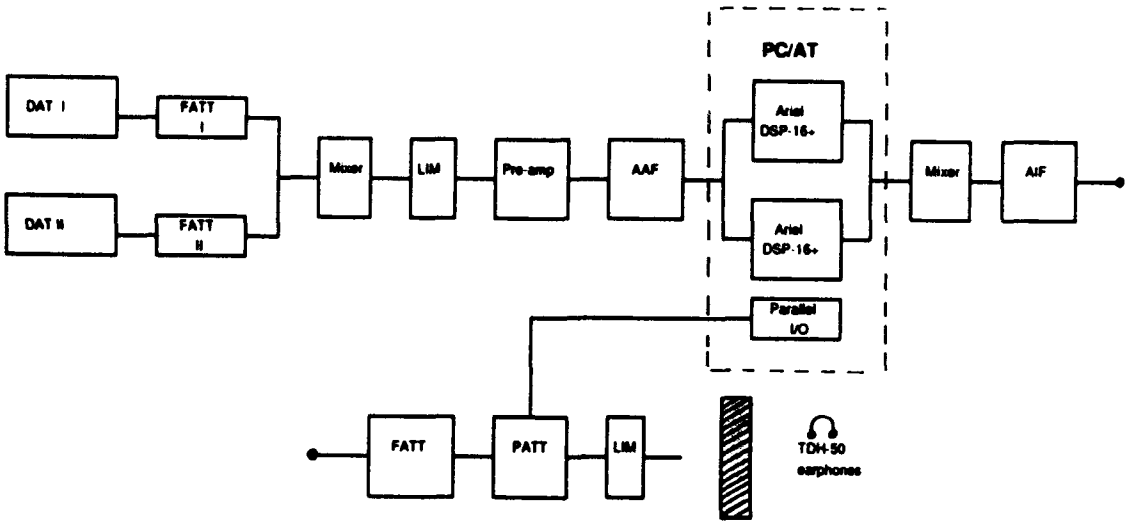

Figure 1.
Block diagram of the basic components of the digital master hearing aid system. DAT = digital audio tape recorder; FATT = fixed attenuator; LIM = limiter; AAF = anti-aliasing filter; AIF = anti-imaging filter; PATT = programmable attenuator; I/O = input/output board.

The processing system was programmed to produce four filter bands with the transition band between filters set at 500 Hz. Each band was spectrally shaped with a 127-tap finite impulse response (FIR) digital filter. The various experimental channels (or bandwidths) were formed by combining the one-third octave bands, starting with the band having a nominal center frequency of 0.315 kHz. The selection of the bandwidths of the desired channels was limited by the transition bandwidth of 500 Hz. Band SPL could be varied in 1 dB increments. The overall level of the stimuli delivered to the earphones was limited to an output level of 118 dB SPL (in a 6 cc coupler) by a second compression/limiter.

Subjects

For this experiment, nine subjects with mild to moderately severe sensorineural hearing loss participated. Three subjects had gradually sloping audiometric configurations, four subjects had steeply sloping audiometric configurations, and two subjects had flat or uniform audiometric configurations. Speech reception thresholds ranged from approximately 15 to 50 dB HL. Of the nine subjects, six subjects were binaural hearing aid users and three subjects had no prior experience with amplification.

Test Stimuli and Instructions

The principal test stimulus used in this experiment was continuous discourse (primary message) recorded by a male talker embedded in a small party noise (background message) containing a variety of male and female talkers. The continuous discourse was recorded on a DAT recorder in 45-minute segments. Each recording contained a complete story on various topics with vocabulary found in fifth-grade readers. **Figure 2** displays the long-term root mean square (rms) level of the stimuli at one-third octave bands from 0.125 to 6.3 kHz. During the experiment, the signals were presented at an S/N ratio of +3 dB. All subjects were able to understand the continuous discourse, because the information in the meaningful sentences contained many contextual cues.

Subjects in this experiment were instructed to base their judgments of preference on several dimensions of speech quality and intelligibility according to their individual standards. The instructions for making the preference judgments were, thus, broadly conceived, and permitted judgments based on the individual's own criterion of comparative importance of intelligibility and quality attributes. In our opinion, the preference judgment for speech in real-life situations is based on a variety of

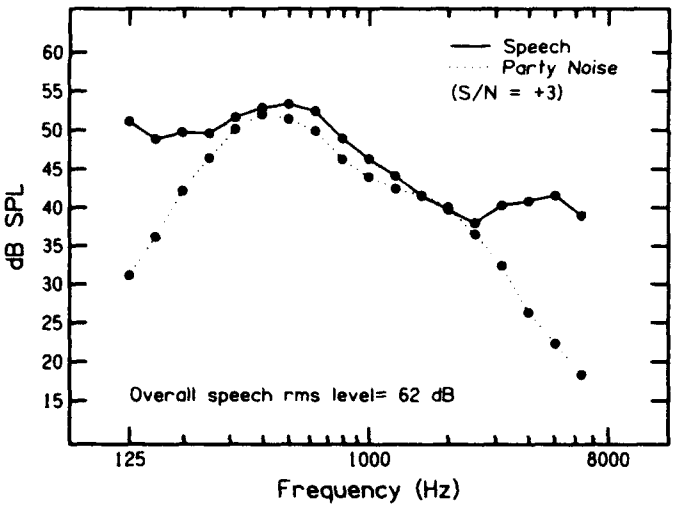

Figure 2.
Long-term rms spectrum of the continuous speech stimuli and the background party noise in one-third octave bands levels.

intelligibility and quality attributes that are highly related and not readily separated.

In addition to the speech and noise stimuli, threshold testing was administered to each subject for descriptive purposes using the modified Hughson-Westlake procedure (6) conducted in 5-dB steps. Loudness judgments were also obtained from each subject using the Loudness Growth in 1/2-Octave Bands (LGOB) method described by Allen, et al. (7). This procedure has been incorporated as part of the Resound Digital Hearing System (8) and was used in the study to describe the comfort loudness levels. In the LGOB procedure, one-half octave bands of noise, centered at 500, 1,000, 2,000, and 4,000 Hz are used as stimuli. The noise bands are presented to the subject (via an insert earphone), randomized over frequency and level, and the subject rates the loudness on a seven-point scale from "cannot hear" to "too loud." A rating of "3," reported in this study, is approximately equivalent to a judgment of most comfortable listening level.

Procedures

In two previous experiments (9), comparisons between the two- and three-channel hearing aid systems were made using a master hearing aid. For those investigations, the signal was presented via a loudspeaker and delivered to a microphone located in the shell of a behind-the-ear hearing aid. After modification by the digital master hearing aid, the signal was routed to a receiver, also located in the shell of the hearing aid, and delivered to the subject in the conventional manner via tubing and an earmold. This method, while realistic, led to several problems that may have interfered with the experimental results. Two of the problems were especially difficult to control. First, the input signal to the microphone was modified by the head diffraction effects and the position of the microphone on the listener, and the output signal varied with the fit and type of earmold. These factors often resulted in discrepancies between the frequency response in the center and surrounding cells of the simplex matrix relative to the desired levels. Various modifications (i.e., Libby horn, dampers, etc.) were needed for every subject in order to match the levels measured at the probe microphone to the desired levels. Second, in a significant number of the subjects, acoustic feedback problems were encountered, especially in cells of the simplex matrix where the gain in the high frequencies was increased by as much as 12 dB over the National Acoustic Laboratory (NAL) predicted gain (10) within the center cell (starting estimate). In order to eliminate these problems, it was decided to conduct the current experiments under earphone conditions. We did, however, incorporate modifications in the software so that the headphone SPL measured in a 6 cc coupler (via the master hearing aid system) simulated the SPL at the eardrum for a sound field hearing aid condition. To obtain the desired coupler response, correction values suggested by Bentler and Pavlovic (11) for the 6 cc-to-eardrum and soundfield-to-eardrum average transfer functions were applied to the long-term rms measured speech levels (**Figure 2**).

In order to obtain the preferred frequency-gain responses for two- and three-channel amplification systems, the modified simplex strategy was used, similar to the procedure described by Neuman, et al. (5), with the exception that the frequency responses in the matrix were not based on loudness. The simplex procedure consisted of a 5×5 matrix of cells for the two-channel system, and a $5 \times 5 \times 5$ matrix of cells for the three-channel system. Each cell contained a different frequency-gain response. The center cell of the simplex procedure was programmed to provide the frequency-gain characteristics predicted by the revised NAL prescription procedure (plus the correction values for simulating

a sound field hearing aid condition, as previously indicated) for each individual subject. The response characteristics in the remaining cells varied systematically, in 6 dB steps, relative to the response of the center cell (NAL). Thus, for the two-channel system, with a crossover frequency of 1,200 Hz, the cell on the vertex of the matrix immediately above the center cell changed by 6 dB in the high-frequency channel while the level in the low-frequency channel remained the same as in the center cell. For a cell on the abscissa adjacent to the center cell, the response was raised by 6 dB in the low-frequency channel, while the high-frequency channel remained unchanged. A similar arrangement was used for the three-channel system, with a 6 dB increase in one of the three channels for each cell in the matrix.

The simplex strategy was conducted in two trials. In the first trial, an initial estimate of the preferred frequency-gain response was obtained using a 12 dB step size. The starting point was always the response in the center cell of the matrix. For the two-dimensional simplex (two-channel system), paired comparisons were obtained between the responses in two cells on the vertical axis, and then a comparison was obtained between two cells on the horizontal axis. Depending upon the outcome, a new set of comparisons was presented, with the simplex moving back and forth between the cells depending upon the outcome of the previous comparisons, until a predetermined number of reversals was reached. A detailed description of the method and a graphic display of a two-dimensional simplex procedure can be found in Neuman, et al. (5) and is highly recommended for the interested reader. The comparative frequency-gain responses were varied by a manual switch controlled by the subject. The subject could switch back and forth between either of the two cells under evaluation as many times as he or she wished. Once the subject decided which response was preferred, a vote was made and then a new set of responses was automatically presented for comparison. Testing was terminated during the initial trial after three reversals in direction for both the horizontal and vertical axes.

After an estimate of the preferred frequency-gain response was made from the initial trial, that winning response then became the starting cell for the final estimate. The strategy just described was again utilized; however, a smaller step size (6 dB) was used, and testing was terminated after five reversals. The efficiency of the adaptive strategy method was improved by this use of a large step size to obtain an initial estimate of the response followed by the use of a small step size to obtain the final estimate.

The same design was used to obtain the frequency-gain response for the three-dimensional (three-channel) simplex, except that the addition of the third dimension required additional comparisons beyond those in the vertical and horizontal plane to accommodate the three components (low-, mid-, and high-frequency). The two-dimensional simplex procedure, in general, required 10–14 minutes for completion, while the three-dimensional required approximately 15–20 minutes.

Because of the potential interaction between the crossover frequency and the preferred frequency-gain response, several simplex procedures were conducted with various crossover frequencies. For the two-channel system, results were obtained with crossover frequencies at 0.562, 0.891, 1.12, 1.78, and 2.82 kHz. These crossovers were chosen because they appeared to provide a representative sample of frequencies across the important audible spectrum of speech.

For the three-channel system, the number of potential combinations for frequency crossovers were numerous; thus, it was necessary for practical purposes to delimit the combinations. Combinations were chosen that included one low-frequency crossover paired systematically with a mid- to high-frequency crossover. Using this rationale, four combinations of crossover frequencies were used: 0.562/1.120, 0.562/1.78, 0.562/2.24, and 0.562/2.82 kHz. Three additional conditions were also tested; 0.891/2.24, 0.891/2.82, and 1.12/2.82 kHz. These seven combinations, therefore, provided a reasonable sample of crossover frequency conditions that might be utilized by hearing-impaired listeners. In summary, there were five frequency-gain response conditions for the two-channel system and seven frequency-gain response conditions for the three-channel system.

In the second part of the experiment, a round-robin strategy, also incorporating a paired comparison method, was then used to compare each preferred response (within the two- or three-channel condition separately) obtained from the simplex procedure with every other preferred response a total of six times. This procedure produced a final

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"winner" from the preferred frequency-gain responses. In addition, the total number of times each competing response was chosen could be rank-ordered for more detailed analysis.

RESULTS

Overall Results

Several descriptive results will be reported initially to provide a general overview of the outcome of the round-robin procedure.

Figure 3 illustrates the average preferred frequency-gain response resulting from the round-robin procedure for the two- and three-channel systems in steeply sloping loss and gradual/uniform loss. Application of the analysis of variance to the data indicated that there were no significant differences between the preferred responses for the two- and three-channel systems. Included in the figures are the average predicted NAL responses for the same subjects at six major test frequencies. Similar to earlier data from this laboratory (9) and from data reported by French-St. George, et al. (12), each of the two groups of subjects in this study preferred slightly more gain in the low-frequency region than the NAL prediction. This result was somewhat more evident for the steeply sloping hearing loss group.

In regard to the preferred frequency-gain/crossover frequency combination, no single frequency(ies) was consistently chosen by all subjects, with one exception. Among subjects with steeply sloping hearing loss, a crossover frequency of 1,120 Hz was chosen as either the first or second preference for the two-channel system. For the gradually sloping/uniform loss group, although no single crossover frequency was favored consistently, in general, the preferred frequency-gain response incorporated one of the mid-frequencies rather than a crossover at the lowest (562 Hz) or highest (2,820 Hz) frequencies available.

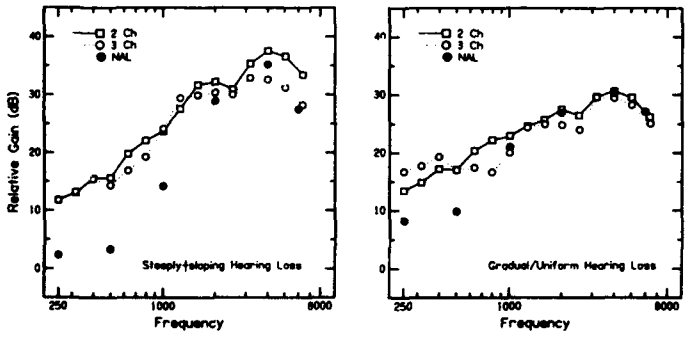

Figure 3.
Average preferred frequency-gain responses resulting from the round-robin procedure for the two- and three-channel systems. The left panel shows the results for the steeply sloping hearing loss group. The right panel shows the results for the gradually sloping/uniform hearing loss group. Included also are the average predictions for both groups from the NAL method.

It is not uncommon in experiments where preferred frequency-gain responses are obtained to instruct the subjects to make judgments on the basis of speech intelligibility and quality factors. Because this study was conducted with a linear system, both the speech and noise changed proportionally as subjects varied the frequency-gain responses within the matrix available. As a consequence, the Articulation Index predictions of intelligibility remained the same for all frequency responses available for an individual subject. It is assumed then that intelligibility was generally constant for the comparisons made by an individual subject; thus, it was reasoned that speech-quality factors may have played a larger role than speech intelligibility in the preference judgment of the subject.

While it was not possible to determine what quality factors were critical to each subject in his or her judgment process, it was possible to estimate one factor, the loudness level of each preferred frequency-gain response, and determine whether preference was dependent on loudness level. (Examples of the five preferred frequency-gain responses for the two-channel system and the seven preferred frequency-gain responses for the three-channel system, from two individual subjects, can be seen in **Figure 6** and **Figure 7**.) The loudness level of each preferred response was estimated in the following manner. First, the preference judgments were rank-ordered in terms of the number of times each preferred frequency-gain response was chosen during the round-robin procedure. Second, the loudness level of each preferred frequency-gain response was estimated using the Zwicker loudness summation model incorporating software based on Zwicker's original programs for calculating loudness in one-third octave bands (13). Frequencies lower than 200 Hz and higher than 6,300 Hz were eliminated from this calculation because of the restricted frequency range of the master hearing aid. The loudness level

of each frequency response was calculated from the aided or amplified speech spectrum obtained from measurements of the long-term rms values of the speech for each preferred frequency response. These loudness levels for each response were rank-ordered from the highest to lowest in terms of loudness for each subject. The rank-ordered results from each subject were then averaged in contingency tables, and chi-square analysis was conducted separately for the results from the two- and three-channel systems. The group results from both analyses were found to be nonsignificant, indicating that the preference judgments made during the round-robin procedure were independent of loudness level.

Rank-order correlations between loudness level and preferred frequency-gain response from the round-robin procedure were also conducted for each individual subject. The relationships varied greatly from an inverse correlation of -0.90 for one subject to a $+0.50$ for another subject. As a group, no clear trend could be found relating loudness level to the "winner" of the round-robin procedure.

Detailed Results

As indicated previously, the results of the round-robin procedure were rank-ordered according to the number of times each competing preferred response (at the various crossover frequencies) was chosen. These results indicated that most subjects preferred several frequency-gain responses at various crossover frequencies that statistically (chi-square analysis) were not significantly different from each other. Since this general result was applicable to each subject, results from two subjects will be detailed as a representative demonstration of group data.

Figure 4 shows the descriptive results from a subject (BH) with a steeply sloping hearing loss. The panel on the left illustrates the audiogram described in SPL values at the eardrum. Also included in the left panel are the results of the LGOB test. Recall that the loudness test incorporates loudness ratings from "cannot hear" to "too loud"; however, the results shown on the graph are only those rated as "comfortable." The top right panel shows the preferred aided speech spectrum response for the two- and three-channel systems (these results were obtained by adding the preferred gain to the long-term rms speech spectrum at one-third octave intervals), while the relative gain is depicted in the lower right panel. Similar results are shown in **Figure 5** for a typical subject (LH) with gradually sloping hearing loss.

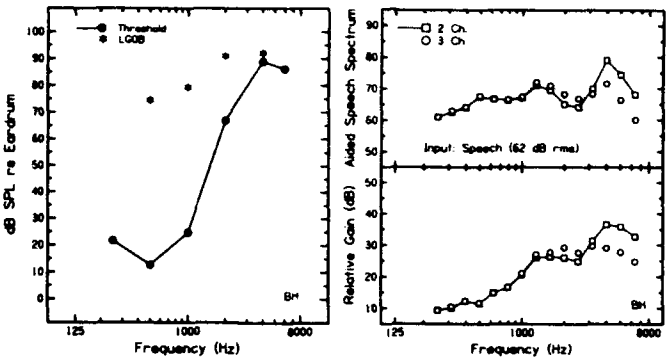

Figure 4.
Descriptive results from a subject (BH) with a steeply sloping hearing loss. The left panel includes the pure tone audiogram and comfort levels from the loudness test. The upper right panel shows the aided speech spectrum and the bottom right panel shows the relative gain for both the two- and three-channel systems.

Despite the large differences in hearing loss for each subject, especially in the low- and mid-frequency region, the preferred gain responses are similar; therefore, the preferred aided speech spectrum values for the two subjects are nearly equivalent. It has been shown that hearing-impaired subjects require amplification such that the amplified speech spectrum corresponds roughly to the loudness contour of comfort loudness levels rather than to audiometric configuration (10,14). Interestingly, despite large differences in audiometric thresholds, the comfort loudness levels as well as the preferred amplified speech spectrum for both subjects are similar. The preferred amplified speech spectrum values for both subjects, shown in the right upper panels of **Figure 4** and **Figure 5**, are slightly lower than the comfort loudness levels measured with the LGOB procedure. Assuming that there should be general correspondence between the comfort loudness level and the preferred amplified speech spectrum, the discrepancy between these values for our subjects is of interest. Recall that the loudness levels in this study (using the LGOB) were based on frequency-specific narrow-band signals, while the preferred aided-speech spectrum was based on broad-band continuous discourse. No allowance has been made for the loudness summation most hearing-impaired subjects experience when listening

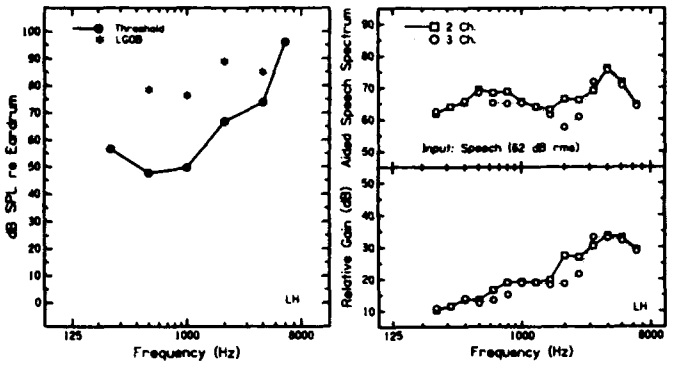

Figure 5.
Descriptive results from a subject (LH) with a gradually sloping hearing loss. The left panel includes the pure tone audiogram and comfort levels from the loudness test. The upper right panel shows the aided speech spectrum and the bottom right panel shows the relative gain for both the two- and three-channel systems.

to broad-band stimuli as compared with narrow-band stimuli. This loudness summation effect varies with input level and the individual hearing-impaired listener but, in general, can be quite large (2), and is probably responsible for the reduced levels of the aided speech spectrum relative to the frequency-specific comfort loudness levels.

Figure 6 shows the preferred frequency-gain responses at the various crossover frequencies for the subject (BH) with the steeply sloping hearing loss. The upper panel of the figure illustrates the results from the two-channel system, while the bottom panel contains similar data from the three-channel system. Also shown in each panel is the number of times each preferred frequency-gain response was chosen during the round-robin procedure. Similar results for the subject (LH) with gradually sloping hearing loss are shown in **Figure 7**.

Two observations from the data in **Figure 6** and **Figure 7** are noteworthy. First, the results of the round-robin procedure do not lead to a clear-cut "winner" within the two- or three-channel systems for either subject. Chi-square analysis was applied to the number of times each preferred response was chosen. In each of the four comparisons (two for each subject), the chi-square was significant (<0.01). This significant result was attributed to the lowest rank-ordered preferred response. (When this latter preferred response was removed from the analysis, the chi-square was not significant.) Thus, the results would suggest that for both the two- and

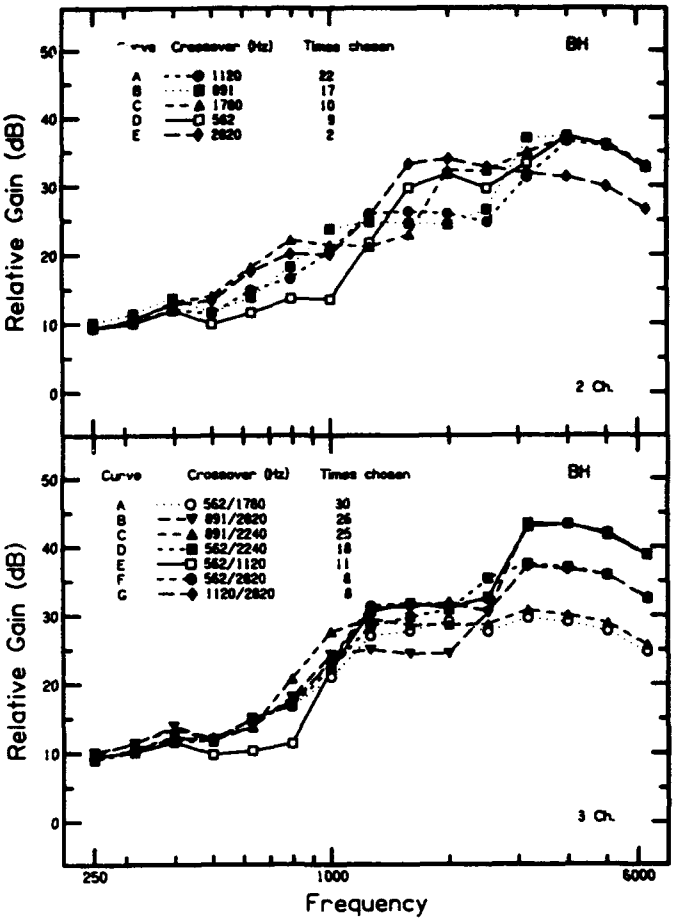

Figure 6.
Preferred frequency-gain responses, at various crossover frequencies for the two- and three-channel systems, for subject BH. Also included are the number of times each response was chosen, at the various crossover frequencies, during the round-robin procedure.

three-channel system, several preferred frequency-gain responses, with different crossover frequencies, might be acceptable to the subjects. Second, it was observed that within each condition, the preferred frequency-gain responses were often quite similar. The similarity between the physical characteristics of many of the preferred responses prompted us to question whether or not subjects could, in fact, appreciate the differences among the responses when comparing the samples. Thus, an additional experiment was conducted to determine the degree to which the subjects, who participated in the initial experiment, could appreciate the differences between the preferred responses using the continuous discourse stimuli.

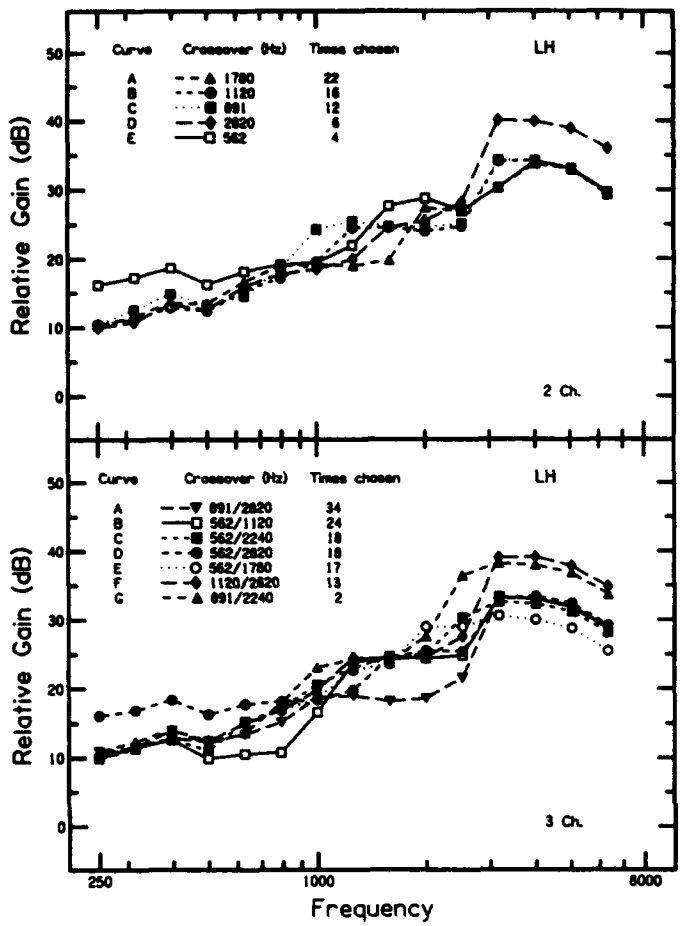

Figure 7.
Preferred frequency-gain responses, at various crossover frequencies for the two- and three-channel systems, for subject LH. Also included are the number of times each response was chosen, at the various crossover frequencies, during the round-robin procedure.

Supplemental Experiment

For this investigation, the round-robin procedure was again utilized, but instead of making a preference judgment, the subjects were instructed to provide a "same/different" judgment between the speech samples heard for the various preferred frequency-gain responses that had been chosen in the first experiments. Each frequency-gain response was compared with every other response a total of four times.

A control condition was included in this experiment in order to verify that the subjects could readily perform the same/different task. Two foil frequency-gain responses (two NAL responses) were paired against each other in the round-robin procedure. Within the experiment, these two foil responses were the only ones that were identical in physical characteristics. No subject had difficulty identifying the two foil responses as the same.

Results. For data analysis, given that each response was compared four times with every other, judgments were considered as "same" if a subject rated three or four of the four comparisons between any two frequency-gain responses as identical. Judgments were considered "uncertain" if two of the comparisons were rated the same and two different. A judgment of "different" was used if the subject rated three or four of the comparisons as different from each other. Subjects were instructed to ignore the obvious fact that each segment of the continuous discourse contained different sentences. Similar to the earlier instructions for making preference judgments, each subject judged the comparative frequency-gain responses as same or different depending on his or her own internal criteria of variations in the quality or intelligibility of the speech.

The results of the same/different task for the nine subjects revealed two somewhat discrete patterns of judgments. One, represented by the results for subject BH, indicated that a majority of the comparisons were judged to be the "same." The results of BH are shown in **Figure 8** in terms of the percent of occurrence of the various ratings for the two- and three-channel systems. Note that the "same" judgment was predominant among the preferred responses for the two-channel system.

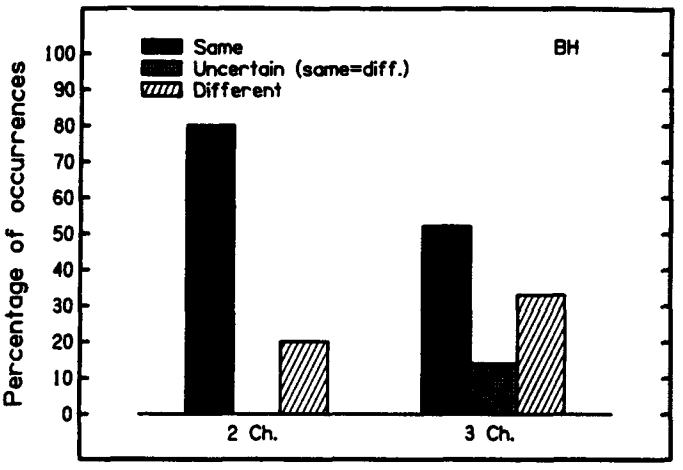

Figure 8.
Percentage of occurrences of the various ratings from the same/different task for subject BH.

While the "same" judgment continued to be in the majority for comparisons made with the three-channel system, the difference in the ratings between "same" and "different" were somewhat more evenly divided. This result seems reasonable if the earlier data (**Figure 6**), which illustrated the preferred frequency-gain responses, are reviewed. Those data indicated relatively little difference in the physical characteristics of the preferred frequency-gain responses chosen for the two-channel system. For the three-channel system, however, the spread in the physical characteristics of the preferred frequency-gain responses was relatively large in the high-frequency channel, and most likely accounted for the more evenly divided same/different ratings for that condition.

Five subjects in this experiment followed the general pattern of BH, implying that the lack of a distinct preferred frequency-gain response (from the round-robin procedure) may be closely related to the inability of these subjects to differentiate perceptually among many of the competing frequency-gain responses. With one exception, the subjects in this group were those with the steeply sloping hearing loss.

Figure 9 contains the pattern of same/different judgments for subject LH. As can be seen, a majority of the comparisons were judged to be "different," especially for the three-channel system. Inspection of the preferred frequency-gain responses of LH (**Figure 7**) again shows relatively large differences between the responses for the three-channel system, not only in the high-frequency region but also in the low- and mid-frequency regions. For the two-channel system, variations between the preferred responses in both the low- and high-frequency regions are observed; however, the differences are not as large as those found for the three-channel system. Four subjects, with gradually sloping or uniform loss, followed the pattern of LH. For those subjects it appeared that even though they were able to perceptually differentiate between the responses, a clear-cut preference still did not result from the round-robin procedure. This result may suggest that a range of frequency-gain responses would be acceptable for that subset of subjects.

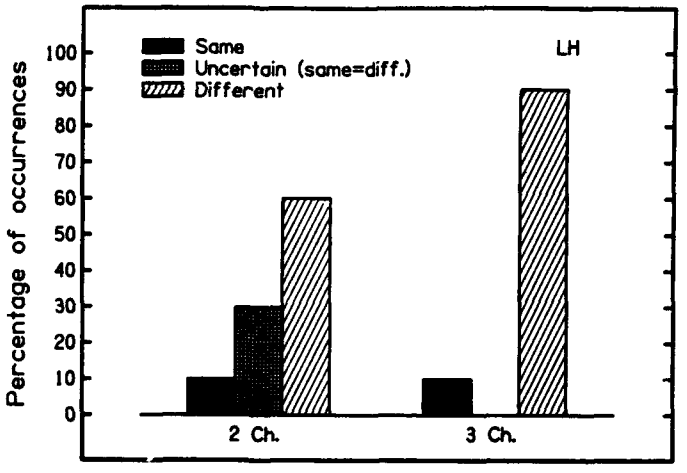

Figure 9.
Percentage of occurrences of the various ratings from the same/different task for subject LH.

As indicated previously, the simplex procedure resulted in five preferred frequency-gain responses for the two-channel system and seven for the three-channel system. From the round-robin procedure a winner was identified, although inspection of the data showed that several frequency-gain responses were chosen nearly as often as the winner. It seems clear from the results of the supplemental experiment that some subjects found it difficult to discriminate between several of the frequency responses that were physically similar. Therefore, for those subjects, the round-robin results may have been significantly influenced by this factor.

An additional analysis was performed on the results from the supplemental experiment. Of interest was the degree to which the frequency-gain curves differed from each other before the curves were judged to be dissimilar. To obtain this information, the percent of same or different judgments was analyzed as a function of the rms differences between the preferred frequency-gain responses. The differences were quantified in the following manner. First, the difference between each frequency-gain curve was calculated at each one-third octave band. The rms difference was then calculated as the square root of the mean of the sum of the differences squared. This calculation provided us with distributions of rms differences for the two- and three-channel systems. The distribution of rms differences ranged from 1 dB to 11 dB. The percent of times a "same" (three or four out of four times) or "different" (three out of four times) judgment occurred was calculated for each rms difference. A rating of "uncertain" was given to comparisons

where the "same" and "different" rating occurred equally.

Figure 10 (two-channel system) and **Figure 11** (three-channel system) illustrate the percent of times subjects judged two comparative frequency-gain response curves as the "same," "uncertain," or "different" as a function of the distribution of rms differences. As might be anticipated, for small rms differences between curves (1–4 dB), a majority of the comparisons were judged the same. For 4 dB rms differences, the same/different judgments were either equal (three-channel system) or approaching equality (two-channel system). For larger differences (>4 dB), a majority of the comparisons were judged to be different. Some irregularities occurred at the highest rms difference principally because of the small number of samples on which to base the estimates. These results suggested that at least one-half of the hearing-impaired subjects could perceptually distinguish rms differences of 3–4 dB of continuous speech in noise. Interestingly, for the simplex procedure we chose a 6 dB step size, based *a priori* on preliminary observations. Given the results from the same/different task just reported, the 6 dB step size appeared in retrospect to be a reasonable choice. For many subjects, a smaller step size would have led to indecisive behavior and thus test poor test efficiency. A larger step size, however, may not have yielded sensitive enough data.

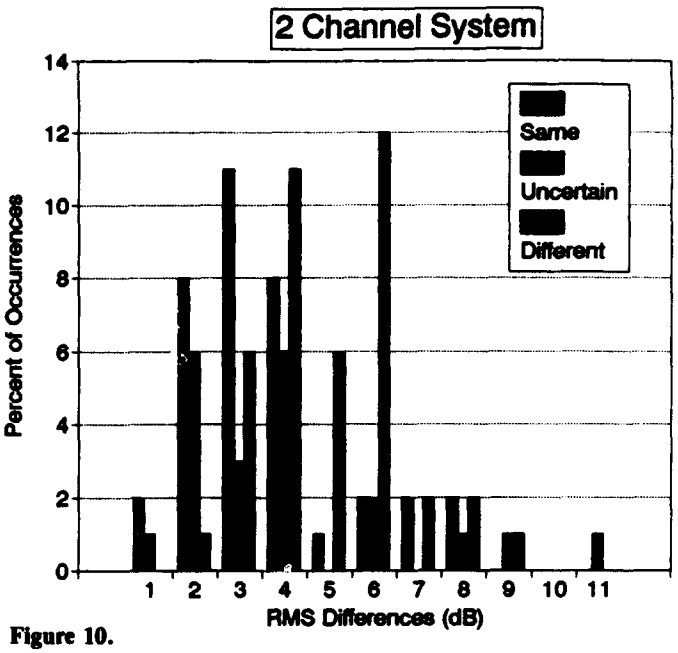

Figure 10.
Percentage of times subjects judged comparative frequency-gain response curves in the two-channel system as "same," "uncertain," or "different" as a function of the rms differences between any two preferred frequency responses.

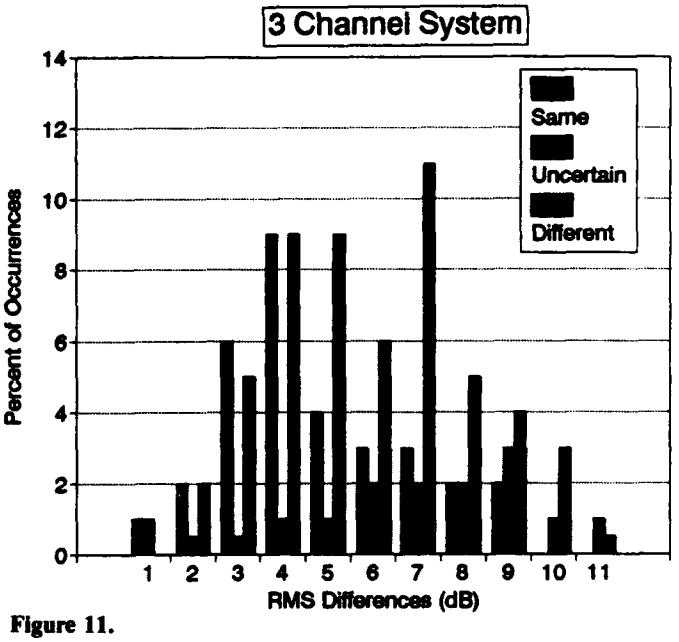

Figure 11.
Percentage of times subjects judged comparative frequency-gain response curves in the three-channel system as "same," "uncertain," or "different" as a function of the rms differences between any two preferred frequency responses.

DISCUSSION

The results from this experiment demonstrated no significant differences between the preferred frequency-gain responses for two- or three-channel amplification systems. This observation applied to both a group of subjects with steeply sloping hearing loss and to a group with gradually sloping or uniform hearing loss. It should be stressed, however, that these studies were conducted under linear amplification conditions, and it is quite possible that a different set of results will apply for systems with various types of compression amplification. Conducting investigations similar to the current study, but incorporating compression parameters, would be especially timely because of advances in technology that have already made two- and three-channel hearing aids commercially available.

Although a representative sample of crossover frequencies was available to the subjects, no single crossover frequency was consistently chosen by all subjects even when grouped by audiometric configuration. This result, however, does not imply that all

available crossover frequencies and the resultant frequency-gain responses were equally acceptable. That frequency-gain curves from several crossover frequencies were chosen approximately the same number of times may imply that the choice was more closely related to the suprathreshold loudness contour (which was observed at more equivalent SPL levels across the frequency range than at threshold) rather than the more varied audiometric shape at threshold. While the round-robin procedure appears to be a very useful technique for establishing an acceptable crossover frequency, this adaptive method is not highly efficient for clinical purposes. In our opinion, no systematic clinical procedure by which to select an appropriate crossover frequency for two- or three-channel hearing aids is currently available. It would be especially useful, however, if principles could be established possibly employing the shape of the loudness contour at comfort level as the means by which to establish an appropriate crossover frequency in the individual case.

As a group, the subjects preferred an average frequency-gain response (**Figure 3**) that approximated the NAL predictions, except in the low frequencies where more gain was routinely preferred than predicted by the NAL. This finding is in agreement with results reported by French-St. George, et al. (12). There are several factors that may have contributed to this preference of more low-frequency gain than predicted by NAL. First, the speech signal in the current study, and that of French-St. George, et al., were both presented at relatively low input levels (55–62 dB SPL). While it is implied that the NAL prediction is applicable at all input levels, there is evidence that the preferred frequency-gain response may change with input level (15). Second, as reasoned previously in the current paper, it appeared that sound quality may have played a larger role than intelligibility in the preference judgments. In the validation studies of the NAL (16), both perceived intelligibility and pleasantness (quality) of the speech were considered to be of importance. Generally, the importance of the mid- and high-frequencies has been associated with improvements in intelligibility. However, evidence (17,18) is also available indicating that increasing the amount of low-frequency gain resulted in judgments of better sound quality. Since the continuous discourse in the current study was generally understood by the subjects, perhaps they chose increased low-frequency gain in order to improve sound quality.

ACKNOWLEDGMENTS

The authors would like to thank Theodore Bell, PhD, for his help in the interpretation of the statistical analyses; Donald Morgan, PhD, for his critical comments; and Laurn Langhofer for programming assistance.

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Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 30 No. 3, 1993
Pages 318-325

Do adaptive frequency response (AFR) hearing aids reduce 'upward spread' of masking?

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Abstract—Speech recognition scores in noise are improved for some subjects who wear hearing aids that reduce low-frequency noise with an adjustable high-pass filter circuit. To evaluate whether these improvements were related to a reduction in upward spread of masking, pure-tone masking patterns for a low-frequency band-pass noise were measured in normal and hearing-impaired subjects. The filter skirt of the noise masker was very steep, with attenuation above the 1000 Hz cutoff greater than 120 dB per octave. Masking patterns for the same noise were also obtained in the presence of a high-pass filter that simulated the effects of an adaptive frequency response (AFR) hearing aid. Differences in the masking patterns were considered a measure of upward spread of masking. On average, subjects with high-frequency hearing loss demonstrated greater amounts of upward spread of masking than did normal-hearing listeners. Further, monosyllabic speech recognition in noise testing indicated improvements in performance of the hearing-impaired subjects related to the decrease of upward spread of masking in the high-pass filtering conditions.

Key words: *adaptive frequency response, hearing aids, high-pass filters, pure-tone masking patterns, speech recognition in noise, upward spread of masking.*

INTRODUCTION

The results of several recent experiments indicate that under some conditions, improved speech recognition in noise is possible with commercially available hearing aids that reduce low-frequency energy via an adjustable high-pass filter circuit (1,2). Recently, a study by Fabry and Van Tasell (3) reported that because speech-to-noise ratios are not improved by these "adaptive frequency response" (AFR) hearing aids, any improvement in speech recognition in noisy backgrounds is related either to auditory factors (such as upward spread of masking) or to nonauditory factors, including distortion or internal noise added by the hearing aid.

There is considerable support for the contribution of either auditory or nonauditory factors to improved speech intelligibility under certain background noise conditions. Preves and Newton suggested that conventional, peak-clipping hearing aids produce greater distortion than AFR hearing aids due to a lack of hearing aid "headroom" (4). They contend that AFR hearing aids prevent the hearing aid from reaching output saturation for lower input signals that saturate conventional devices. Thus, one explanation for results showing improved speech recognition in noise by subjects wearing AFR hearing aids is that the hearing aid used for comparison (in most instances peak-clipping, "linear" hearing aids) added significant amounts of distortion. This argument assumes, however, that distortion will degrade speech intelligibility. Although hearing aid distortion has been linked to poor speech quality (5), it is unclear whether it affects speech intelligibility adversely.

Psychophysical data suggest that auditory effects, such as upward spread of masking, may

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contribute to poor speech intelligibility by hearing-impaired subjects. Trees and Turner (6) and Gagne (7) reported that hearing-impaired subjects with precipitous high-frequency hearing loss showed "excessive" upward spread of masking relative to normal-hearing subjects for narrow-band noise masking experiments. Upward spread of masking effects are most pronounced for low-frequency, band-limited noises (8); presumably, high-pass filtering via AFR filter circuitry would be maximally effective under those conditions.

In the present study, the effects of *nonauditory* factors were minimized via a laboratory model of an AFR hearing aid that added very little distortion or noise. By isolating the auditory factors, the intention of the present study was to determine whether upward spread of masking was reduced by the processing used in AFR hearing aids, and if so, whether that reduction is accompanied by a change in speech recognition.

The following experimental questions were considered:

1. Is upward spread of masking excessive in subjects with precipitous high-frequency hearing loss?
2. Does the filtering imposed by commercially available adaptive frequency response hearing aids improve speech recognition by reducing upward spread of masking?

METHODS

Subjects

Eight male hearing-impaired subjects between the ages of 20 to 45 years of age participated in this experiment. All subjects had precipitous high-frequency hearing loss in the frequency region between 1000 and 2000 Hz, with no air-bone gaps greater than 5 dB measured at any audiometric frequency (250–8000 Hz). Audiologic and immittance findings excluded middle-ear and retrocochlear pathology.

Four subjects (two females and two males) with normal hearing also participated in this study; they ranged in age from 28 to 50 years old and had thresholds of 20 dB HL or more for all audiometric frequencies between 250 and 8000 Hz.

Apparatus

The output of a noise generator was shaped by a Fern digital filter to provide a band-pass low-frequency noise with cutoff frequencies of 200 Hz and 1000 Hz. The filter slope on the low-pass filter exceeded 120 dB/octave (**Figure 1**). This noise was attenuated and mixed with the channel 1 output of a Grason-Stadler GSI-10 diagnostic audiometer, which was equipped for either Bekesy tracking or delivery of tape-recorded stimuli. Subsequently, the output of the mixer (noise plus tones or recorded speech) was high-pass filtered by a Krone-Hite filter at either 200 Hz or 1500 Hz, amplified, and delivered to a TDH-49 earphone located in a sound-isolated suite.

PROCEDURES

Masking Patterns

Continuous Bekesy tracking was used with sinusoidal stimuli swept from 200 to 6000 Hz at a rate of 0.5 octaves/min; stimulus intensity was varied by 5 dB/sec increments. Each sweep took approximately 9 min. Each subject completed a threshold sweep at the beginning and end of the test session, and the average of the two measures at selected frequencies defined quiet threshold.

After subjects finished the first quiet threshold run, they completed several masked threshold traces in the presence of the low-frequency noise (**Figure 1**). For each subject, masking patterns were measured under earphones in the presence of this shaped

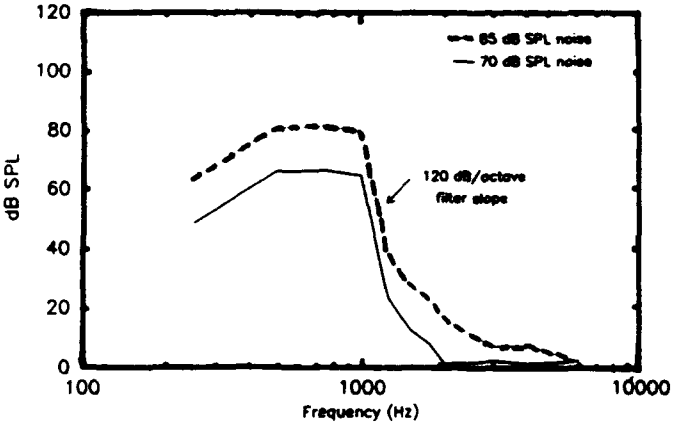

Figure 1.
Spectral measurements of band-pass noise for 70 dB SPL (solid line) and 85 dB SPL (dashed line) conditions.

noise at overall presentation levels of 70 dB SPL and 85 dB SPL (spectrum levels of 40 and 55 dB SPL), with the Krohn-Hite high-pass filter set to either 200 Hz or 1500 Hz.

Data collected with the filter set to 200 Hz comprised the unprocessed, or AFR-off, condition. In addition, the low-pass noise was high-pass filtered at 1500 Hz to simulate the processing imposed by the average of three commercially available AFR hearing aids (**Figure 2**). In this, the AFR-on condition, the noise was filtered as shown in **Figure 3**. Each subject completed a total of eight masking patterns, comprising two masking patterns (test-retest) for both noise levels (70 and 85 dB SPL) under both test conditions (AFR-off and AFR-on). The experimental conditions were counterbalanced across subjects to avoid order effects.

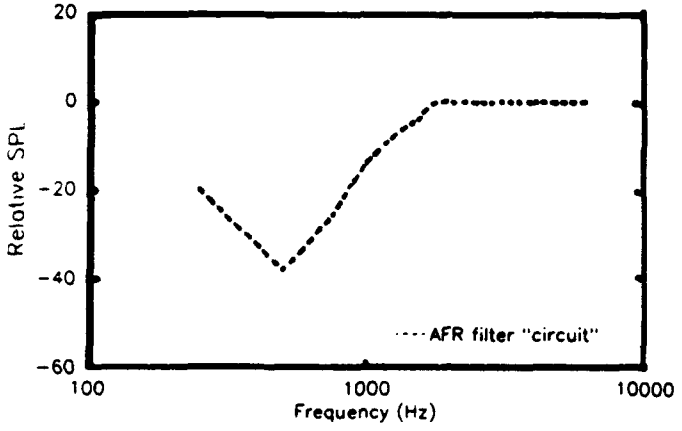

Figure 2.
Frequency response characteristics of the simulated adaptive frequency response (AFR) circuit used in the present study.

Speech Recognition Testing

Monosyllabic word recognition was measured for each subject under both AFR-on and AFR-off conditions using 200 words from Northwestern University's NU-6 recorded tests Forms C and D. Speech presentation levels were 72 dB SPL and 88 dB SPL; speech and noise were mixed and filtered together at either 150 Hz or 1500 Hz for AFR-off and AFR-on conditions, respectively. This condition was designed to simulate the performance of a single-microphone AFR hearing aid, with speech and noise mixed at the input microphone.

RESULTS

Masking Pattern Data

Normal-hearing Subjects. Averaged results from the four subjects with normal hearing are shown for AFR-off and AFR-on conditions in **Figure 4** and **Figure 5**, respectively. Data points illustrate selected frequencies for analysis from the Bekesy tracings; intersubject variability was less than 5 dB across all test frequencies. For the 70 dB SPL masker in the AFR-off condition (**Figure 4**, solid line) there is some "upward spread" of

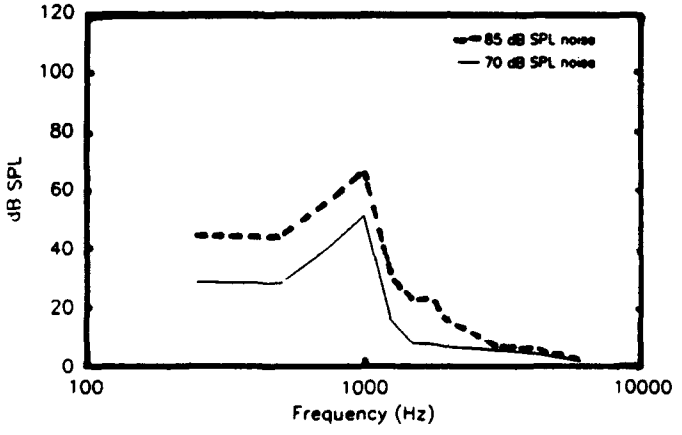

Figure 3.
Spectral characteristics of noise filtered by AFR circuit from **Figure 2** for the 70 dB SPL (solid line) and 85 dB SPL (dashed line) conditions.

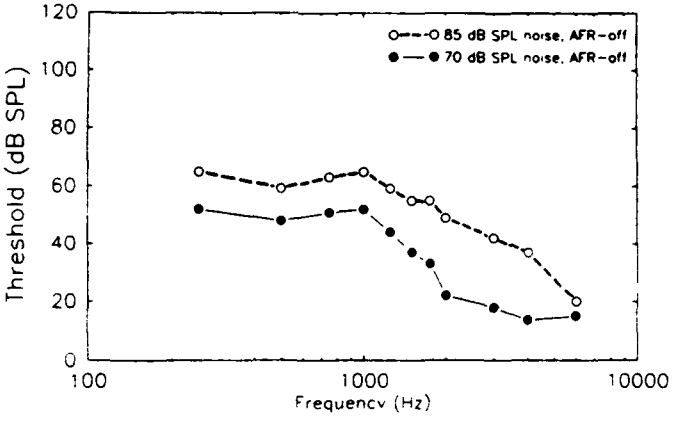

Figure 4.
Average masking pattern data from four normal-hearing subjects for the AFR-off condition for 70 dB SPL (solid line) and 85 dB SPL (dashed line) band-limited noise.

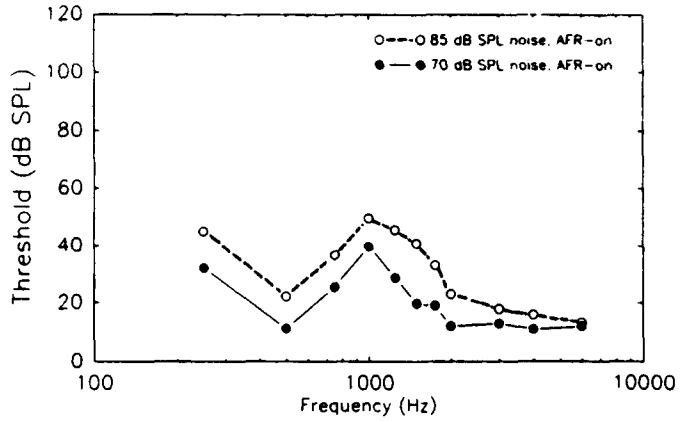

Figure 5.
Average masking pattern data for four normal-hearing subjects for the AFR-on condition for 70 dB SPL (solid line) and 85 dB SPL (dashed line) band-limited noise.

masking above 1000 Hz, compared with the noise spectra (**Figure 1**). For example, the difference between the average masked threshold and the noise spectrum at 1500 Hz was 28 dB. The disparity between masked thresholds and spectral measurements is even greater (33 dB) for the 85 dB SPL noise condition. These findings are similar to previous data for expected upward spread of masking reported by the ANSI (1969) Standard for Calculation of the Articulation Index (9), which were based on work by Carter and Kryter (10).

Hearing-impaired Subjects. Masking pattern data obtained from normal subjects formed the basis of the "reference" masked conditions. Using the methods employed by Gagne (7) and Trees and Turner (6), the quiet thresholds of hearing-impaired subjects were used to compare their masking patterns to those obtained from subjects with normal hearing. For a given condition, averaged masking patterns from normal-hearing subjects were compared with the masking patterns obtained from each hearing-impaired subject and his thresholds in quiet. For a given subject, "excess" spread of masking is indicated by the difference between the observed masking pattern and the normal masked condition *or* quiet threshold, whichever is higher.

Figures 6–9 show data from hearing-impaired subject H-1. The hatched areas in each figure indicate the region(s) of excess masking. For the 85 dB SPL noise level, it is clear that the region of excess upward spread of masking is reduced under the AFR-on condition (**Figure 7**) compared with the AFR-off condition (**Figure 6**). For the 70 dB SPL noise (**Figure 8** and **Figure 9**), data from this subject showed very little departure from the expected reference condition. That is, even for the AFR-off condition, there was only slightly more upward spread of masking than would be expected on the basis of his quiet thresholds. Under the AFR-on

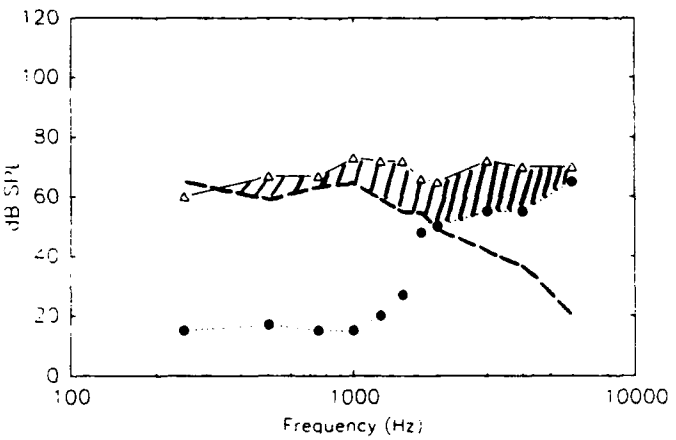

Figure 6.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-off condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-1 for the 85 dB SPL, AFR-off condition. Hatched areas indicate region of excessive upward spread of masking.

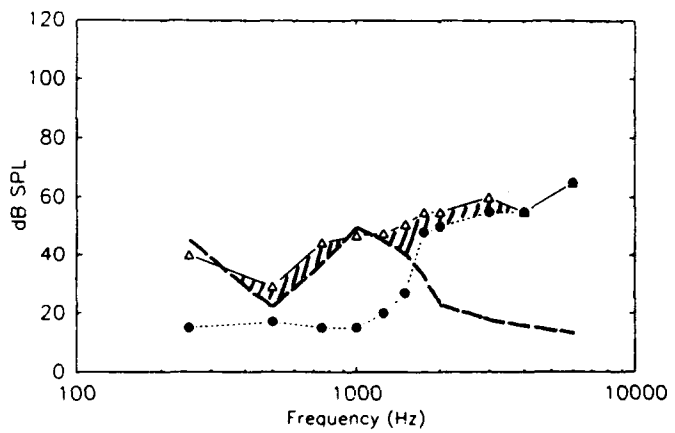

Figure 7.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-on condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-1 for the 85 dB SPL, AFR-on condition. Hatched areas indicate region of excessive upward spread of masking.

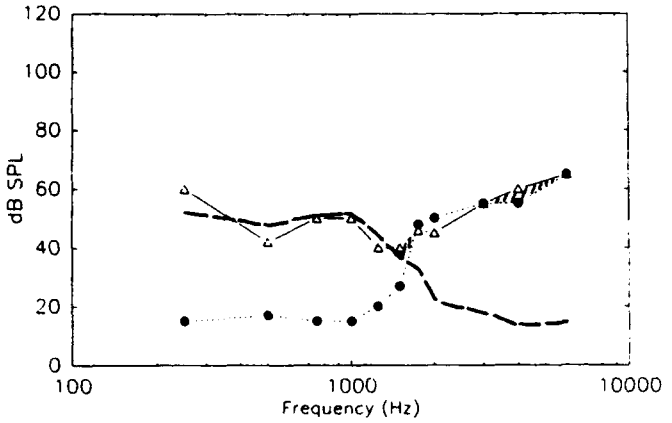

Figure 8.
Dashed line indicates normal masking pattern for 70 dB SPL, AFR-off condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from Subject H-1 for the 70 dB SPL, AFR-off condition. Hatched areas indicate region of excessive upward spread of masking.

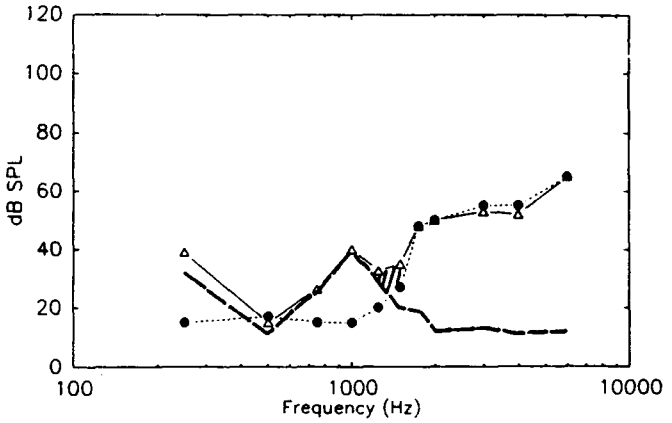

Figure 9.
Dashed line indicates normal masking patten for 70 dB SPL, AFR-on condition; quiet thresholds (filled circles) and masked threshold (open triangles) from Subject H-1 for the 70 dB SPL, AFR-on condition. Hatched areas indicate region of excessive upward spread of masking.

condition, the hatched areas indicating upward spread of masking have been reduced marginally. At least for this subject, the high-pass filtering imposed by the AFR-on conditions reduced upward spread of masking for the high-level background noise, but it was unnecessary for the 70 dB SPL noise condition. This rather large change in the amount of upward spread of masking between AFR-on and AFR-off conditions for the 85 dB SPL noise was found for five of eight hearing-impaired subjects (HI-1, HI-2, HI-5, HI-6, HI-8).

Data from the three remaining subjects were similar to those obtained from subject HI-4 (**Figure 10** and **Figure 11**). Masking patterns from that subject indicate that excessive upward spread of masking was present for *both* AFR-off (**Figure 10**)

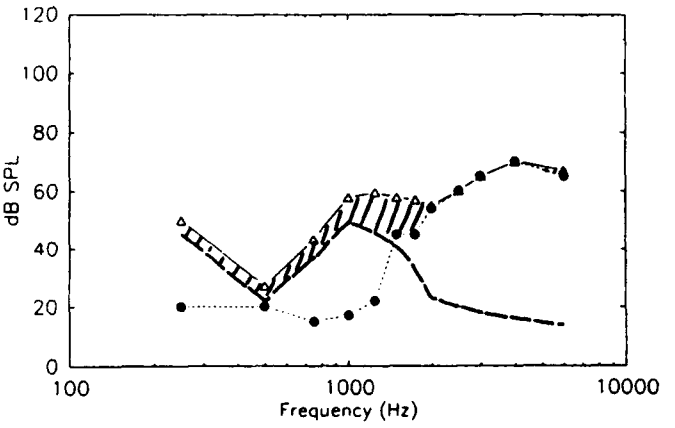

Figure 10.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-off condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-4 for the 85 dB SPL, AFR-off condition. Hatched areas indicate region of excessive upward spread of masking.

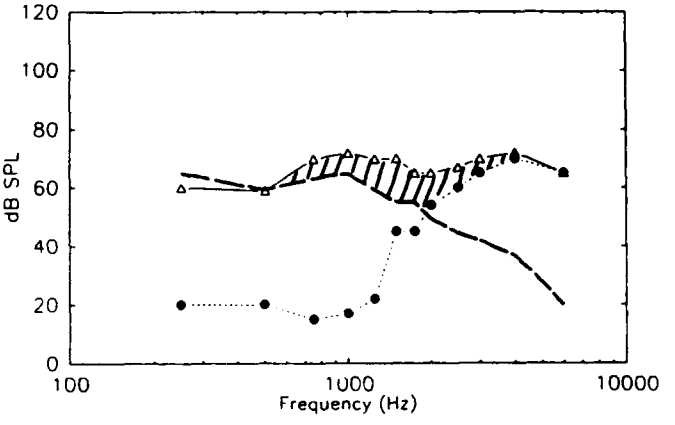

Figure 11.
Dashed line indicates normal masking pattern for 85 dB SPL, AFR-on condition; quiet thresholds (filled circles) and masked thresholds (open triangles) from subject H-4 for the 85 dB SPL, AFR-on condition. Hatched areas indicate region of excessive upward spread of masking.

and AFR-on (**Figure 11**) conditions. Even when low frequencies were reduced by the high-pass filter, masked thresholds were greater than predicted from the normal masking patterns and HI-4's quiet thresholds for both the 70 and 85 dB SPL noise conditions.

Speech Recognition Testing

Table 1 shows the difference in speech recognition scores between AFR-on and AFR-off conditions for normal and hearing-impaired subjects. Positive numbers indicate that speech recognition was higher for the AFR-on condition than for AFR-off; this was the case for all subjects except HI-3 (for the 70 dB noise level).

Additionally, masking pattern data were correlated with changes in speech recognition scores. Assuming that improved performance on NU-6 word lists reflected real-world changes in speech intelligibility (admittedly, a rather large intuitive jump), a predictive measure of benefit would be of use clinically to determine the efficacy of AFR hearing aids for a specific individual.

Figure 12 shows a scatterplot of the dB change (AFR-off minus AFR-on) at 1500 Hz versus the percent change in speech recognition (AFR-on minus AFR-off) for all hearing-impaired subjects and conditions. The correlation between these data was modest, at 0.61, but it was substantially better than the correlation between hearing threshold sensitivity and changes in speech recognition performance of 0.21.

Articulation Index (11) values were calculated from the relationship between the long-term spectral peaks of speech stimuli and each subject's masked- or quiet-threshold for AFR-on and AFR-off conditions. The long-term speech spectrum was measured, using a signal analyzer, for the monosyllabic word lists presented at 70 and 85 dB SPL. Articulation Index (AI) values were computed from the speech-to-masked-threshold or speech-to-threshold ratio, whichever was less, in each of 15 one-third-octave bands between 200 Hz and 6000 Hz. Pavlovic's bandweights for "average speech" comprised the band importance function (12). The data are shown in **Figure 13**, along with Black's (13) transfer function relating calculated AI to monosyllabic word recognition. Although the *absolute* speech recognition scores were not predicted for all subjects, one finding consistent with previous studies (3) is that within-subject changes in AI were related monotonically to speech intelligibility.

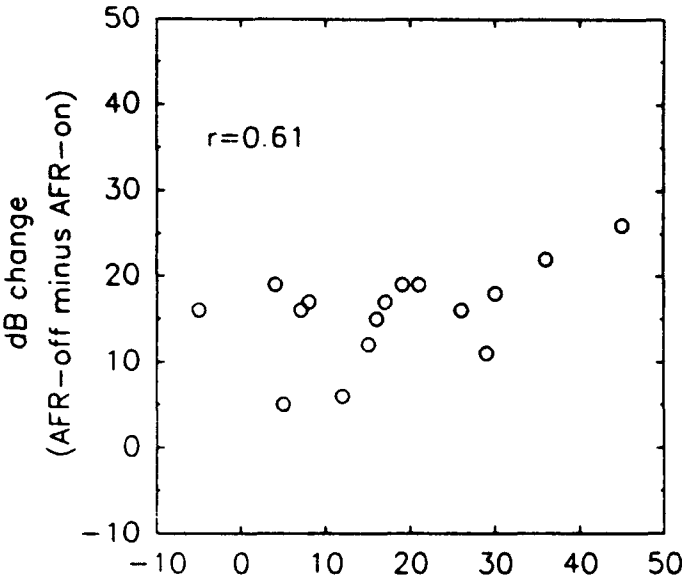

Figure 12.
Data compare the change in masked threshold at 1500 for AFR-on and AFR-off conditions to the percent change in speech recognition scores under the same conditions. Data on the ordinate are the AFR-on masked thresholds minus AFR-off thresholds for the same subject; data on the abscissa are the difference in speech recognition for AFR-on minus AFR-off conditions.

Table 1.
Improvement in Speech Recognition

	Percentage	
	70 dB SPL	85 dB SPL
Normals	8	30
HI-1	12	36
HI-2	29	45
HI-3	−5	8
HI-4	15	7
HI-5	30	27
HI-6	4	19
HI-7	5	17
HI-8	19	26

DISCUSSION

Previously, Fabry and Van Tasell (3) calculated AI values for subjects wearing actual AFR hearing

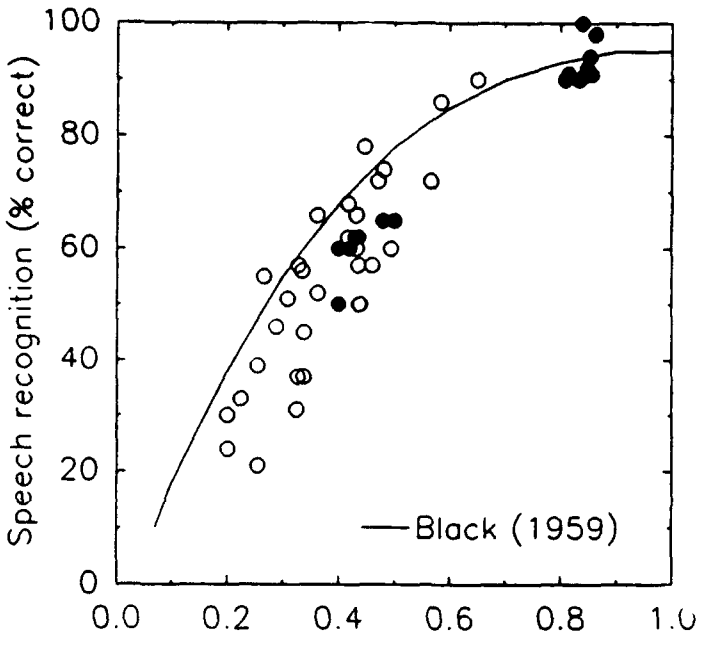

Figure 13.
Speech recognition scores for normal (filled circles) and hearing-impaired (open circles) subjects plotted as a function of AI for AFR-on and AFR-off conditions. Solid line depicts the AI transfer function developed by Black (13).

aids in background noise, and found that AI uncorrected for upward spread of masking effects typically over-predicted speech recognition scores. In the present study, the deleterious effects of hearing-aid-related factors (such as saturation and distortion), were minimized, because hearing aid performance was modeled with a laboratory system. This allowed for better isolation of auditory factors, such as upward spread of masking, to be assessed directly via the masking pattern data. As a result, the AI predictions were more accurate than in the Fabry and Van Tasell (3) study. This has several implications for using the AI as a tool for assessing performance of signal processing techniques on wearable hearing aids.

First, it may be possible to use masked threshold data to predict benefit from AFR hearing aids. Presumably, if hearing-impaired persons differ in the degree to which they suffer from upward spread of masking, then they would be expected to differ in expected benefit from devices that attenuate low-frequency energy. If 1500 Hz is used as a guide, it is speculated that "satisfied" hearing aid users will show greater reduction in masked threshold than unhappy users. Caution is advised, however, when measuring *aided* masked thresholds with actual hearing aids. Data from the present study are consistent with previous work that suggests that substantial amounts of harmonic and intermodulation distortion may be produced when actual hearing aids are evaluated under conditions of band-limited noise (14).

Second, although AI results were related monotonically to speech recognition for all subjects, this conclusion holds true only for speech and noise levels that are below the threshold of discomfort. At least one recent study has reported decreases in speech recognition for high presentation levels (15).

Finally, although AI predicted speech recognition scores reasonably well, it does not allow for user preference on factors not related to speech intelligibility. It is possible that these factors, such as speech quality or improved listening ease, may play an important role in acceptance of signal processing hearing aids.

CONCLUSIONS

1. Upward spread of masking was excessive for several of the hearing-impaired subjects used in this study.

2. For some hearing-impaired subjects, high-pass filtering resulted in improved speech recognition that was related in a somewhat predictable sense to reduced upward spread of masking. This benefit is restricted to band-pass noise conditions, and improvements in speech intelligibility are usually no greater than those achieved by subjects with normal hearing.

ACKNOWLEDGMENTS

The preparation of this manuscript was supported, in part, by the Department of Clinical Investigation, Walter Reed Army Medical Center, Washington, DC, and by the Sheldon F. Reese Foundation. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the Department of Army or the Department of Defense.

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Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 30 No. 3, 1993
Pages 326-332

Effects of prolonged lack of amplification on speech-recognition performance: Preliminary findings

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Abstract—The purposes of this investigation were twofold: 1) to prospectively investigate the effect of prolonged lack of binaural amplification in the unaided ears of adults with bilaterally symmetrical sensorineural hearing impairment (BSSHI) fitted monaurally; and, 2) to prospectively investigate the effects of amplification on speech-recognition performance in the aided ears of monaurally and binaurally fitted subjects. Subjects consisted of 19 monaurally aided adults, 28 binaurally aided adults, and 19 control adults. Both ears of the experimental subjects (binaurally and monaurally aided adults) had BSSHI. The speech measures included the W-22 CID suprathreshold speech-recognition test, nonsense syllable test, and speech-perception-in-noise test. Initial testing was done between 6 and 12 weeks following hearing-aid fitting. Retests were performed approximately 1 year following the initial test. The results revealed that the mean aided minus unaided ear score for the nonsense syllable and W-22 tests increased significantly from the initial test to retest, reflecting a slight improvement in speech performance in the aided ear and a slightly greater decrement in the unaided ear. The findings were interpreted with respect to the theories of auditory deprivation and acclimatization.

Key words: *acclimatization, auditory deprivation, binaural amplification, monaural amplification, nonsense syllable test, speech perception in noise, suprathreshold speech-recognition ability, word-recognition test.*

INTRODUCTION

Silman, Gelfand, and Silverman (1) were the first to report the phenomenon of late-onset auditory deprivation in the unaided ears of monaurally fitted subjects with bilaterally symmetrical sensorineural hearing impairment (BSSHI). In their retrospective study of adult males with BSSHI consistent with a noise-induced origin, they reported that at approximately 4–5 years post hearing-aid fitting, the W-22 suprathreshold speech-recognition scores (SSRSs) decreased significantly under phones in the unaided, as compared with the aided ears of monaurally fitted subjects. An auditory-deprivation effect was absent in both ears of the binaurally fitted subjects.

Hood's findings supported the concept of auditory deprivation. He found that the SSRSs of the impaired ears (under phones) of persons with unilateral sensorineural hearing impairment due to Meniere's disease were lower than those of matched ears of persons with bilateral sensorineural hearing impairment due to Meniere's disease. Also, the SSRSs of the poorer ears were markedly poorer than those of the better ears of persons with only slightly asymmetrical, sensorineural hearing impairment due

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This study was supported by the Department of Veterans Affairs Rehabilitation Research and Development Service, Washington, DC.

to Meniere's disease. Hood suggested that these findings resulted from "neglect" of the poorer ear because of dependence on the better ear (2,3).

Silman, Gelfand, and Silverman's (1) findings for the unaided ears of monaurally fitted subjects versus the aided ears of monaurally and binaurally fitted subjects were substantiated by the published retrospective and prospective findings of several investigators in this country (4,5,6,7,8), and abroad (9,10,11,12,13,14).

Gatehouse (11,12) evaluated the signal-to-noise (S/N) ratio for 50 percent performance using single words (taped, under phones) presented at 65, 70, 75, 80, 85, and 90 dB SPL in a noise background in a group of 24 monaurally fitted subjects seen at a mean time of 4.8 years post hearing-aid fitting. Although speech-recognition performance was unavailable for the subjects at the time of hearing-aid fitting, the pure-tone thresholds were symmetrical. The results revealed significantly higher S/N ratios in the unaided as compared with aided ears at the two highest presentation levels, consistent with the results of other investigations on auditory deprivation; reverse findings were obtained at the lowest presentation level. His finding raised the question of whether auditory deprivation is apparent for relatively low-intensity speech.

In more recent studies, Gatehouse (13,14) prospectively examined speech-recognition-in-noise ability in four subjects with BSSHI at the time of monaural hearing-aid fitting, and at weekly intervals of up to 12 weeks post-fitting, using the speech materials employed in his earlier studies. Significant decrements in speech-recognition-in-noise ability were observed when speech was presented under phones to the unaided ears of monaurally fitted subjects at a level equivalent to 65 dB SPL plus aid gain with a flat frequency response and at a level equivalent to 65 dB SPL with an aid-processed frequency response. Gatehouse reported that these findings could be interpreted as demonstrating the existence of auditory-deprivation effects occurring within 3 months post-fitting, at least for speech-in-noise materials. This finding of an auditory-deprivation effect at 65 dB SPL supports the concept of auditory deprivation being apparent for relatively low-intensity as well as high-intensity speech. Gatehouse also reported that speech-recognition-in-noise ability improved in the fitted ears of monaurally fitted subjects when speech was presented at 65 dB SPL through an aid-processed frequency response and at 65 dB SPL plus aid gain with an aid-processed frequency response (13,14). He interpreted this improvement in speech-recognition-in-noise in the fitted ear as manifesting the effects of acclimatization to the hearing aid and its frequency response.

The prospective studies that have been done on auditory deprivation are case studies. Therefore, prospective, larger sample studies are needed to investigate the phenomenon of auditory deprivation. Moreover, no published prospective research has investigated auditory deprivation in binaurally fitted subjects. The question must be raised as to whether acclimatization occurs in the binaurally fitted subjects as Gatehouse reported for the aided ears of monaurally fitted subjects (13,14).

Therefore, the purposes of this investigation were twofold: 1) to prospectively investigate the effect of prolonged lack of binaural amplification in the unaided ears of BSSHI adults fitted monaurally; and, 2) to prospectively investigate the effects of amplification on speech-recognition performance in the aided ears of monaurally and binaurally fitted subjects.

METHODS

Subjects

Subjects consisted of 19 monaurally aided adults (12 males and 7 females) aged 23 to 84 years (M = 65.8 years, SD = 13.5 years); 28 binaurally aided adults (21 males and 7 females) aged 40 to 80 years (M = 65.4 years, SD = 13.4 years); and 19 control adults (3 males and 16 females) aged 28 to 79 years (M = 62.0 years, SD = 14.0 years). Both ears of the experimental subjects (binaurally and monaurally aided adults) met the following criteria for BSSHI: 1) pure-tone average (PTA) (based on 500, 1000, and 2000 Hz) of at least 25 dB HL; 2) air-bone gaps not exceeding 10 dB at the audiometric frequencies between 500 and 4000 Hz and not exceeding 15 dB at 250 Hz; and, 3) acoustic-immittance results consistent with the absence of conductive or retrocochlear pathology. All of the experimental subjects had the following characteristics: 1) negative history of neurologic involvement; 2) interaural air-conduction threshold difference not exceeding 25 dB at each audiometric frequency; 3)

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interaural speech-recognition threshold (SRT) difference not exceeding 10 dB; and, 4) interaural SSRS difference not exceeding 20 percent.

Both ears of the control, normal-hearing subjects met the following criteria for inclusion in the study: 1) pure-tone, air-conduction thresholds no poorer than 25 dB HL at the audiometric frequencies between 250 and 2000 Hz, and no poorer than 35 dB HL at 4000 Hz; 2) SRT no poorer than 25 dB HL; 3) air-bone gaps not exceeding 10 dB at the audiometric frequencies between 500 and 4000 Hz, and not exceeding 15 dB at 250 Hz; and, 4) acoustic-immittance results consistent with the absence of conductive or retrocochlear pathology. All of the control subjects had a negative history of neurologic involvement.

Speech Materials

The speech materials consisted of: 1) the Auditec of St. Louis recording (male talker) of the 50-word, CID W-22 word lists; 2) a modified recording (male talker) of the speech perception in noise (SPIN) test (15); and, 3) a City University of New York recording (male talker) of the Nonsense Syllable Test (CUNY/NST) (16).

The "high predictability" (PH) sentences of the SPIN test were employed. These sentences were modified following Gelfand, Ross, and Miller (17) such that the average levels of the sentences fell within ± 1.5 dB of each other; several items were omitted because of possible distortions, leaving a total of 96 sentences. The noise was the 12-talker babble from the SPIN. The babble was dubbed onto the test tapes so that for each item the noise would come on first, nominally 1 second before the sentence began, and would remain on until about 1 second after the sentence ended.

The CUNY/NST consists of seven subtests, each of which contains seven to nine nonsense syllables of the CV or VC type. Each subtest employs a closed-set format and the response foils are essentially all of the remaining syllables within the subtest.

Procedure

All testing was done in a two-room audiometric suite meeting ANSI S3.1 (1977) standards for audiometric environments. All pure-tone, acoustic-reflex activating, and taped signals were routinely calibrated with a sound-level meter (B&K 4150) and coupler (NBS-9A).

Binaural amplification was recommended for all of the experimental subjects, who were first-time hearing-aid users. Those subjects who rejected binaural amplification in favor of monaural amplification because of financial or cosmetic reasons comprised the monaural group. Those subjects who accepted binaural amplification comprised the binaural group. Initial testing (Year 1 of this study) of the experimental subjects was done between 6 and 12 weeks post hearing-aid fitting. Retesting was done within 12 weeks following the annual anniversary of the initial test. All subjects who were retested indicated that they wore amplification for at least 4 hours per day.

A blind design was employed. That is, the interviewer who obtained the history and provided counseling at the initial and retest evaluations and the test administrator were not the same person for a given subject and the test administrator was not informed about the hearing-aid status (monaural versus binaural) of the experimental subjects.

The following tests were administered to each ear of each patient: 1) pure-tone, air-conduction testing at the octave frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz; 2) bone-conduction testing at the octave frequencies of 250, 500, 1000, 2000, and 4000 Hz; 3) SRT testing using taped spondaic W-1 words; 4) suprathreshold speech-recognition testing using taped CID W-22 monosyllabic PB words; 5) static-acoustic middle-ear admittance testing; 6) admittance-pressure function testing; 7) contralateral acoustic-reflex threshold testing using the 500-Hz, 1000-Hz, and 2000-Hz tonal activators and 226-Hz probe tone; 8) speech-recognition-in-noise threshold testing using the high PH sentences of the taped SPIN test; and, 9) taped NST.

The presentation level of the W-22, high PH SPIN sentences, and NST tests was 40 dB SL re: SRT whenever possible. It was reduced whenever necessary to accommodate the output limits of the audiometer or tolerance problems. For the SPIN materials, the up-down adaptive procedure (18,19) was applied to the intensity of the 12-talker babble to derive the S/N ratio corresponding to 50 percent sentence recognition.

The routine, audiologic tests preceded the speech-recognition tests. The order of the routine audiologic tests was as follows: 1) pure-tone, air-

conduction thresholds; 2) pure-tone, bone-conduction thresholds; 3) SRT; 4) static-acoustic middle-ear admittance; 5) admittance-pressure function; and, 6) contralateral acoustic reflex threshold testing. The order of the W-22, SPIN, and NST tests was counterbalanced. At the initial test, the ear tested first was randomized. At the retest, the ear tested first was contralateral to the ear tested first at the initial test.

Scores consisted of individual ear scores, aided minus unaided ear scores for the monaurally aided group, right minus left ear scores for the binaurally aided and control groups, unaided plus aided ear scores for the monaurally aided group, and right plus left ear scores for the binaurally aided and control groups. A comparison using *t*-testing was made between the initial and retest scores in the monaurally aided, binaurally aided, and control groups.

RESULTS AND DISCUSSION

The means and standard deviations of the air-conduction thresholds and SRTs for the right and left ears of the binaurally aided and control groups and for the aided and unaided ears of the monaurally aided group at the initial test (Year 1) and retest (Year 2) are shown in **Table 1**. Inspection of **Table 1** reveals that the air-conduction thresholds and SRTs are symmetrical for the binaurally aided and control groups at the initial test and retest. Inspection of this table further indicates that the air-conduction thresholds and SRTs are slightly higher for the aided than unaided ears at the initial test and retest. Also, the SRTs and air-conduction thresholds of the monaurally aided and binaurally aided groups are essentially similar. There is essentially no change in the air-conduction thresholds or SRTs from the initial test to retest in the monaurally aided, binaurally aided, and control groups.

Table 2 shows the means and standard deviations of the W-22 SSRSs, SPIN S/N ratios, and NST SSRSs for each ear condition at the initial test (Year 1) and retest (Year 2) in the monaurally aided group. Inspection of the mean data in **Table 2** reveals that at the initial test, speech performance on the W-22, SPIN, and NST tests appeared to be slightly poorer in the aided than unaided ears of the monaurally aided group. This finding probably reflects the slightly poorer air-conduction thresholds and SRTs in the aided than unaided ears of the monaurally aided group.

Inspection of **Table 2** also shows that the mean aided minus unaided W-22 score significantly increased ($p<0.05$) from the initial test to the retest, reflecting a slight improvement in speech performance in the aided ear and a slightly greater decrement in the unaided ear. Similarly, the mean aided minus unaided NST score significantly in-

Table 1.
Means (M) and standard deviations (SD) of the air-conduction thresholds and SRTs for the right ears (RE) and left ears (LE) of the binaurally aided and control groups and for the aided (A) and unaided (UA) ears of the monaurally aided group at years 1 and 2.

	Frequency						
Group	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**SRT**
Monaural							
Yr 1 A M	28.8	30.3	37.4	49.7	60.5	70.8	33.4
UA M	20.3	25.0	30.5	40.5	55.0	64.2	28.4
Yr 1 A SD	14.2	11.8	9.8	10.6	15.0	20.4	11.2
UA SD	8.7	8.5	10.4	11.3	18.8	13.1	7.5
Yr 2 AM	25.6	30.8	38.4	50.5	60.8	72.4	35.9
UA M	23.2	26.3	32.6	43.4	57.9	65.4	28.9
Yr 2 A SD	12.9	11.9	10.4	11.7	16.1	19.2	11.1
UA SD	11.3	11.5	13.4	11.7	14.4	16.7	10.4
Binaural							
Yr 1 RE M	23.3	27.0	34.8	50.5	68.0	79.4	31.6
LE M	25.2	27.5	35.0	50.7	69.1	74.4	31.8
Yr 1 RE SD	13.7	14.1	14.9	13.2	14.2	15.1	12.6
LE SD	16.8	16.9	15.8	13.7	14.5	15.1	17.0
Yr 2 RE M	21.9	27.1	36.4	51.3	69.8	79.4	33.1
LE M	24.8	28.2	36.6	51.3	69.2	76.2	33.4
Yr 2 RE SD	12.3	13.9	15.6	13.6	14.3	14.0	13.2
LE SD	15.8	16.7	16.1	13.0	12.6	14.7	16.6
Control							
Yr 1 RE M	10.3	10.8	9.5	9.5	9.7	22.3	10.5
LE M	11.8	12.6	9.5	10.8	12.6	22.4	10.8
Yr 1 RE SD	8.6	7.9	7.8	9.6	10.6	16.7	10.1
LE SD	7.5	6.5	9.8	8.4	8.6	15.0	9.5
Yr 2 RE M	11.1	10.5	10.8	10.3	10.7	26.5	11.6
LE M	12.5	11.8	10.3	11.4	10.7	26.7	11.8
Yr 2 RE SD	6.3	10.5	10.4	10.5	9.0	16.8	8.5
LE SD	7.8	9.9	9.5	9.4	9.2	17.5	7.7

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Table 2.
Means (M) and standard deviations (SD) of the W-22 suprathreshold speech-recognition scores, SPIN S/N ratios, and NST suprathreshold speech-recognition scores for each ear condition at years 1 and 2 in the monaurally aided group.

	Ear Condition			
Test	**Aided**	**Unaided**	**Aid-Unaid**	**Aid + Unaid**
W-22				
Year 1 M	79.37	84.00	−4.63	163.37
Year 1 SD	12.76	12.54	13.48	20.84
Year 1 N	19	19	19	19
Year 2 M	82.00	77.47	4.53	159.47
Year 2 SD	9.55	15.60	12.77	21.90
Year 2 N	19	19	19	19
SPIN				
Year 1 M	20.35	14.41	5.94	34.77
Year 1 SD	14.40	15.38	12.55	26.21
Year 1 N	17	17	17	17
Year 2 M	19.59	16.77	2.82	36.35
Year 2 SD	11.23	9.55	8.84	18.32
Year 2 N	17	17	17	17
NST				
Year 1 M	0.5975	0.6958	−0.0984	1.2933
Year 1 SD	0.1547	0.1120	0.1041	0.2417
Year 1 N	17	17	17	17
Year 2 M	0.6622	0.5989	0.0633	1.2612
Year 2 SD	0.1310	0.1756	0.2280	0.2035
Year 2 N	17	17	17	17

creased ($p<0.05$) from the initial test to the retest, reflecting a slight improvement in the aided ear and a slightly greater decrement in the unaided ear.

The finding that the W-22 and NST mean aided minus unaided ear scores were significantly increased at the retest as compared with the test was substantiated by the following trends: 1) the retest mean W-22 and NST scores were slightly higher than the test mean scores in the aided ears; 2) the retest mean W-22 and NST scores were slightly lower than the test mean scores in the unaided ears; and, 3) the retest aided plus unaided mean W-22 and NST scores were slightly lower than the test scores.

These findings, which show a trend toward improvement in the aided ear, are consistent with the findings reported by Gatehouse (13,14). Gatehouse has interpreted improvement in the aided ear as evidence of acclimatization to the hearing aid. These findings also show a trend toward decrement in the unaided ear and are consistent with the finding of auditory deprivation in the unaided ear that was reported by several investigators (1,4,5,6,7,8,9,10,11,12,13,14). The trend toward improvement in the aided ear from test to retest and the trend toward a decrement in the unaided ear from test to retest yielded an aided minus unaided ear score that was significantly greater at the retest than test.

Although the mean aided minus unaided ear SPIN score at the retest was not significantly different from that at the initial test, inspection of the mean data in **Table 2** shows that speech performance in noise worsened from the test to retest in the unaided ear and improved from test to retest in the aided ear. Again, the decrement in the unaided ear appeared greater than the improvement in the aided ear. These findings were substantiated by the trend toward a decrease in the mean aided minus unaided ear SPIN score and in the mean aided plus unaided ear SPIN score.

Based on finding of a significant difference in the aided minus unaided ear scores between the retest and initial test for the W-22 and NST but not SPIN measures, it appears that the W-22 and NST measures are more sensitive than the SPIN measure to the effects of auditory deprivation in the unaided ear and acclimatization in the aided ear. Perhaps a significant difference between the retest and test mean SPIN scores will develop over time. Interestingly, Gatehouse (13,14) observed significant findings for the unaided and aided ears with his speech-in-noise test in the monaurally aided group at the retest performed only 12 weeks post hearing-aid fitting. In contrast, the speech-in-noise test employed in this study failed to show significant auditory deprivation or acclimatization findings at the retest performed one year post hearing-aid fitting. One possible explanation of this discrepant finding is related to the sensitivity of the speech measure and the procedure for measuring the S/N ratio. The speech-in-noise measure employed by Gatehouse (13,14) was a forced-choice word identification test based on the rhyme test principle. In

contrast, the SPIN test employed by the present investigators is an open-set sentence test. Gatehouse determined the S/N ratio for 70.7 percent correct identification, whereas the present investigators determined the S/N ratio for 50 percent correct identification. Thus, the speech-in-noise measure employed by Gatehouse was more of a suprathreshold test than the SPIN measure; perhaps the effects of auditory deprivation and acclimatization are more apparent on suprathreshold than on threshold tests.

Table 3 shows the means and standard deviations of the W-22 SSRSs, SPIN S/N ratios, and NST SSRSs for each ear condition at the initial test and retest in the binaurally aided group. The results of *t*-testing revealed that the mean retest score did not differ significantly from the mean retest score under any of the ear conditions in the binaurally aided group. This is consistent with the finding of absence of auditory deprivation in binaurally aided persons reported by Silman, Gelfand, and Silverman (1) and others. Inspection of **Table 3** reveals a trend toward improvement at the retest as compared with the initial test for most of the ear conditions and speech measures.

Table 4 shows the means and standard deviations of W-22 SSRSs, SPIN S/N ratios, and NST

Table 3.
Means (M) and standard deviations (SD) of the W-22 suprathreshold speech-recognition scores, SPIN S/N ratios, and NST suprathreshold speech-recognition scores for each ear condition at years 1 and 2 in the binaurally aided group.

	Ear Condition			
Test	Right	Left	Right-Left	Right + Left
W-22				
Year 1 M	77.43	76.07	1.36	153.50
Year 1 SD	13.83	18.75	14.38	29.11
Year 1 N	28	28	28	28
Year 2 M	81.70	78.96	2.74	160.67
Year 2 SD	15.93	15.97	12.00	29.00
Year 2 N	28	28	28	28
SPIN				
Year 1 M	16.09	14.64	1.46	30.73
Year 1 SD	10.57	11.30	9.46	19.28
Year 1 N	24	24	24	24
Year 2 M	15.33	14.17	1.17	29.50
Year 2 SD	12.74	10.84	9.87	21.05
Year 2 N	24	24	24	24
NST				
Year 1 M	0.6404	0.6150	0.0254	1.2554
Year 1 SD	0.1329	0.1323	0.1197	0.2317
Year 1 N	25	25	25	25
Year 2 M	0.6642	0.6143	0.0499	1.2785
Year 2 SD	0.1329	0.1342	0.1168	0.2354
Year 2 N	25	25	25	25

Table 4.
Means (M) and standard deviations (SD) of the W-22 suprathreshold speech-recognition scores, SPIN S/N ratios, and NST suprathreshold speech-recognition scores for each ear condition at years 1 and 2 in the control group.

	Ear condition			
Test	Right	Left	Right-Left	Right + Left
W-22				
Year 1 M	96.30	97.30	−1.00	193.2
Year 1 SD	3.73	3.06	2.87	6.27
Year 1 N	20	20	20	20
Year 2 M	97.68	95.26	2.63	193.0
Year 2 SD	2.77	4.82	5.08	5.98
Year 2 N	20	20	20	20
SPIN				
Year 1 M	1.65	1.70	0.15	3.35
Year 1 SD	2.50	1.50	1.90	3.65
Year 1 N	20	20	20	20
Year 2 M	1.05	1.25	0.00	2.30
Year 2 SD	1.82	1.97	1.84	3.26
Year 2 N	20	20	20	20
NST				
Year 1 M	0.8235	0.8246	−0.0003	1.6577
Year 1 SD	0.0811	0.0570	0.0702	0.1069
Year 1 N	20	20	20	20
Year 2 M	0.8437	0.8094	0.0344	1.6553
Year 2 SD	0.0748	0.0769	0.0998	0.1145
Year 2 N	20	20	20	20

SSRSs for each ear condition at the initial test and retest in the control group. The results of *t*-testing revealed that, similar to the results for the binaurally aided group, the mean retest score did not differ significantly from the mean test score under any of the ear conditions and speech measures. This is consistent with the expected finding of an absence of auditory deprivation and acclimatization in normal-hearing persons. Inspection of **Table 4** reveals the absence of any trends in the retest scores as compared with the initial test scores for any of the ear conditions and speech measures.

The decrement in the unaided ear appeared to be of greater magnitude than the improvement in the aided ear in the monaurally aided group. It is likely that more time will be required for a significant acclimatization effect to emerge in the aided ears of both the monaurally and binaurally aided groups than for a significant auditory-deprivation effect to emerge in the unaided ears of the monaurally aided group.

The subjects in this study are being followed over a 3-year period. Based on the findings reported here, it is hypothesized that speech-recognition performance in the unaided ear will decrease significantly and speech-recognition performance in the aided ear will improve significantly at future retest as compared with the initial test on all of the speech measures. The findings of this preliminary report supports the use of binaural amplification in persons with BSSHI.

ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of Susan Barker, Angela Benjamin, Michael Bergen, Eleanor Kempin, Debra Ludwig, and Christine Rota-Donahue with data collection and tabulation.

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Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 30 No. 3, 1993
Pages 333-341

High-frequency testing techniques and instrumentation for early detection of ototoxicity

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Abstract—Veteran patients with certain types of infections and cancers are routinely treated with therapeutic agents having ototoxic potential, thus threatening loss of hearing sensitivity which preexists in the majority of these patients. To prevent communication deficits requiring intervention, this laboratory is developing instrumentation and techniques for early detection of ototoxicity. For this study, conventional ($\leq$8 kHz) and high-frequency ($\geq$8 kHz) hearing thresholds were monitored behaviorally in hospitalized veterans receiving treatment with ototoxic drugs. Data analysis revealed that monitoring only the high-frequency range would have identified 67% of ears showing change. A five-frequency range of hearing, specific to each individual, was identified for its high sensitivity to early ototoxic change. Monitoring of only these five frequencies in each patient would have identified 82% of ears that showed behavioral change. Auditory brainstem responses (ABR) were obtained in a subgroup using clicks and high-frequency (8-14 kHz) tone bursts. ABR latency/morphology changes were observed in 95% of ears demonstrating behavioral change. High-frequency tone-burst-evoked ABRs alone would have identified 93% of initial changes. Monitoring of high-frequency audition using these techniques shows promise for early detection of ototoxicity with potential for prevention of hearing loss in frequencies essential for verbal communication.

Key words: *early detection, high frequency, instrumentation, monitoring, ototoxicity, prevention, technique.*

INTRODUCTION

As a major cause of communication disorders, hearing loss has a serious impact on the general population. Because of its importance to communication, hearing loss can profoundly affect the ability of a person to function socially and vocationally. More than 28 million individuals in the United States have hearing impairment (1). In men over the age of 55, the prevalence of reduced high-frequency hearing sensitivity has been estimated at 55 percent (2). A majority of the population served by the VA Medical Center system falls within this age group. In fact, the largest group of veterans with service-connected disabilities consists of those with hearing loss.

Because of their high probability of preexisting hearing loss, a particularly significant issue for veteran patients is ototoxicity from treatment with therapeutic drugs such as aminoglycoside antibiotics (AMG) and the chemotherapeutic agent cisplatin (CDDP). Exacerbation of hearing loss by ototoxic

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Funding for this study was provided by the Department of Veterans Affairs, Rehabilitation Research and Development Service, Washington, DC.

Editor's Note: The John Kendall VA Research Award, given to the Portland VA Medical Center researcher making the most significant contribution to biomedical science each year, was presented to Stephen Fausti, PhD, on March 23, 1993. Dr. Fausti received this award for his work in designing and developing a rapid technique for use in monitoring high-frequency audition in unresponsive patients.

drugs can be functionally devastating to the veteran if speech recognition ability is impaired. Furthermore, the ability of the VA to treat individuals in programs such as speech and language pathology, alcohol and drug dependency, blind rehabilitation, and post-traumatic stress disorders can be significantly affected by hearing loss. The patient is best served if rehabilitation is obviated by successful prevention of the handicapping condition.

Animal studies have suggested that hearing loss from ototoxicity begins in the highest audible frequencies (3,4,5). Human auditory testing programs monitoring drug-induced hearing loss with conventional audiometers ($\leq$8 kHz) also have shown that the highest frequencies evaluated were the first to be affected (6,7). An initial ototoxic symptom often reported by patients is increased difficulty in understanding speech in a noisy environment. When a communication deficit becomes subjectively apparent, it is likely that significant hearing loss below 4,000 Hz has been sustained. In medical centers where patients receiving ototoxic drugs are monitored for hearing changes, the procedure usually involves conventional audiometry ($\leq$8 kHz). However, when detected with this procedure, hearing loss will have progressed either into or near the range where speech communication is affected. Since hearing loss from most ototoxic agents appears to begin in the highest audible frequencies with progression to lower frequencies, monitoring of high-frequency ($\geq$8 kHz) thresholds should detect hearing change earlier than testing only with lower, conventional frequencies.

Fausti, et al. (8) evaluated available instrumentation for use in high-frequency ($\geq$8 kHz) testing, and found insufficient maximum power output, poor signal-to-noise (S/N) ratios and difficulty in calibrating transducers. A component high-frequency evaluation system was developed which provided the necessary outputs and high S/N ratios required for the study of high-frequency thresholds. This system was demonstrated to be reliable (9) and valid (10), and was used to conduct a series of studies evaluating the side effects on high-frequency hearing from ototoxic drug administration (11,12,13,14). Based on the development of the laboratory high-frequency evaluation system, a high-frequency audiometer was subsequently commercially manufactured. The 1980s saw the emergence of three additional high-frequency audiometers in the United States, thus providing instrumentation capable of full-frequency-range behavioral ototoxic monitoring.

It is common that medical centers have a significant number of hospitalized patients receiving potentially ototoxic medications who cannot be evaluated by behavioral audiometric techniques. It was estimated that more than 30 percent of veteran hospitalized patients administered potentially ototoxic drugs at the VA Medical Center, Portland, Oregon, were unable to be tested by behavioral auditory evaluation methods (15). These unresponsive patients typically do not receive any auditory monitoring for detection of ototoxic effects. In addition to unresponsive patients, many patients can respond to behavioral testing, but due to their illness may provide unreliable results over time. Thus, there is a need for an objective method of monitoring hearing in unresponsive patients to provide information as early as possible regarding hearing change (or absence of change).

Evoked otoacoustic emissions (EOAE) may have potential as an objective technique for ototoxic monitoring (16). However, the usefulness of current EOAE instrumentation and techniques is restricted to regions of good hearing sensitivity. For ototoxic monitoring and early detection of hearing change, high-frequency ($\geq$8 kHz) evaluation is desired, and sensitivity in this range is reduced even in the normal-hearing patient. For the eventual application of on-the-ward monitoring for ototoxicity, we have chosen the more widely used, noninvasive auditory brainstem response (ABR) technique.

The ABR evoked by click stimuli has proven valuable as an objective auditory monitoring tool for patients unable to respond reliably to behavioral testing and has been demonstrated to be a potential objective indicator of ototoxicity (17,18,19,20). However, click stimuli, as well as traditional tonebursts ($<$8 kHz), detect changes in hearing sensitivity in the conventional-frequency range. Tonebursts at frequencies of 8 kHz and above could be expected to objectively detect initial ototoxicity if reliable ABRs could be obtained with these stimuli.

Early studies in this laboratory demonstrated the feasibility of high-frequency toneburst ABR using a rack-mounted laboratory system that presents high-frequency tonebursts at 8, 10, 12, and 14 kHz (8,21). Later studies using this system analyzed the effects of rise time and center fre-

quency on the ABR (22) and demonstrated the reliability of ABRs to these high-frequency toneburst stimuli in normal-hearing subjects (23). This high-frequency toneburst system was designed for evaluating responsive subjects in the laboratory environment. Testing unresponsive, nonambulatory patients, however, required the development of a portable system, described in Fausti, et al. (15), which could be transported to a patient's bedside. Validity of measurements collected on the portable system was demonstrated by confirming that responses were equivalent to those elicited by the laboratory system (24).

Any means of reducing or preventing hearing loss is clearly desirable. To minimize or prevent ototoxicity, this laboratory has focused on the development of instrumentation and techniques for high-frequency (8–20 kHz) hearing threshold evaluation. Development has systematically branched in two directions, the first involving high-frequency puretone audiometric techniques, and the second being objective techniques designed for subjects who cannot respond to behavioral methods. Development of both of these methods would enable the majority of patients being treated with potentially ototoxic agents to receive efficacious auditory monitoring during the course of their treatment. Results are reported from a midpoint of an ongoing study of hospitalized veterans receiving ototoxic drug treatment. These patients were prospectively monitored behaviorally in both conventional- and high-frequency ranges for the purpose of identifying frequency regions most susceptible to threshold change as a result of treatment. A subgroup of patients also received click- and high-frequency toneburst-evoked ABR monitoring to look for concurrent changes between latency/morphology of waveforms and puretone thresholds.

METHODS

Subjects

Subject inclusion criteria included: *(a)* no active aural pathology; *(b)* ≥ 4 days of treatment for AMG, or ≥ 1 dose for CDDP; *(c)* baseline audiogram obtained within 72 hours after the initial dose of AMG, or within the period of 1 week prior to 24 hours after the initial dose of CDDP; and, *(d)* behavioral baseline thresholds ≤ 100 dB SPL at 10 and 11.2 kHz. These criteria were met by 83 patients (averaging 56 years of age) who were included as subjects in this study. Of these subjects, a total of 131 ears have been included in puretone data analyses to date, including 94 AMG-treated ears and 37 CDDP-treated ears.

Instrumentation

For evaluation of puretone thresholds (0.25–20 kHz), the Virtual Corporation Model 320 (V320) audiometer was used. Reliability and validity of subject responses to high-frequency stimuli using this instrument have been documented (25). Earphones used when testing conventional frequencies were TDH-50P in MX-41/AR cushions. Modified Koss Pro/4X Plus earphones were used for high-frequency testing (25). All instrumentation was calibrated daily prior to testing. Puretones from 0.25 to 8 kHz were calibrated in accordance with ANSI standards (26). Puretones from 9 to 20 kHz were calibrated as described in Fausti, et al. (8). Tympanometry and acoustic reflex testing were done with a Virtual Corporation Model 310 aural acoustic-immittance system.

ABR signal averaging and presentation of click stimuli were performed with a Bio-logic Traveler. Earphones utilized with click stimuli were TDH-39P, while those used for all toneburst stimuli were the modified Koss Pro/4X Plus. Toneburst stimuli at 8, 10, 12, and 14 kHz were produced by the portable stimulus generator designed and developed in this lab (15). Tonebursts utilized were ramp-windowed, with 0.2 msec rise-fall times and 1.6 msec plateaus. Click and toneburst stimuli were calibrated as described in Fausti, et al. (22).

Procedures

Baseline evaluation for all subjects included immittance testing (tympanometry at 226 and 678 Hz, and contralateral acoustic reflexes at 0.5, 1, 2, and 4 kHz), and behavioral thresholds to air-conducted puretones (0.25, 0.5, 1, 2, 3, 4, 6, 8, 9, 10, 11.2, 12.5, 14, 15, 16, 18, and 20 kHz). The modified Hughson-Westlake technique of Carhart and Jerger (27) was used to obtain all behavioral thresholds. Following baseline evaluation, puretone thresholds (0.25–20 kHz) were obtained from AMG-treated subjects every 2–3 days during treatment. CDDP-treated subjects were evaluated prior to each dose. Follow-up evaluations occurred immediately

after termination of treatment, and at 1 month and 6 months post-treatment.

The subgroup evaluated with ABR received ABR baseline testing and monitoring on the same schedule as the behaviorally tested subjects. ABRs were obtained to clicks and to tonebursts of 8, 10, 12, and 14 kHz. For clicks and each toneburst stimulus condition, 1,000 stimuli were presented during each ABR averaging run, and all runs were replicated. A two-channel electrode montage was utilized with ground placement on the forehead, noninverting on the vertex, channel-1 inverting on the right mastoid, and channel-2 inverting on the left mastoid. Ipsilateral and contralateral recordings were collected simultaneously. Absolute impedance for all electrodes was ≤ 2 kΩ, and interelectrode impedance differences were ≤ 1 kΩ. Bioamplifier filter settings were 100–1500 Hz, and the artifact rejection mode was enabled.

Because of large differences in high-frequency hearing thresholds in the targeted veteran patients, a suprathreshold level of 60 dB sensation level (SL) was selected for ABR testing rather than a fixed peak-equivalent SPL (peSPL). Levels were based upon behavioral thresholds to click and toneburst stimuli established at baseline and were held constant for all subsequent evaluations. When a 60 dB SL presentation level was not attainable because of poor hearing thresholds, an output level of 125 dB peSPL was presented. Objective thresholds could not be determined because of the excessive time involved in obtaining ABR latency-intensity functions. Ill patients must be tested in as little time as possible so as not to exacerbate their condition, cause them unnecessary discomfort or interfere with their treatment.

Guidelines for wave identification in ABRs to high-frequency toneburst stimuli were based on techniques used with click stimuli (28,29). Peak identification was facilitated by comparing ipsilateral waveforms to simultaneously collected contralateral waveforms and to added ipsilateral waveforms from replicated runs.

Ototoxic Change Criteria

Ototoxic change was computed in relation to baseline measures, with each subject serving as his own control. Behavioral criteria for change in hearing were operationally defined as: *(a)* ≥ 20 dB change at any single frequency; *(b)* ≥ 10 dB change at any two consecutively tested frequencies; or, *(c)* loss of response at any three consecutively tested frequencies.

Puretone behavioral threshold changes were the standard of reference for comparison with ABR latency/morphology changes. Criteria for defining change in ABR were established from previous studies of latency-intensity (L-I) functions (30) and intersession reliability (23) of ABRs to high-frequency tonebursts in normal-hearing individuals. Based on these normative values, a change in click or toneburst ABR latencies as compared to baseline was operationally defined as: *(a)* a latency shift greater than 0.3 msec at wave I or wave V or *(b)* a scorable response degrading to an unscorable response.

RESULTS

Of the 131 study ears, 91 showed behavioral change according to our operational definition of ototoxicity. Ears that demonstrated ototoxic change were analyzed to determine whether initial change was detected in the high-frequency range, conventional-frequency range, or in both ranges concurrently. Of all change ears, 52 percent were first detected in the high-frequency range only, 15 percent in both frequency ranges concurrently, and 33 percent in the conventional-frequency range only (**Figure 1**). Thus, 67 percent of all ears demonstrating initial ototoxic change were detected by high-frequency evaluation as compared to 48 percent by conventional-frequency evaluation.

It was observed that baseline high-frequency thresholds greater than 100 dB SPL showed fewer changes throughout drug treatment than thresholds at or below 100 dB SPL. This led to data analyses focusing on a frequency range of hearing where ototoxicity was most likely to initially appear. Considering the unique hearing threshold configuration of each patient, frequencies with thresholds at or below 100 dB SPL were examined for each test ear. The result was identification of a frequency range, unique to each individual, within which the initial detection of ototoxicity was most probable. This range was identified as five consecutive frequencies which contained, on average, three frequencies from the high-frequency range (i.e., at or above 8 kHz).

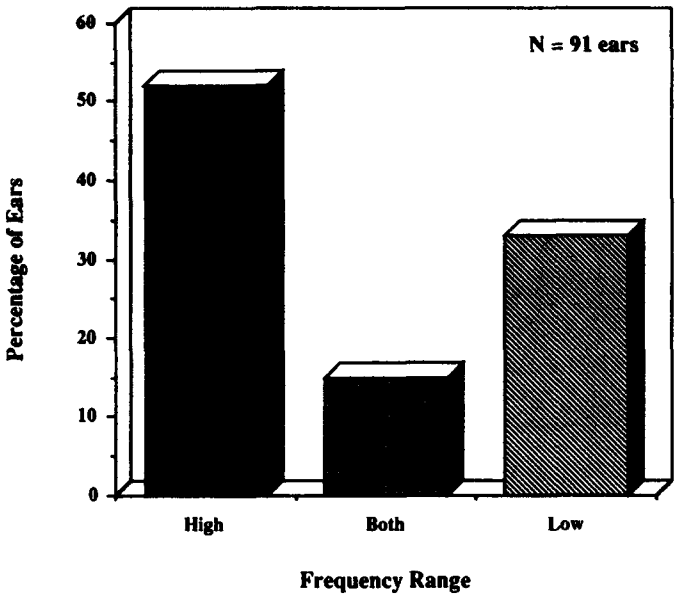

Figure 1.
Frequency-range categorization of initial puretone change for ears demonstrating ototoxicity: High (high-frequency range only, i.e., ≥8 kHz), Both (high- and conventional-frequency ranges concurrently), and Low (conventional-frequency range only, i.e., ≤8 kHz).

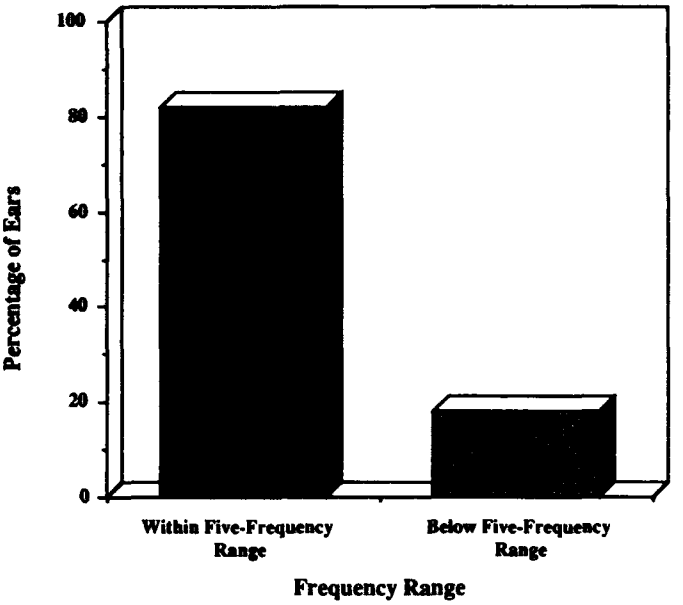

Figure 2.
Detection of initial hearing change in relationship to the five-frequency range. If only the frequencies within the five-frequency range had been tested, 82 percent of ears that changed would have been identified.

Data from change ears were analyzed to determine what the detection rate would have been if patients had been tested only in their five-frequency range. Initial change was seen to occur only in this restricted range in 58 percent of change ears. Change was seen concurrently in both the five-frequency range and in lower frequencies in 24 percent of the ears, with only 18 percent of all the change ears demonstrating initial change solely in the frequencies below the five-frequency range. Thus, if these patients had been monitored for auditory thresholds within their five-frequency range only, 82 percent of ears showing change would have been detected when they first demonstrated ototoxicity (**Figure 2**).

From the subgroup of responsive subjects monitored both behaviorally and objectively, 29 ears showed behavioral change. **Figure 3** displays frequency ranges where initial changes were seen both behaviorally and objectively for all 29 ears. Initial behavioral puretone change is indicated on the left side of the figure and includes High (high frequencies only, i.e., ≥8 kHz), Both (high and conventional frequencies concurrently), and Low (conventional frequencies only). Listed at the top of the

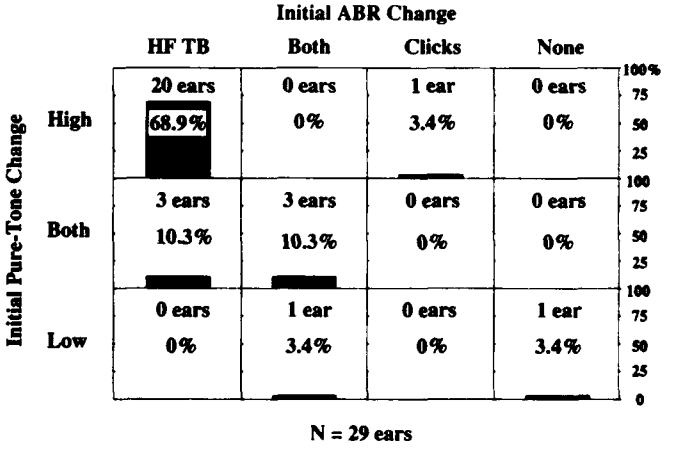

Figure 3.
Grid analysis of frequency ranges of initial detection of ototoxicity in ears concurrently monitored behaviorally and objectively. (Top of graph: HF TB = high-frequency toneburst; Both = HF TB and clicks; None = no change detected. Left side of graph: High = high-frequency range; Both = high- and conventional-frequency ranges; Low = conventional-frequency range.)

graph are frequency ranges where initial change was detected objectively, including HF TB (high-frequency tonebursts only), Both (high-frequency

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tonebursts and clicks concurrently), Clicks (clicks only), and None (no change detected objectively). It can be seen that of the 21 ears that changed behaviorally in the high-frequency range only, 20 were also seen to change in response to high-frequency tonebursts, and 1 ear changed in response to clicks. Six ears changed behaviorally in both the high and conventional frequency ranges concurrently, of which three were detected solely with high-frequency tonebursts and three were detected with high-frequency tonebursts and clicks concurrently. Two ears changed behaviorally in the conventional range only, of which one was detected objectively with high-frequency tonebursts and clicks concurrently, and one was not detected objectively. If these 29 ears had been monitored only with high-frequency toneburst ABR, 27 ears (93 percent) would have been detected according to our ABR change criteria.

Subsequent data analysis of ABR results has been performed to determine differential wave sensitivity to initial change. Of the individual response waves (I, III, and V), wave V demonstrated the most persistence and provided the highest percentage of detection with respect to ototoxic change. Wave V responses to high-frequency tonebursts met the criteria for change in 82 percent of those ears that changed objectively. Also, 48 percent of wave V changes occurred in the highest ABR frequency at which a response was obtained for each subject, and 87 percent of changes were seen in the two highest frequencies. Finally, at either of the two highest response frequencies for each individual, in 61 percent of change ears wave V was degraded from initially scorable to a nonscorable trace.

DISCUSSION

The risk of hearing loss in an individual as a consequence of ototoxic drug treatment is essentially unknown. The ototoxicity literature is highly variable with respect to reports of incidence and monitoring methodology. Most studies have limited hearing threshold evaluation to the conventional-frequency range. However, once hearing loss is detected with this conventional method, damage has already invaded the frequency range that can affect communication ability. In early studies, data collection methods were either unreported or widely variable, and the definition for ototoxic change was inconsistent. Standards, or even agreed-upon guidelines, for monitoring ototoxic effects still do not exist.

Since ototoxic hearing loss seems to begin in the high frequencies, identification of initial loss in the high-frequency region should give health care providers an early warning of ototoxicity and allow the appraisal of potential treatment alternatives before the loss progresses to include frequencies critical for verbal communication. Unfortunately, biases exist against audiometric monitoring of patients receiving treatment with potentially ototoxic drugs. A common misconception is that ongoing monitoring of hearing during treatment is inconsequential if the patient's chance of survival is considered minimal. For example, patients administered CDDP are often considered terminal cases, but the efficacy of CDDP treatment has increased their survival rate (31,32), arguing for the need to protect their hearing. Another misconception is that high-frequency (8–20 kHz) thresholds are unobtainable in patients with preexisting hearing loss, especially those patients over 40 years of age. As was shown by our sample of middle-aged males, high-frequency thresholds are obtainable in patients with preexisting hearing loss.

In continuing investigations regarding the efficacy of strategies for early detection of ototoxicity, this laboratory has attempted to examine and define those frequencies most susceptible to the ototoxic action of AMG and CDDP. Data reported in this study have been analyzed at an interim point of our ongoing research. This data pool is being continually expanded, as the need exists for further continuing research to obtain a larger database from which a more thorough analysis can be made. This will facilitate development of instrumentation and testing techiques to monitor the most sensitive frequency regions of hearing.

At the time of this data analysis, 131 ears were behaviorally monitored for ototoxicity, of which 91 showed a loss of hearing meeting our criteria. Collection of thresholds from 0.25 to 20 kHz during baseline and all monitoring allowed a retrospective comparison of three behavioral monitoring protocols (shortened from evaluating all frequencies from 0.25 to 20 kHz) for efficacy in early detection of ototoxicity: *(a)* high frequencies only, *(b)* conventional frequencies only, and *(c)* five-frequency range. If only the high frequencies had been

monitored in these patients, 67 percent of changes would have been identified when change first took place. This compares to 48 percent of changes that would have been identified using conventional-frequency audiometry on the same schedule. Analysis of the five-frequency range, specific to each individual's unique hearing threshold configuration, revealed that, had only these frequencies been monitored, 82 percent of all initial changes would have been detected. These results are beginning to clarify methodology for monitoring the hearing in these patients when testing time is a factor. Monitoring all frequencies from 0.25 to 20 kHz is a lengthy procedure that exceeds the abilities of many patients to provide reliable responses, and thus shortened protocols are essential for these patients.

In a hospital setting, there still remains a large number of patients unable to respond to any type of behavioral test, including patients who are unconscious or comatose and those who are simply too ill to provide reliable responses over the time needed for monitoring. These behaviorally unresponsive individuals may be even more susceptible to communicatively handicapping hearing impairment than persons able to provide subjective information (33). The need to prevent hearing loss in these unresponsive patients warrants the development of instrumentation and techniques to monitor their hearing during treatment with potentially ototoxic agents.

In the subgroup of patients who were monitored behaviorally and objectively, high-frequency toneburst-evoked ABRs were successful in identifying over 90 percent of all ears demonstrating behavioral change. Further data analysis revealed some notable points: the two highest ABR toneburst frequencies monitored for each individual were generally the most indicative of initial objective change; wave III responses were sparse, and of waves I and V, wave V was shown to be the best indicator of initial change; the most frequently observed change was from a scorable to an unscorable response; and ABRs evoked by high-frequency tonebursts were demonstrated to be clearly superior to click-evoked ABRs in early detection of ototoxicity. These results are presented as preliminary findings toward the development of a clinical tool to objectively monitor patients receiving potentially ototoxic medication. Based on the observed relationship between behavioral and ABR changes, this technique shows considerable promise. There is evidence that high-frequency evaluation is an early detector of ototoxicity, and that the high-frequency toneburst-evoked ABR method can be a valuable tool in early ototoxic detection with heretofore difficult-to-test subjects.

As with behavioral testing, the time involved in auditory monitoring with evoked potentials is a concern with seriously ill patients. To obtain repeated ABR latency-intensity functions with tonebursts at multiple frequencies and intensities, at least 1 hour of averaging time is required to evaluate a single ear. To shorten testing time, other stimuli for evoking the ABR at high frequencies are currently being examined, including a high-frequency click that would stimulate an entire range of frequencies within the high-frequency range of hearing, and multiple frequency and intensity toneburst stimuli delivered in a single pulse train (34). The technique utilizing pulse trains has received preliminary investigation in this laboratory. This technique uses the concept that an auditory stimulus produces a refractory area which has dimensions in time, frequency, and intensity. If the refractory areas of successive stimuli overlap, the response will be adapted. Conversely, if successive stimuli are presented outside the refractory area of preceeding stimuli, adaptation can be avoided.

A multiple-frequency stimulus-train generator was designed and fabricated to digitally synthesize stimulus trains. Stimulus trains containing four interleaved tonebursts (8, 10, 12, and 14 kHz) have been utilized to evoke repeatable ABRs without waveform degradation as compared to single frequency toneburst presentations. This methodology is potentially clinically useful in routine ABR testing, and especially in situations where more rapid frequency-specific information is required, such as neonatal testing and intraoperative and ototoxicity monitoring.

In the prospective monitoring of ill subjects receiving ototoxic drugs, whether tested behaviorally or with objective measures, more rapid techniques which can provide sufficient information with which to make alternative treatment judgments will significantly increase the number of patients in whom ototoxicity can be detected before the occurrence of communicatively disabling hearing loss.

CONCLUSION

The overall goal of this research program is to monitor a broad spectrum of patients in order to develop techniques and methods for early detection and possible prevention of ototoxic hearing loss, regardless of the ability of the patient to provide behavioral responses. This goal will be pursued by designing and conducting studies using large patient populations which should yield refinement of the various behavioral and objective techniques presented here as preliminary findings. The key to success in this area is the early detection of ototoxic hearing loss, regardless of the response capabilities of the patient. Early detection enables steps to be taken for the prevention of handicapping hearing loss which would negate the necessity for rehabilitative measures.

ACKNOWLEDGMENTS

Portions of the data reported were obtained from information collected in an ongoing multi-site Rehabilitation Research and Development Service study at the following auditory research laboratories in cooperation with the participating investigators: VA Medical Center, Augusta, GA (Vernon Larson, PhD); VA Medical Center, Long Beach, CA (Richard Wilson, PhD); and VA Medical Center, West Los Angeles (Douglas Noffsinger, PhD).

In addition, the authors wish to acknowledge significant contributions to this research by Curtin R. Mitchell, PhD, Oregon Hearing Research Center; and David S. Phillips, PhD, Professor of Biostatistics at Oregon Health Sciences University.

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Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 30 No. 3, 1993
Pages 342-351

CLINICAL REPORT

Development and Use of Auditory Compact Discs in Auditory Evaluation

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Abstract—Two audio compact discs have been developed by the Department of Veterans Affairs for use in the assessment of auditory function. This report focuses on 1) the development of the first compact disc, which contains speech materials used in routine audiologic evaluations, and 2) an introduction to the second compact disc, which contains tonal and speech materials used in more elaborate auditory evaluations. The first disc (*Speech Recognition and Identification Materials, Disc 1.1*), which is in its second generation, contains spondaic words, several monosyllabic word tests (Rush Hughes PB-50s, CID W-22, Maryland CNCs, and Northwestern University [NU] No. 6), and the Synthetic Sentence Identification materials. The second disc (*Tonal and Speech Materials for Auditory Perceptual Assessment*), which was produced in conjunction with the Dartmouth-Hitchcock Medical Center, contains spondaic words in the MLD paradigm, dichotic materials (chords, nonsense syllables, digits, and sentences), segmented/alternated CNCs, high-pass and low-pass NU No. 6 materials, 45% and 65% compressed NU No. 6 materials, the same 45% and 65% compressed materials compounded with 0.3-s reverberation, frequency tone patterns, and duration tone patterns.

Key words: *auditory assessment, auditory compact discs, auditory evaluation.*

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This work was supported by the Rehabilitation Research and Development Service and the Medical Research Service of the Department of Veterans Affairs, Washington, DC.

INTRODUCTION

For several centuries, speech has been used to assess hearing abilities. Advances in the use of speech to evaluate hearing are tied directly to advances in instrumentation. For example, the phonograph was invented by Edison in 1877; shortly thereafter, Lichtwitz developed a phonograph that contained speech materials at various levels (1). In 1924, Jones and Knudsen developed an audiometer that contained an electronic circuit that could vary the level of speech presentations. Today, recorded speech materials and circuits on audiometers for speech are an everyday occurrence.

During the past 40–50 years, one of the major activities of audiologists within the Department of Veterans Affairs has been the conduct of auditory compensation and pension (C&P) examinations. In the 1950s, a major problem with these examinations was to ensure that the performance of a veteran on an auditory C&P examination would be the same, regardless of the site at which the testing was conducted. When properly calibrated, pure-tone stimuli are identical from one site to another. The real dilemma was with speech stimuli. The psychometric characteristics of speech stimuli delivered by monitored live voice are different from time to time with the same speaker, and certainly are different among speakers.

The solution to the problem of the same speech materials spoken by the same speaker was the development of the CID W-1 (spondaic words), and

CID W-22 (monosyllabic words) on audio (vinyl) records (2). The records were not a perfect medium in that the records deteriorated rapidly because of the mechanical action of the stylus on the records; records also were susceptible to physical damage from other sources. To avoid problems with deterioration, the records were replaced after 25 uses. An inconvenience of the records was that the records had to be changed for different speech stimuli and for different randomizations.

In the 1970s, because of the problems and inconveniences of the vinyl records, the recording medium was changed to audio tape, initially reel-to-reel, then cassette. Because of the mechanical nature of audio tape and tape recorders, deterioration continued to be a problem due to the mechanical action of the tape crossing the tape heads, the tape being stretched and broken, and other physical abuses. The problem of tape deterioration was overcome by replacing the tapes every 6 months, which was a big advancement over the replacement schedule of the vinyl records after 25 uses. Even the audio tapes involved the time-consuming inconveniences of advancing, rewinding, and changing tapes to access different materials.

Many of the problems encountered with audio tape were overcome with the development of the audio compact disc technology in the mid-1980s. Compared with audio record and audio tape analog technology, the audio compact disc (CD) digital technology offers the following advantages:

1. high-fidelity recordings with enhanced signal-to-noise ratio, virtually infinite channel separation, and no "print-through";
2. identical recordings from one disc to another;
3. a recording medium that does not deteriorate as a function of use and time, and, therefore, does not need replacing;
4. almost instantaneous access to any one of 100 tracks (i.e., no winding or rewinding to access a particular word list); and,
5. 144 minutes of recorded materials per disc.

Additionally, compact disc players offer an extremely favorable "quality-value ratio" (i.e., the players are relatively inexpensive). Because the "light amplification by stimulated emission of radiation" (laser) read mechanism does not contact the disc, there is no wear on either the disc or the recorder. The following are some useful features for compact disc players used in auditory evaluation: 1) random, not sequential, track selection; 2) display of track and time remaining while playing; 3) AB segment define and play; 4) remote control; and, 5) variable output level.

The following two sections detail the development of the two audio compact discs developed by the Department of Veterans Affairs for use in the assessment of auditory function. The first disc, entitled *Speech Recognition and Identification Materials, Disc 1.1,* contains speech materials that for the most part are used in routine audiologic evaluations. The second disc, entitled *Tonal and Speech Materials for Auditory Perceptual Assessment,* which was produced in conjunction with the VA Medical Center (VAMC), West Los Angeles (Doug Noffsinger, PhD) and with Dartmouth-Hitchcock Medical Center (Frank Musiek, PhD), contains tonal and speech materials used in more sophisticated evaluations of the auditory system.

METHOD AND MATERIALS

Speech Recognition and Identification Materials, Disc 1.1

Material Selection

The basic auditory evaluation performed during a C&P examination by the Department of Veterans Affairs (VA) includes pure-tone thresholds for air conduction and bone conduction, aural acoustic immittance measurements, speech-recognition thresholds, and word-recognition performance at multiple presentation levels. Guidelines mandate that word recognition be assessed using an approved recording of six of the Maryland CNC word lists (3). Thus, the guidelines for the C&P examination dictated that spondaic words and the Maryland CNC word lists be included on the compact disc. The question then became, What other speech materials should be included on the compact disc? For obvious reasons, we wanted to include speech materials that: 1) had an existing literature, and 2) were in the public domain or could be donated. Because the compact disc was being developed primarily for use within the Department of Veterans Affairs, it was important to get opinions from other VAMCs concerning what speech materials audiologists would like to have. Thus, the Compact Disc

Survey was sent to 97 VA Audiology Clinics to determine the speech recognition/identification materials that VA audiologists would prefer to have on the compact disc. Of the 88 survey responses that were returned (91 percent), the 10 most often-requested speech materials were as follows:

1.	CID W-22	61%
2.	Spondaic words	49%
3.	Northwestern University No. 6	43%
4.	Synthetic Sentence ID (SSI)	35%
5.	Staggered Spondiac Words (SSW)	26%
6.	California Consonant Test	18%
7.	Continuous discourse	15%
8.	Speech Perception in Noise (SPIN)	15%
9.	MAC Battery	12%
10.	Multitalker babble	11%

The first four materials listed were included on the compact disc, along with several other sets of speech materials.

Material Preparation

For each of the seven speech materials selected for inclusion on the compact disc, analog copies of the master analog tapes were acquired. Each word was digitized and placed in a unique file. Then each file was edited to minimize the silence before and after the stimulus item and to eliminate noises, such as clicks. The majority of the monaural file for the two channels were interleaved into one stereo file so that the onsets of the two channels were concurrent. The stereo files, including a 1000-Hz calibration tone, then were recorded onto digital audio tape (DAT) (Sony, PCM-2500A) with nominal 4- to 6-s interstimulus intervals (ISI). The audio mastering studio then recorded the materials from the DAT along with the appropriate time code onto Sony 1630 format tape, from which the glass master of the compact disc was made. Details of this process are provided later in this section.

Finally, a Macintosh IIci was used to design and produce the art work for the compact disc, for the jewel box insert, and for the booklet that was to be included in the jewel box. A script detailing the materials on the compact disc was prepared as a 24-page booklet. The following section, which was taken from the booklet that accompanies each disc, details the contents of the compact disc.

The *Speech Recognition and Identification Materials, Disc 1.1* compact disc is a revision of the *Speech Recognition and Identification Materials, Disc 1* that was produced by the VA Medical Center, Long Beach, in 1989 for use by VA audiologists who use the six Maryland CNC word lists in the assessment of the word-recognition performance of patients undergoing C&P examinations. The remaining recognition and identification materials contained on the disc (see **Table 1**) were selected based on 1) the results of a survey of the VA audiology clinics, and 2) the availability of the materials through the generosity of the individuals responsible for the materials, including G. Donald Causey, PhD (spondaic words, Maryland CNC lists, and NU No. 6), Bob Brose (Technisonic Studios, St. Louis: Charles E. Harrison, producer of the CID W-22 lists, and the Rush Hughes recordings of the PB-50 lists), and James Jerger, PhD (Synthetic Sentence Identification materials).

The speech materials contained on Version 1.1 of the *Speech Recognition and Identification Materials* are identical to the speech materials contained on the initial Version 1.0 disc. The differences between the two compact discs are related to the digital characteristics used to process the materials. With *Disc 1,* the materials were processed digitally with a 12-bit A/D and D/A converter (20,000-Hz rate and a 5,000-Hz filter cutoff with a 115-dB/octave rejection). With *Disc 1.1,* tracks 1–26 were processed using a 16-bit A/D and D/A converter and the following characteristics: 1) tracks 1–18 were processed with a 44,100-Hz rate and a 19,800-Hz filter cutoff (96 dB/octave); 2) tracks 19–26 were processed with a 20,000-Hz rate and an 8,800-Hz filter cutoff (96 dB/octave); and, 3) tracks 27–35, which were unchanged from *Disc 1,* were processed on a 12-bit converter with a 20,000-Hz rate and a 5,000-Hz cutoff.

The text that follows describes briefly the materials that are contained on each track of the *Speech Recognition and Identification Materials, Disc 1.1* compact disc. A detailed script of each track and references are provided in the booklet that accompanies each disc. Several characteristics of the recordings should be noted. First, the ISI with the various materials are the times between successive stimulus onsets. Second, with all of the 50-item

Table 1.
An index of the audio compact disc *Speech Recognition and Identification Materials, Disc 1.1*, produced in 1991.

Track	Left Channel	Right Channel	Time
1	1000-Hz Calibration Tone	1000-Hz Calibration Tone	0:30
2	Spondaic Words (72, 4-s, ISI)[1]	Spondaic Words (144, 2-s, ISI)	4:51
3	Maryland CNC List 1 (1-25)[1]	CID W-22 List 1A (1-25)[2]	1:47
4	Maryland CNC List 1 (26-50)	CID W-22 List 1A (26-50)	1:47
5	Maryland CNC List 3 (1-25)	CID W-22 List 2A (1-25)	1:47
6	Maryland CNC List 3 (26-50)	CID W-22 List 2A (26-50)	1:47
7	Maryland CNC List 6 (1-25)	CID W-22 List 3A (1-25)	1:46
8	Maryland CNC List 6 (26-50)	CID W-22 List 3A (26-50)	1:46
9	Maryland CNC List 7 (1-25)	CID W-22 List 4A (1-25)	1:46
10	Maryland CNC List 7 (26-50)	CID W-22 List 4A (26-50)	1:46
11	Maryland CNC List 9 (1-25)	Rush Hughes PB-50 List 8B (1-25)[2]	1:47
12	Maryland CNC List 9 (26-50)	Rush Hughes PB-50 List 8B (26-50)	1:47
13	Maryland CNC List 10 (1-25)	Rush Hughes PB-50 List 9B (1-25)	1:46
14	Maryland CNC List 10 (26-50)	Rush Hughes PB-50 List 9B (26-50)	1:46
15	Picture ID Task List 1A (1-25)[3]	Rush Hughes PB-50 List 10B (1-25)	2:32
16	Picture ID Task list 1A (26-50)	Rush Hughes PB-50 List 10B (26-50)	2:32
17	Picture ID Task List 2A (1-25)	Rush Hughes PB-50 List 11B (1-25)	2:31
18	Picture ID Task List 2A (26-50)	Rush Hughes PB-50 List 11B (26-50)	2:31
19	NU No. 6 CNC List 1A (1-25)[1]	Competing Sentences	1:55
20	NU No. 6 CNC List 1A (26-50)	Competing Sentences	1:58
21	NU No. 6 CNC List 2A (1-25)	Competing Sentences	1:56
22	NU No. 6 CNC List 2A (26-50)	Competing Sentences	1:56
23	NU No. 6 CNC List 3A (1-25)	Competing Sentences	1:56
24	NU No. 6 CNC List 3A (26-50)	Competing Sentences	1:56
25	NU No. 6 CNC List 4A (1-25)	Competing Sentences	1:56
26	NU No. 6 CNC List 4A (26-50)	Competing Sentences	1:56
27	Synthetic Sentence ID Random #1[4]	Competing Message Story	1:43
28	Synthetic Sentence ID Random #2	Competing Message Story	1:41
29	Synthetic Sentence ID Random #3	Competing Message Story	1:39
30	Synthetic Sentence ID Random #4	Competing Message Story	1:40
31	Synthetic Sentence ID Random #5	Competing Message Story	1:41
32	Synthetic Sentence ID Random #6	Competing Message Story	1:42
33	Synthetic Sentence ID Random #7	Competing Message Story	1:39

(Continued on next page)

Table 1. (*Continued*)
An index of the audio compact disc *Speech Recognition and Identification Materials, Disc 1.1*, produced in 1991.

Track	Left Channel	Right Channel	Time
34	Synthetic Sentence ID Random #8	Competing Message Story	1:39
35	Synthetic Sentence ID Random #9	Competing Message Story	1:41

[1]Spondaic words, Maryland CNC lists, and NU No. 6 CNC lists reproduced compliments of G. Donald Causey, Ph.D., Consultant in Audiology, VA Medical Center, Washington, DC.
[2]CID W-22 lists and PB-50 lists (Rush Hughes) reproduced from the original recordings produced by Charles E. Harrison at Technisonic Studios, St. Louis, MO.
[3]Picture Identification Task lists reproduced compliments of Audiology Section, VA Medical Center, Long Beach, CA.
[4]Synthetic Sentence Identification materials reproduced compliments of James Jerger, Ph.D., Baylor College of Medicine, Houston, TX.

word lists recorded on this compact disc, words 1–25 are recorded on one track; words 26–50 are recorded on the subsequent track. Third, the beginning of tracks 2 through 35 are indexed for access under software control.

Track 1. Both channels contain a 30-s, 1000-Hz calibration tone that reflects the peaks of the speech materials as monitored on a calibrated VU meter (4,5). It should be noted that many meters used on audiometers are not "true" VU meters and/or are not properly calibrated (6). The 1000-Hz calibration tone, therefore, may not reflect accurately the peaks of the speech materials on non-VU meters and on non-calibrated VU meters.

Track 2. The left channel (A) contains two randomizations of the 36 CID W-1 spondaic words spoken by a female with 4-s interstimulus intervals; the right channel (B) contains four randomizations of the 36 CID W-1 spondaic words spoken by a female with 2-s ISI. Normative data for these materials are given in Cambron, Wilson, and Shanks (7). Total time is 291 s.

Tracks 3 and 4. The left channel contains List 1 of the Maryland CNC materials recorded by a male (3), whereas the right channel contains a copy of the CID W-22 List 1A materials recorded by Technisonic Studios (2). Track 3 has words 1–25 and track 4 has words 26–50. Both channels have 4.2-s ISI; the total time/track is 107 s.

Tracks 5 and 6. The left channel has List 3 of the Maryland CNC words; the right channel has List 2A of the CID W-22 words. The ISI is 4.2 s with 107 s/track.

Tracks 7 and 8. The left channel has List 6 of the Maryland CNC words; the right channel has List 3A of the CID W-22 words. The ISI is 4.2 s with 106 s/track.

Tracks 9 and 10. The left channel has List 7 of the Maryland CNC words; the right channel has List 4A of the CID W-22 words. The ISI is 4.2 s with 106 s/track.

Tracks 11 and 12. The left channel has List 9 of the Maryland CNC words; the right channel has the Rush Hughes recording (8) of List 8B of the Harvard PB-50 words (9). (For the Rush Hughes recordings, slight modifications [one to six words/list] were made in the original PB-50 lists.) The ISI is 4.2 s with 107 s/track.

Tracks 13 and 14. The left channel has List 10 of the Maryland CNC words; the right channel has the Rush Hughes recording of List 9B of the PB-50 words. The ISI is 4.2 s with 106 s/track.

Tracks 15 and 16. The left channel has List 1A of the Picture Identification Task materials (10,11); the words on both tracks are indexed. The right channel has the Rush Hughes recording of List 10B of the PB-50 words. The ISI is 6.0 s with 152 s/track.

Tracks 17 and 18. The left channel has List 2A of the Picture Identification Task materials; the right channel has the Rush Hughes recording of List 11B of the PB-50 words. The ISI is 6.0 s with 151 s/track.

Tracks 19 and 20. The left channel has List 1A of the NU No. 6 recorded by a female; the right channel has competing sentences—modified Bell Telephone Sentences—recorded by a male (12). Normative data for these materials in quiet, in broadband noise, and in the competing message (ipsilateral) are given in Wilson, Zizz, Shanks, and Causey (13). The ISI is 4.6 s with 115 (Track 19) and 118 (Track 20) s/track.

Tracks 21 and 22. The left channel has List 2A of NU No. 6; the right channel has competing sentences. The ISI is 4.6 s with 116 s/track.
Tracks 23 and 24. The left channel has List 3A of NU No. 6; the right channel has competing sentences. The ISI is 4.6 s with 116 s/track.
Tracks 25 and 26. The left channel has List 4A of NU No. 6; the right channel has competing sentences. The ISI is 4.6 s with 116 s/track.
Tracks 27 through 35. The left channel of each track contains a randomization of the 10 sentences that comprise the Synthetic Sentence Identification materials (14,15); the right channel contains the Davy Crockett competing message story. The 10 sentences were digitized and reconfigured for each of the 9 segments of the competing message story. Thus, the temporal alignment between the sentences and competing message is not the same as in the original recordings. The ISI is 9.5 s with nominally 100 s/track.

Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0

The *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1* compact audio disc was produced to provide a collection of high-quality auditory materials for use in assessing auditory perceptual (central) abilities. The tonal and speech materials contained on the disc were selected based on the availability of the materials either through the public domain or through the generosity of the individuals responsible for the materials, including G. Donald Causey, PhD (NU No. 6), Bob Brose (Technisonic Studios, Inc., St. Louis, Charles E. Harrison, producer of the CID W-1 lists), Kresge Hearing Research Laboratory of the South, New Orleans (dichotic CVs), and James Jerger, PhD (Dichotic Sentence Identification).

The speech materials contained on the *Tonal and Speech Materials for Auditory Perceptual Assessment* disc were digitized from analog master tapes using an analog-to-digital converter (Antex, Model SX10) with the following characteristics: 16-bit, 20,000 samples/s, 8,800-Hz filter cutoff (96 dB/octave rejection). The tonal materials were generated digitally using in-house routines. All materials were compiled on digital audio tape (Sony, Model PCM-2500A) from which the Sony 1630 format master was made.

The text that follows describes briefly the materials that are contained on each track of the compact disc (see **Table 2**). The ISI with the various materials are the times between successive stimulus onsets.

Track 1. Both channels contain a 300-ms, 1000-Hz tone burst, followed by a 1-s silent interval and a 30-s, 1000-Hz calibration tone that reflects the peaks of the speech materials as monitored on a calibrated VU meter (4,5). The tone burst can be used to check the ballistic characteristics of a VU meter. The needle on a calibrated VU meter will swing from −20 vu to 0 vu with minimal overshoot when a 300-ms tone burst is placed across the meter. For a variety of reasons, the materials on several tracks do not peak at 0 vu. These exceptions are noted in the text that follows.
Track 2. This stereo track contains spondaic words embedded in bursts of broadband noise in the SπNo paradigm; that is, the spondaic words (S) are 180° out-of-phase on the two channels and the bursts of broadband noise (N) in-phase on the two channels. The 10 spondaic words that are used repetitively are from the Technisonic Studio recording of the W-1 lists (2) and were selected based on earlier masking-level difference data (16). The words start 500 ms into the 2000-ms noise bursts that have 200-ms rise-fall times. Four words are recorded at each of 16 signal-to-noise ratios in 2-dB decrements from 0 dB to −30 dB. To avoid "pegging" the VU meter on the noise/word composite signals at 0 dB S/N, the levels are calibrated to −1 vu with reference to the 1000-Hz calibration tone. Because the words are 180° out-of-phase, monitoring the words will be difficult if both channels are fed to one loudspeaker at the same levels. To avoid this problem, monitor only one channel. The ISI is 5 s with a 318-s total time. For relative phase calibration purposes, Track 18 contains 100-Hz tone bursts recorded 180° out-of-phase on the two channels (17,18,19).
Track 3. This 296-s stereo track contains 30 dichotic chords with simultaneous onsets (20,21). The 1-s target chords, which are different in each ear, are followed by a 1-s silent interval, and in turn are followed by four simultaneous response chords that are the same in each ear. The response chords are 500 ms with a 500-ms silent interval between response chords. The chords peak at about 0.5 vu. The task of the subject is to indicate which of the two response chords correspond to the two target

Table 2.
An index of the audio compact disc *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0*, produced in 1992.

Track	Left Channel	Right Channel	Time
1	1000-Hz Calibration Tone	1000-Hz Calibration Tone	0:32
2	Spondaic Words SπNo MLD[1]	Spondaic words SπNo MLD	5:18
3	Dichotic Chords	Dichotic Chords	4:56
4	Dichotic Chords (90-ms lag)	Dichotic Chords	4:57
5	Dichotic Nonsense Syllables[2]	Dichotic Nonsense Syllables	3:02
6	Dichotic Nonsense Syllables (90-ms lag)	Dichotic Nonsense Syllables	3:04
7	Dichotic Digits	Dichotic Digits	3:39
8	Dichotic Sentence Identification[3]	Dichotic Sentence Identification	4:59
9	Consonant Segments CNCs List 5A	Vowel Segments CNCs List 5A	3:54
10	Consonant Segments CNCs List 5B	Vowel Segments CNCs List 5B	3:55
11	NU No. 6, High-Pass Filtered List 3C[4]	NU No. 6, Low-Pass Filtered List 3C	4:00
12	NU No. 6, High-Pass Filtered List 4C	NU No. 6, Low-Pass Filtered List 4C	4:04
13	Frequency Tone Patterns	Duration Tone Patterns	7:03
14	NU No. 6, 45% Compress + Reverb List 5	NU No. 6, 45% Cmpressed List 5	3:59
15	NU No. 6, 45% Compress + Reverb List 6	NU No. 6, 45% Compressed List 6	4:01
16	NU No. 6, 65% Compress + Reverb List 7	NU No. 6, 65% Compressed List 7	4:02
17	NU No. 6, 65% Compress + Reverb List 8	NU No. 6, 65% Compressed List 8	4:02
18	100-Hz, Pulsed Phase Cal. Tone	100-Hz, Pulsed Phase Cal. Tone	0:18

[1]CID W-1 Spondaic Words were reproduced from the original recordings produced by Charles E. Harrison at Technisonic Studios, Inc., St. Louis, MO.
[2]Dichotic Nonsense Syllables (CVs) provided by Kresge Hearing Research Laboratory of the South, New Orleans, LA.
[3]Dichotic Sentence Identification materials reproduced compliments of James Jerger, Ph.D., Baylor College of Medicine, Houston, TX.
[4]The NU No. 6 recordings used for the degraded speech tasks were with the compliments of G. Donald Causey, Ph.D., Consultant in Audiology, VA Medical Center, Washington, DC.

chords. The six chords are composed of the following sinusoids with the respective crest factors (CF):

1.	512 Hz	640 Hz	768 Hz	CF = 2.36
2.	550 Hz	682.7 Hz	825 Hz	CF = 2.38
3.	576 Hz	733.3 Hz	880 Hz	CF = 2.42
4.	618.7 Hz	768 Hz	896 Hz	CF = 2.38
5.	640 Hz	825 Hz	990 Hz	CF = 2.38
6.	682.7 Hz	880 Hz	1024 Hz	CF = 2.36

Track 4. This 297-s stereo track is identical to track 3, except the target chord in the left channel lags by 90 ms the target chord in the right channel. Again, the response chords are simultaneous.

Track 5. This 182-s stereo track contains the 30 possible pairings of 6 nonsense (CV) syllables (BA, DA, GA, PA, TA, and KA) in a dichotic format (22). The syllables were digitized (from the right channel of an analog tape produced by Kresge Hearing Research Laboratory, New Orleans), edited, and aligned at the VA Medical Center, Long Beach. The levels of the syllables do not reach 0 vu because the duration of each syllable is less than the integration time of a VU meter. The task of the subject is to repeat the dichotic nonsense syllables.

Track 6. This 184-s stereo track is identical to track 5, except the nonsense syllable in the left channel lags by 90 ms the nonsense syllable in the right channel.

Track 7. This 219-s stereo track contains the 36 possible pairings of 9 digits (1, 2, 3, 4, 5, 6, 8, 9, and 10) in a dichotic format. The levels of the digits do not reach 0 vu because the duration of each digit is less than the integration time of a VU meter. The task of the subject is to repeat the dichotic digits (23,24).

Track 8. This 299-s stereo track contains the 30 possible pairings of 6 synthetic sentences (25) in a dichotic format. This version of the Dichotic Sentence Identification Test was produced (digitized, compressed and expanded as needed, and aligned) at the VA Medical Center, Long Beach. The task of the subject is to identify the dichotic sentences in a list of six sentences.

Track 9. This 234-s stereo track contains 50 CVC words that are segmented at the approximate phoneme boundaries and are alternated such that the carrier phrase ("Show me") is in both channels, the initial consonant segment is in the left channel, the vowel segment is in the right channel, and the final consonant segment is in the left channel (26). Because the carrier phrases on the two channels are recorded 180° out-of-phase (to prevent the patient from experiencing a mid-line image with the carrier phrase), the materials will sound "rough" when both channels are monitored in a single loudspeaker. The task of the subject is to repeat the monosyllabic word. Minimal correct recognition of the words is obtained from either channel individually; maximum correct recognition of the words is obtained when both channels are presented simultaneously.

Track 10. This 235-s stereo track is identical to track 9, except that the 50 CVC words are in a different randomization.

Track 11. This 240-s track contains monosyllabic words from List 3 of the NU No. 6 (N.U. No. 6) spoken by a female (13). The words on the left channel (1) are high-pass filtered (2100-Hz cutoff; 115 dB/octave rejection), whereas the words on the right channel (2) are low-pass filtered ' '-Hz cutoff; 115 dB/octave). The high-pass words on the left channel peak at −15 to −10 vu; the low-pass words on the right channel peak at −3 to 0 vu. The materials sound normal if both channels are fed to a single loudspeaker. Because the words are simultaneous on the two channels, a binaural fusion task can be created by presenting the words in the stereo mode (27,28,29).

Track 12. This 244-s track is identical to track 11, except that the materials are List 4 of the NU No. 6.

Track 13. The left channel (1) contains 60 frequency-pattern sequences (6 patterns by 10 randomizations). The low-frequency tone (L) is 880 Hz and the high-frequency tone (H) is 1122 Hz. Both tones are 150 ms with 10-ms rise-fall times (cosine squared). The frequency-pattern sequences have 200-ms ISI and 6-s interpattern intervals. Because the frequency pattern tones are shorter than the integration time of a VU meter, the VU meter peaks at −2 to −3 vu with reference to the 1000-Hz calibration tone (30,31,32,33). The right channel (B) contains 60 duration-pattern sequences (6 patterns by 10 randomizations). The tones are 1000 Hz with 10-ms rise-fall times (cosine squared). The long tone (L) is 500 ms, the short tone (S) is 250 ms, the ISI is 300 ms, and the interpattern interval is 6 s (32,34). The task of the subject is to repeat (mimic) the tonal pattern. The track time is 423 s. The following are the various combinations of pattern sequences:

Frequency Patterns	Duration Patterns
LLH = 880 Hz, 880 Hz, 1122 Hz	LLS = 500 ms, 500 ms, 250 ms
LHL = 880 Hz, 1122 Hz, 880 Hz	LSL = 500 ms, 250 ms, 500 ms
LHH = 880 Hz, 1122 Hz, 1122 Hz	LSS = 500 ms, 250 ms, 250 ms
HLH = 1122 Hz, 880 Hz, 1122 Hz	SLS = 250 ms, 500 ms, 250 ms
HLL = 1122 Hz, 880 Hz, 880 Hz	SLL = 250 ms, 500 ms, 500 ms
HHL = 1122 Hz, 1122 Hz, 880 Hz	SSL = 250 ms, 250 ms, 500 ms

Track 14. The right channel (2) contains 50 carrier phrase and word stimuli from the NU No. 6 pool of 200 words that are compressed 45 percent (i.e., 45 percent of the carrier phrase and word has been removed). This list is designated List 5 because it contains a composite of words from the original four NU No. 6 lists. The left channel (1) contains the same 50 carrier phrases and words that are compressed 45 percent and reverberated 0.3 s. The task of the subject is to repeat the word that follows the carrier phrase. The track time is 239 s (35,36,37).

Track 15. This track is identical to track 14, except that a different group of 50 words from the NU No. 6 pool of 200 words is used; hence, the designation is List 6. The track time is 241 s.

Track 16. The right channel (2) contains 50 carrier phrase and word stimuli from the NU No. 6 pool of 200 words that are compressed 65 percent (i.e., 65 percent of the carrier phrase and word has been removed). This list is designated List 7 because it contains a composite of words from the original four NU No. 6 lists. Because the words have been compressed so much, the words peak at less than 0 vu. The left channel (1) contains the same 50 carrier

phrases and words that are compressed 65 percent and reverberated 0.3 s. The task of the subject is to repeat the word that follows the carrier phrase. The track time is 242 s.

Track 17. This track is identical to track 16, except that a different group of 50 words from the NU No. 6 pool of 200 words is used; hence, the designation is List 8. The track time is 242 s. NOTE: Tracks 14 and 15 contain 100 words; similarly, Tracks 16 and 17 contain 100 words. The two groups of 100 words contain 52 common words.

Track 18. This 18-s stereo track contains 100-Hz tone bursts that are 50-ms on and 50-ms off recorded 180° out-of-phase on the two channels. These tone bursts are for the relative phase calibration of the two channels of audiometers. The procedure for phase calibration requires an NBS-9A, 6 cm^3 coupler, a microphone, a microphone amplifier or sound-level meter, and an oscilloscope. The output of the amplifier or meter is fed to the oscilloscope. If the earphones are in-phase with each other, then the tone bursts will be out-of-phase at the oscilloscope (i.e., the onset of the waveform through one earphone will be positive whereas the onset of the waveform through the other earphone will be negative). If these results are not obtained, then reversing the leads to one earphone will produce the correct phase relation.

CONCLUSION

In summary, the auditory compact disc medium has enhanced the quality of materials available to audiologists for use in diagnostic and rehabilitation procedures. In addition to the materials described in this report, several other compact discs have been produced, including: 1) three discs from the Massachusetts Eye and Ear Infirmary (Aaron Thornton, PhD) that contain both traditional and unique speech materials; 2) one disc from Brigham Young University (Richard Harris, PhD) that contains traditional and specialized word lists; and, 3) one disc from Auditec of St. Louis (William Carver, PhD) that contains traditional materials for adults and children. This first generation of compact discs has simply replicated the format contained on analog tapes (i.e., word lists with 5-s or so ISI). In this format, the majority of the compact disc is occupied by the silent intervals between stimulus items. In all probability, the next generation of compact disc will use a format similar to the CD-ROM on which the stimulus items will be packed tightly and a computer used to access the materials. Materials from many first-generation compact discs will fit on one disc using the CD-ROM format. Finally, for special applications, a niche will be developed for the digital audio tape (DAT).

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of Nancy K. Cambron, MS, who edited the speech materials and produced the art work for the jewel box insert and the brochure; Chris Bellman, the audio mastering engineer; and Jo Ann Marshall who provided continuous support. In addition, the following individuals made contributions to various aspects of the two projects: Steven P. Bornstein, PhD, Charles Martinez, MA, and John P. Preece, PhD.

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ABSTRACTS OF RECENT LITERATURE

by
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Abstracts are drawn primarily from the orthotics and prosthetics literature. Selections of articles were made from these journals:

American Journal of Physical Medicine & Rehabilitation
Journal of Biomechanics
Journal of Medical Engineering Technology
Paraplegia
Physical Therapy
Prosthetics and Orthotics International
Scandinavian Journal of Rehabilitation Medicine

PROSTHETICS, ORTHOTICS, AND RELATED PRODUCTS

Analysis of the Reproducibility and Individuality of Dynamic Pedobarograph Images. Facey OE, Hannah ID, Rosen D. Reprinted from *J Med Eng Tech* 13:9-15, 1993.

Results are presented to demonstrate and establish a methodology of comparison of pedobarograph (PBG) images. Dynamic PBG images were processed so that contours of equal pressure could be extracted. After normalization for size, position and orientation, a representative contour was selected from each image and compared with the representative contours from other images. The comparisons yielded dissimilarity coefficients. The dissimilarity coefficients obtained from intercomparisons of the contours from the 57 PBG images of unshod and 35 PBG images of shod footsteps used in this study were subjected to agglomerative cluster analysis. The results, involving many hundreds of intercomparisons, group together the images made by an individual subject and clearly separate the three subjects studied.

Automatic Suspension Device for Gait Training. Kawamura J, Ide T, Hayashi S, Ono H, Honda T. Reprinted from *Prosthet Orthot Int* 17:120-125, 1993.

The automatic suspension device (REHABOT) suspends the patient's body in a standing position allowing the patient to walk around the circular handrail without forward propulsion. Reduction of body weight is accurately maintained automatically while safely supporting the patient.

The device was used for 23 patients with orthopaedic disorders or central nervous system disorders who were chosen because of their initial difficulties with gait training in parallel bars.

Its advantages are that (1) it may be used for patients with open wounds or cardiac problems, or patients using prostheses or orthoses, (2) preparation and walking practice are simpler both for patients and staff than the therapeutic pool and walking trolley, (3) running costs are lower than the therapeutic pool. Its drawbacks are that the initial cost is relatively high, only one patient can be trained at a time, and the effect of warm water is missing.

The automatic suspension device will become one of the new and fundamental pieces of equipment for gait training, especially for hospitals where there are many elderly patients and also severely and multiple disabled persons.

Biomechanical Model of the Human Foot: Kinematics and Kinetics During the Stance Phase of Walking. Scott SH, Winter DA. Reprinted from *J Biomech* 26:1091-1103, 1993.

A model of the human foot is proposed in which the foot is represented as eight rigid segments and eight monocentric, single-degree-of-freedom joints. The soft tissue under the foot is divided into seven

independent sites of contact, or loading, and each of these is modelled as a nonlinear spring and a nonlinear damper in-parallel. The model was used to estimate the kinematics and kinetics of the foot during the stance phase of walking. The force sustained at each loading site was calculated from walking trials in which only portions of the foot landed on a small force platform. The position of the calcaneus was defined by surface markers, whereas the position of the distal segments were based upon chalk footprints and an estimate of the compression of the plantar soft tissue. The results suggest that the joints that constitute the longitudinal arch extend slightly when the forefoot is loaded. During push-off, these joints flex as the metatarsophalangeal joints extend. Similar kinematic results were estimated when the distal segments of the foot were defined by surface markers. The magnitude of the joint moments of force depended largely on the distribution of the load under the foot which varied considerably between subjects. The stable, yet resilient properties of the foot, as highlighted by this model, should be considered in three-dimensional dynamic models used to study human locomotion. The model provides an objective tool to quantify foot motion and loading, which may prove useful for describing foot function in normal and pathological conditions.

The CAT-CAM Socket and Quadrilateral Socket: A Comparison of Energy Cost During Ambulation. Gailey RS, Lawrence D, Burditt C, Spyropoulos P, Newell C, Nash MS. Reprinted from *Prosthet Orthot Int* 17:95-100, 1993.

Twenty unilateral trans-femoral amputees fitted with either the Contoured Adducted Trochanteric-Controlled Alignment Method (CAT-CAM) socket (n = 10) or the quadrilateral (QUAD) socket (n = 10), and a "non-amputee" control group (n = 10) participated in the study. Subjects meeting the following criteria were studied: healthy males between the ages of 18 and 55 years, amputation due to non-vascular pathology, an unaffected sound limb, at least six months use of the test prosthesis, and a minimal stump length of 15 cm. Subjects ambulated in two randomized trials separated by 20 minutes of rest at 2 assigned speeds: a pace reflecting normal walking speed (97 m/min = 2.5 mph) or a slower speed (48.5 m/min = 1.25 mph). Heart rate (HR) and Oxygen uptake (VO_2) measured during steady state walking were analyzed via two-way ANOVA. Differences among means were further analyzed using Tukey post hoc and simple effects tests. Significant differences were observed between the control group and CAT-CAM subjects with respect to VO_2 ($p<0.05$) and HR ($p<0.01$) at the slower speed. The control group and subjects using the QUAD socket also differed with respect to VO_2 ($p<0.01$) and HR ($p<0.01$) at the slower pace. Faster pace required more energy expenditure ($p<0.01$) and produced higher HR ($p<0.01$) than slower speeds. At faster pace, a significantly higher energy expenditure in the QUAD than the CAT-CAM group was observed ($p<0.01$). It is concluded that ambulating at normal pace using the CAT-CAM socket design uses less energy than when using a QUAD socket design.

Comparison of Gait Using a Multiflex Foot Versus a Quantum Foot in Knee Disarticulation Amputees. Boonstra AM, Fidler V, Spits GMA, Tuil P, Hof AL. Reprinted from *Prosthet Orthot Int* 17:90-94, 1993.

The subjective responses and gait patterns of unilateral knee disarticulation amputees wearing prostheses fitted first with the Multiflex foot and then with the Quantum foot were studied. Nine amputees were included in the trial.

A questionnaire asked the amputees about their preference for one of the feet.

Gait analysis was performed measuring temporal parameters and goniometry of hips, knees and ankles in the sagittal and frontal planes.

There was a slight preference for the Quantum foot. Preference seemed not to be related to physical characteristics of the amputees nor to gait parameters.

There were no differences in gait as far as the temporal factors were concerned.

The main differences in the range of motion of the joints were in the frontal plane: the eversion-inversion movement of the ankle and the adduction-abduction movement of the hip. During walking at comfortable speed with the Multiflex foot the ankle and hip range of motion averaged 2.1 and 3.1 degrees respectively, less than during walking with the Quantum foot.

A Comparison of Paraplegic Gait Performance Using Two Types of Reciprocating Gait Orthoses. Winchester PK, Carollo JJ, Parekh RN, Lutz LM, Aston JW. Reprinted from *Prosthet Orthot Int* 17:101-106, 1993.

This study examined the energy cost of ambulation using the reciprocating orthosis (RGO) and the modified Isocentric RGO in paraplegic spinal cord injured subjects. In 4 subjects, the rates of O_2 consumption per minute, O_2 cost per metre, heart rate (HR), respiratory exchange ratio, velocity, and physiologic cost index (PCI) were measured during ambulation with the two orthotic devices. PCI was calculated by dividing the difference between walking and resting HR by velocity. PCI was significantly lower during ambulation trials with the Isocentric RGO compared to the RGO, but was the only measurement that detected a significant difference between the two orthotic devices. These results indicate that energy costs of ambulation at self-selected speeds were lower with the Isocentric RGO compared to the standard RGO. Furthermore, PCI could be used as a sensitive indicator of gait efficiency in spinal cord injury subjects.

Effects of Arch Height of the Foot on Angular Motion of the Lower Extremities in Running. Nigg BM, Cole GK, Nachbauer W. Reprinted from *J Biomech* 26:909-916, 1993.

It has been suggested that a relationship exists between the height of the medial longitudinal arch of the foot and athletic injuries to the lower extremities. However, the functional significance of arch height in relation to injury is not well understood. The purpose of this study was to determine the influence of arch height on kinematic variables of the lower extremities that have been associated with the incidence of injury in running in an attempt to gain some insight into a functional relationship between arch height and injury. The three-dimensional kinematics of the lower extremities were measured during running for 30 subjects using high-speed video cameras. A joint coordinate system was used to calculate the three-dimensional orientation of the ankle joint complex for a single stance phase. Simple, linear regression analyses showed that arch height does not influence either maximal eversion movement or maximal internal leg rotation during running stance. However, assuming that knee pain in running can result from the transfer of foot eversion to internal rotation of the tibia, a functional relationship between arch height and injury may exist in that the transfer of foot eversion to internal leg rotation was found to increase significantly with increasing arch height. A substantial (27%), yet incomplete, amount of the variation in the transfer of movement between subjects was explained by arch height, indicating that there must be factors other than arch height that influence the kinematic coupling at the ankle joint complex. Additionally, the transfer of movement is only one factor of many associated with the etiology of knee pain in running. Therefore, it is suggested that a running-injury-related foot typology based on arch height is not possible at this time.

Enhancement of Hemiplegic Patient Rehabilitation by Means of Functional Electrical Stimulation. Kralj A, Acimovic R, Stanic U. Reprinted from *Prosthet Orthot Int* 17:107-114, 1993.

This presentation will review briefly the current practice and state of the art in functional electrical stimulation (FES) as applied to stroke, head injured or brain tumour operated patients. A similar application is used in paretic patients following trauma or other aetiology. Over 20 years experience in the application of FES, as practised in Ljubljana, will be highlighted and the devices currently in use will be described. The statistics show the results obtained on 2,500 hemiplegic patients examined for FES application during the last 10 years. The statistics and results of the Slovenian population indicate 0.15–0.20% new cases annually or 1,500 new cases per million inhabitants. Up to 63% of annual cases are candidates for an FES based therapeutic locomotion rehabilitation programme. Experience indicates that 60% of hemiplegic patients received single-channel stimulation to correct equinovarus or foot drop, 30% obtained dual or even three channel stimulation treatment and only 10% of patients were involved in multichannel FES of four to six or even eight channels of stimulation. The benefits and outcome of rehabilitation will be presented and discussed in regard to current trends in the field of FES for hemiplegic and paretic patients. The partly inactive but very important field of FES application to the upper extremity in hemiplegic and paretic

patients will be discussed and the relatively modest achievements presented. Future developments will be presented together with advances foreseen by steadily improving technology.

The Functional Independence Measure: A Comparative Study of Clinician and Self Ratings. Grey N, Kennedy P. Reprinted from *Paraplegia* 31:457-461, 1993.

In recent years the Functional Independence Measure has emerged as a standard assessment instrument for use in rehabilitation and therapy programmes for disabled persons, including those with spinal cord injury (SCI). This measure was devised to be rated by a clinician familiar with the patient. We studied 40 spinal cord injury patients who were rated on the FIM by a clinician within the 6 weeks prior to discharge, and who then rated themselves on the FIM at one month post discharge. There was a strong correlation between the differently rated scores. This suggests that the FIM can be given to patients as a self-report questionnaire, thus reducing time of assessment and increasing assessment potential.

Hip Joint Loading During Walking and Running, Measured in Two Patients. Bergmann G, Graichen F, Rohlmann A. Reprinted from *J Biomech* 26:969-990, 1993.

The resultant hip joint force, its orientation and the moments were measured in two patients during walking and running using telemetering total hip prostheses. One patient underwent bilateral joint replacement and a second patient, additionally suffering from a neuropathic disease and atactic gait patterns, received one instrumented hip implant. The joint loading was observed over the first 30 and 18 months, respectively, following implantation. In the first patient the median peak forces increased with the walking speed from about 280% of the patient's body weight (BW) at 1 km h^{-1} to approximately 480% BW at 5 km h^{-1}. Jogging and very fast walking both raised the forces to about 550% BW; stumbling on one occasion caused magnitudes of 720% BW. In the second patient median forces at 3 km h^{-1} were about 410% BW and a force of 870% BW was observed during stumbling. During all types of activities, the direction of the peak force in the frontal plane changed only slightly when the force magnitude was high. Perpendicular to the long femoral axis, the peak force acted predominantly from medial to lateral. The component from ventral to dorsal increased at higher force magnitudes. In one hip in the first patient and in the second patient the direction of large forces approximated the average anteversion of the natural femur. The torsional moments around the stem of the implant were 40.3 N m in the first patient and 24 N m in the second.

Intrasubject Reliability of Spinal Range of Motion and Velocity Determined by Video Motion Analysis. Robinson ME, O'Connor PD, Shirley FR, MacMillan M. Reprinted from *Phys Ther* 73:626-631, 1993.

Background and Purpose. The purpose of this study was to investigate the repeatability of spinal range of motion (ROM) and movement velocity measurements of patients with chronic low back pain, using a two-dimensional motion analysis system. This apparatus uses reflective markers placed on anatomical landmarks and video digitization to derive ROM measurements from three segments of the spine and associated velocities through the respective ROMs. **Subjects.** Forty-two patients with chronic LBP underwent ROM and movement velocity testing. **Methods.** Each subject was tested twice without removal of the markers to minimize error contribution from differences in marker placement. **Results.** Results indicated that both the ROM measures and the velocity measures were highly repeatable. Intra-class correlations for the ROM measures ranged from .77 to .96. Velocity measures were also reliable, with intraclass correlation coefficients ranging from .75 to .97. **Conclusion and Discussion.** Overall, the results seem to indicate that the video motion analysis system used in this study yields repeatable ROM and velocity measures on a clinical population. In practice, however, the measures may reflect greater errors due to the need of examiners to relocate markers at different testing sessions. These systems also offer distinct advantages over other means of obtaining ROM and velocity measures. The results of this study indicate that these measures may be obtained without undue concern for measurement artifact due to the instrumentation reliability.

Joint Moments and Muscle Activity in the Lower Extremities and Lower Back in Lifting and Lowering Tasks. DeLooze MP, Toussaint HM, Van Dieen JH, Kemper HCG. Reprinted from *J Biomech* 26:1067-1076, 1993.

The mechanical loading on the body during the act of lifting has been estimated frequently. The opposite act of lowering has received much less attention. The aim of the present study was to compare the mechanical loading of the musculoskeletal system in lifting and lowering. Eight subjects repetitively lifted and lowered a load, using two different techniques (a leg and a back technique). The ankle, knee, hip and lumbosacral joint moments were estimated and the myoelectrical (EMG) activity of seven (leg and back) muscles was recorded.

The differences between the lifting and lowering phase for the leg technique were similar to those observed when the back technique was applied. The joint moment curves in lifting showed a high level of agreement with the (time-reversed) moment curves in lowering. Peak moments in lowering were only slightly lower than in lifting (peak lumbar moments were 5.4% lower). These small differences were related to different acceleration profiles at the centre of gravity of the body/load complex.

The EMG activity was considerably lower in lowering than in lifting. The mean EMG in lowering (average for seven muscles) was only about 69% of the EMG in lifting. This was attributed to the different types of muscle actions involved in lifting (mainly concentric) and lowering (mainly eccentric). Furthermore, the EMG results suggest that similar inter-muscular coordination is involved in lowering and lifting. The results give rise to the assumption that in lifting and lowering similar muscle forces are produced to meet the (nearly) equal joint moments, but in lowering these forces are distributed over a smaller cross-sectional area of active muscle, which might imply a higher risk of injury.

Kinematic Gait Analysis in Hemiplegic Patients. Ozgirgin N, Bolukbasi N, Beyazova M, Orkun S. Reprinted from *Scand J Rehabil Med* 25:51-55, 1993.

Temporal-distance variables of gait were investigated in 8 female and 23 male hemiplegic patients in order to assess the distribution of these variables according to functional ambulation category and to evaluate their validity. Video-recording technique was used for obtaining the temporal-distance values. Velocity, step-time, stride length and stride length in relation to lower extremity length proved to be valuable measures in the gait analysis, while cadence, step-time and step-time differential values seemed to be less important.

Lightweight Prostheses for Bilateral Below-Elbow Amputees. Rout SN. Reprinted from *Prosthet Orthot Int* 17:126-129, 1993.

In view of the anticipated activity of the patient and working environment, lightweight prostheses were designed for an adult female, bilateral below-elbow (BE) amputee at NIRTAR to provide the greatest degree of function. The prostheses were fabricated using lightweight materials and new techniques. Depending on the stump length there were two different types of lightweight prostheses designed and successfully used, (1) an endoskeletal BE prosthesis and (2) an exoskeletal BE prosthesis. After periodic follow-up and evaluation the function of the prostheses was found to be most satisfactory. By reducing the weight considerably compared to other available alternatives, it is more likely that the amputee will make use of the prostheses to efficiently perform various activities. The new prosthesis designs may counteract the high rejection rate of old conventional ones and the principle may be applied to the fabrication of all BE prostheses.

Report on a Conference on Motor Prostheses for Workplace Mobility of Paraplegic Patients in North America. Kantor S, Andrews BJ, Marsolais EB, Solomonow M, Lew D, Ragnarsson KT. Reprinted from *Paraplegia* 31:439-456, 1993.

On May 18, 1992 a symposium at Case Western Reserve University in Cleveland, Ohio, USA had the goal of defining the tasks needed to reach clinical utility of investigational neural prosthetic ambulation devices. The characteristics and stage of development of four systems were detailed: the Louisiana State University reciprocating orthosis (LSU-RGO) with muscle stimulation; the m dular hybrid functional neuromuscular stimulation (NS) orthosis; the Cleveland VA-Case Western Re rve

University (VA-CWRU) implant system; and the Parastep® system. Multicenter clinical trials are underway for the Parastep® system and are planned to start within the next 2 years for the LSU-RGO with muscle stimulation, the VA-CWRU 8-channel system, and the floor reaction orthosis component of the modular hybrid FNS system. Current investigational systems provide little advantage over the standing wheelchair in some occupations but they do expand social, recreational, and exercise capabilities. Disabled people and some leading rehabilitation physicians are willing to test basic ambulation devices but the regulatory approvals must first be obtained for multicenter clinical trials. Corporate partners are central to the development of devices, their clinical testing, and their subsequent marketing. A key requirement for developing and disseminating motor prostheses is the education of clinicians so that they will participate in trials and be prepared to prescribe the prostheses when they reach the market.

Transcutaneous Oxygen Pressure: An Effective Measure for Prosthesis Fitting on Below-Knee Amputations. Casillas M-M, Michel C, Aurelle B, Becker F, Marcer I, Schultz S, Didier J-P. Reprinted from *Am J Phys Med Rehabil* 72:29-32, 1993.

After amputation for arterial occlusive disease of the lower limbs, healing and local adaptation to a prosthesis depend on the oxygen ratio in the tissue. Transcutaneous oxygen tension ($TcPo_2$) is a noninvasive microcirculatory exploration. Forty six below-knee stumps were selected without any prosthetic problem excepting vascular, with a follow-up mean duration of 23 months. They were classified into different prosthetic categories. The first was the worst because it required further amputation on the thigh and the fourth the best, which displayed complete adaptation to a socket contact. These groups were related to their $TcPo_2$ values on the anterior and exterior face of the stumps in both reclined and seated positions. It seems that it is impossible to achieve healing when the $TcPo_2$ value is lower than 15 mm Hg in lying position. However, healing is possible above 20 mm Hg but socket contact is not possible when $TcPo_2$ values are under 40 mm Hg. When $TcPo_2$ values are above 40 mm Hg, a good prosthesis fitting is possible when no problems are encountered other than vascular ones.

Vertical Ground Reaction Force Feedback to Enhance Stroke Patients' Symmetrical Body-Weight Distribution While Rising/Sitting Down. Engardt M, Ribbe T, Olsson E. Reprinted from *Scand J Rehabil Med* 25:41-48, 1993.

A force platform with an auditory output consisting of two electronic balances was used to reinforce symmetrical body-weight distribution in stroke patients. Forty patients randomly assigned to an experimental group or a control group practised rising and sitting down for 15 min, thrice daily, 5 days a week for 6 weeks. The experimental group but not the control group received ground reaction force feedback through the auditory output. Vertical ground reaction forces under each foot were measured with two force plates. Mean difference in improvement of body weight distribution on the paretic leg was 13.2 ± 10.7 (M, SD) per cent total body weight in the experimental group and 5.1 ± 6.7 per cent in the control group in rising ($p < 0.01$) and 12.7 ± 7.5 per cent total body weight and 4.6 ± 6.6 per cent in sitting down tests ($p < 0.001$). The patients in the experimental group achieved in average close to a symmetrical body-weight distribution while rising and sitting down. Improvements in physical performance and sit-stand tests were greater in the experimental group ($p < 0.05$ and $p < 0.01$, respectively). No differences were seen in improvement in performance of activities of daily living. Symmetry in body-weight distribution in rising and sitting down correlated with high scores in physical performance, motor function in rising, and with functional ability.

A Video-Based System for the Estimation of the Inertial Properties of Body Segments. Sarfaty O, Ladin Z. Reprinted from *J Biomech* 26:1011-1016, 1993.

A system for the estimation of the inertial properties of human body segments using advanced video technology and computer image processing was developed. The system is based on the photogrammetric technique, were three-dimensional information is determined from two separate two-dimensional video images. The inertial properties are

calculated using an image-processing algorithm which provides volumetric information, coupled with a database of anatomical densities provided in the literature. In order to determine the accuracy of the system and its limitations, the system estimates of the inertial properties of solid bodies were compared to theoretically calculated values. The application of the system to kinesiological studies is illustrated by measuring the inertial properties of the shank of three subjects, and comparing the results to data generated using regression equations provided in the literature.

Human factors, such as segment boundaries identification and color thresholds selection, were found to introduce the largest errors. A proper selection of the optical setting can reduce the errors to levels of 5% or better. On the average, the system overestimated the inertial properties of solid objects by 2.51% for mass, 1.21% for center of mass, 4.53% for transverse moments of inertia and 3.65% for longitudinal moment of inertia. The video-based estimates of the mass and center of mass of the shank were comparable to values obtained from anthropometric-based regression equations. The predictions of the transverse moment of inertia of the shank varied considerably among the methods. The findings suggest that a video-based system represents a promising technique for estimating inertial properties of human body segments for *individual subjects*. Further studies of the inertial properties of cadaver body segments and the comparison to MRI-generated values are required to test the system estimates further.

Walking Speed of Normal Subjects and Amputees: Aspects of Validity of Gait Analysis. Boonstra AM, Fidler V, Eisma WH. Reprinted from *Prosthet Orthot Int* 17:78-82, 1993.

This study investigated some aspects of the validity of walking speed recording in 15 normal subjects, 16 trans-femoral amputees and 8 knee disarticulation amputees. The variability and test-retest reliability of walking speed and the influence of simultaneous recording of EMG and goniometry on comfortable and fast walking speeds were studied.

The variability between sessions was mainly determined by the variance within each session. The variance of speed within sessions while walking with fast speed, was higher when walking without equipment than when walking with equipment. The variances of speed within sessions of the normal subjects were higher than those for both amputee groups. The test-retest reliability, expressed by the intra-class correlation coefficient, was good: between 0.83 and 0.98. The speed when walking without equipment was significantly higher both in normal subjects and amputees than the speed when walking with equipment.

BOOK REVIEWS

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Directory of Services for Blind and Visually Impaired Persons in the United States and Canada. 24th edition. New York: American Foundation for the Blind, 1993.

If value is determined by popularity, then the fact that this volume has passed through two dozen editions rates it as an overwhelming success. And it should be. For one thing, its production deserves to be called "beautiful" (or "handsome," if its heft stamps it as a masculine effort). For another, its coverage is unusually complete and detailed. All Canadian provinces and territories and all states in the U.S. are represented. For each of the two countries, federal agencies, national consumer and professional organizations are listed. Descriptions of and addresses for manufacturers and distributors, including mail-order houses, are included. The total listings add to an impressive 3,000 or so entries. The reader can search the directory for public libraries that accommodate blind persons, for early childhood and geriatric services, low-vision clinics, manufacturers and distributors of products, and more. The extensive detail includes such items as mission and history of the agency, eligibility requirements, purview, types of services, size of budget, and source of funding. It is difficult to picture a serious practitioner and concerned administrator who would not want this book near at hand for day-to-day client referrals, planning services, and administering their programs for blind and low-vision clients.

The History of Special Education: From Isolation to Integration. Margret A. Winzer. Washington, DC: Gallaudet University Press, 1993. 463 pp.

For special education, whose substantial beginnings date only from the eighteenth century, history is short; but as Dr. Winzer notes, the history of persons with disabilities extends back to the beginnings of humanity—which does not mean that the task confronting a historian of this specialty has an easy task. Indeed, a major problem confronting the historian is sorting through the torrent of words that has been printed about the education of students with disabilities. It is important, therefore, to say at the outset of this review, that Dr. Winzer has done the sifting of wheat and chaff very well.

Her guiding philosophy is that "economic and social conditions both define and drive educational arrangements and possibilities"; hence, her book "mirrors our progress toward appreciating the basic humanity of all people" (p. xi). She bestows credit on those who pioneered the field, but also notes that these pioneers included "not a few reprobates." But does she consider the *major issues* raised over the past 200 years by those in support of, and those opposed to, special education?

Dr. Winzer painstakingly examines the roots of today's surge toward integration ("mainstreaming") of students with disabilities and largely lets the facts speak for themselves, though she does comment that it remains "a social experiment that continues to be more influenced by ideology and political and philosophical justifications than by empirical findings" (p. 384). She examines the costs of special education, the contents of its curriculums and instructional methods, the disciplines that have been involved in it, the roles played by educational and psychological measurement (with attention to "the IQ myth"), and the attacks made upon the civil rights of various disabled groups. She presents dispassionately, though not approvingly, Bell's opposition to marriages between deaf people, and sterilization laws aimed at persons with mental retardation. Altogether, Dr. Winzer has assembled an imposing amount of information and structured it coherently.

Dr. Winzer, Associate Professor of Education,

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University of Lethbridge, has two earlier books to her credit: *Closing the Gap* (1989), and *Children with Exceptionalities* (1993). Among her articles is a survey of Canadian education of deaf students and well-researched articles on the history of educating deaf students. Her Canadian citizenship and her own unusual knowledge about deafness becomes clear to the reader. Counting entries in the book's index, readers will note 159 references to deafness, 3 to autism, 63 to blindness, 1 to brain damage, 11 to epilepsy, 39 to mental illness, and 84 to mental retardation. Readers will also find that the book contains a generous portion of information about special education in Canada, something missing in most special education textbooks. New insights emerge from a close look at how that democratic country has met its obligations to its citizens with disabilities.

The author states that she has written as a special educator for an audience of special educators. Unquestionably, she has met her self-imposed goal. But her ambition may be exceeded by the result: her book should find a large audience among government officials, parents, general educators, rehabilitationists, and persons with disabilities. The latter, especially, will find her work balanced favorably between sympathy and pathos, between generalization and detail. Regardless of their backgrounds, readers will appreciate her view that special education is one indicator of the value a society places on all of its citizens, whether disabled or not.

Independence Without Sight or Sound: Suggestions for Practitioners Working with Deaf-Blind Adults. Dona Sauerburger. New York: American Foundation for the Blind, 1993. 194 pp. Illustrated.

The author has been an orientation and mobility instructor for 20 years. She has written a book that is described in its preface, by Robert Smithdas, as, "An integrated study of the needs of deaf-blind people who are reaching out to life and its human activities" (p. vii). The text is rich in anecdotes and has numerous, appropriate pictures. Its first four chapters concern communication, a decision that will appear justified to those who work with deaf-blind clients. A slight demurrer: in discussing interpreters, the author often implies that interpreters can solve all communication problems. Of course, she is aware that not all who represent themselves as interpreters (even those with some kind of certification) will adequately communicate with particular deaf-blind clients; however, more explicit treatment of this issue would be worthwhile. The next two chapters concern psychological consequences of loss of both distance senses. The discussions of hallucinations and delusions contain some vivid cases that might be misunderstood to imply that these are common in this client group. Again, the author is certainly aware that they are not, though the presentation should make that point clear beyond a doubt. Chapter 7 introduces orientation and mobility training. The chapter is written, "For O&M specialists who teach blind and visually impaired people . . . [and who] may be surprised to realize that except for specialized communication techniques, they probably already know the majority of what they need to teach deaf-blind people to travel independently" (p. 105). The remaining two chapters take up street crossings (when to attempt them independently and when not to), and teaching deaf-blind persons with limited language skills. Three appendices complete the volume: "Instructions for Making a Mobility Muff"; "Experiments in Sensory Deprivation"; and "Survey of Dog Guide Schools." The first and the last are appropriate, but the discussion of experiments in artificial sensory deprivation strikes this reviewer as naive, and its place in this volume as misleading. The author herself notes, "It is not clear whether the information about sensory deprivation derived from these experiments applies to the experience of deaf-blind people. Many of the changes caused by the deprivation decreased as the subjects adapted to the condition" (p. 155). A decisive editing would have eliminated this lengthy appendix from this otherwise valuable book. The author writes clearly and with considerable insight. She cites little scientific research, except for the preceding appendix, electing instead to pitch the text to practitioners. In a number of the chapters she has sought and acknowledges the assistance of other authorities. In soliciting their contributions, the author may have unwittingly encouraged them to offer more lurid examples and sensational points than she herself would have chosen. In any event, this book will

reward those who now work with, or who desire to learn more about, deaf-blind clients.

Mental Health Services for Deaf People. Edited by Barbara A. Willigan and Susan J. King. Washington, DC: Gallaudet Research Institute, Gallaudet University, 1992. 210 pp.

The editors had the cooperation of the American Deafness and Rehabilitation Association and the University of California Center on Deafness in compiling this directory. The current edition grew out of a survey of organizations and practitioners in Canada and the United States; admittedly incomplete, but still a sizable effort and one that has resulted in an illuminating document. Each such potential source was sent a questionnaire requesting information about its services, governance, purview, sources of support, program size, fees charged, and related data. Helpfully, the editors supplement the respondents with a list of the names and addresses of those who sent incomplete information, or did not reply at all. This policy increases the book's usefulness, since users are urged to check all information that it contains. The editors caution that all information in the directory is based on unverified self-reports, so checking on its leads is wise. As a result of these policies, the directory lists 266 organizations (5 in Canada) and 110 private practitioners, all in the U.S. Scanning the contents, the reader will find that eight states, and all but three Canadian provinces have no organizations serving the mental health needs of deaf people. Three of Canada's five organizations are in Ontario, highlighting the paucity of these services in that country. As for private practitioners, Canada lists none; the U.S. has none in 21 states. Administrators, as well as service providers, will find this directory useful: the former being able to use it as a basis for planning for the appropriate distribution of mental health services where they are absent or inadequate. Survey researchers will also be pleased to find the questionnaire in one of the appendices; it will serve as a useful guide to future surveys.

PUBLICATIONS OF INTEREST

This list of references offers *Journal* readers significant information on the availability of recent rehabilitation literature in various scientific, engineering, and clinical fields. The *Journal* provides this service in an effort to fill the need for a comprehensive and interdisciplinary indexing source for rehabilitation literature.

All entries are numbered so that multidisciplinary publications may be cross-referenced. They are indicated as *See also* at the end of the categories where applicable. A listing of the periodicals reviewed follows the references. In addition to the periodicals covered regularly, other publications will be included when determined to be of special interest to the rehabilitation community. To obtain reprints of a particular article or report, direct your request to the appropriate contact source listed in each citation.

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Contact: Michael S. Pinzur, MD, Dept. of Orthopaedic Surgery, Loyola University Medical Center, 2160 S. First Ave., Maywood, IL 60153

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Contact: Joseph Ghika, Chuv, Lausanne, Switzerland

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Contact: David M. Brienza, School of Health and Rehabilitation Sciences, Dept. of Electrical Engineering, University of Pittsburgh, Pittsburgh, PA 15260
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BIOMECHANICS

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Contact: Audny Anke, Sunnaas Rehabilitation, 1450 Nesoddtangen, Norway

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Contact: Vithal G. Wagle, MD, Dept. of Neurosurgery, Hartford Hospital, 80 Seymour St., Hartford, CT 06115

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Contact: Robert L. Waters, MD, Clinical Professor of Orthopedic Surgery, University of Southern California, Rancho Los Amigos Medical Center, HB-117, 7601 East Imperial Highway, Downey, CA 90242

164. A New Bladder Stimulator—Hand-Held Controller and Miniaturized Implant: Preliminary Re-

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Contact: Mohamad Sawan, PhD, Dept. of Electrical Engineering, Ecole Polytechnique de Montreal, PO Box 6079, Station "A," Montreal, Quebec, H3C 3A7 Canada

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Contact: Dr. J.R. Silver, National Spinal Injuries Centre, Stoke Mandeville Hospital, Aylesbury, Buckinghamshire HP21 8AL UK

166. Report on a Conference on Motor Prostheses for Workplace Mobility of Paraplegic Patients in North America. Kantor C, et al., *Paraplegia* 31(7):439-456, 1993.
Contact: E.B. Marsolais, MD, PhD, Cleveland VA Medical Center, 10701 East Blvd., Cleveland, OH 44106

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Contact: Anthony Mawson, DrPH, 1831 Bordeaux St., New Orleans, LA 70115

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Contact: N.V. Petrova, MD, Senior Research Worker, GN Gabrichevsky Institute of Epidemiology and Microbiology, Moscow, Russia

169. Spine Injuries in Combat Troops—Panama, 1989. Parsons TW, et al., *Milit Med* 158(7):501-502, 1993.
Contact: Capt. Theodore W. Parsons, III, USAF MC, Dept. of Orthopaedic Surgery, Wilford Hall USAF Medical Center, Lackland AFB, San Antonio, TX 78236-5300
*See also*51, 52, 54, 55, 130, 136, 137, 176, 179, 181

SURGERY

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VASCULAR DISORDERS

170. Foot Microcirculation and Blood Rheology in Diabetes. Zioupos P, et al., *J Biomed Eng* 15(2):155-158, 1993.
Contact: J.C. Barbenel, Bioengineering Unit, Wolfson Centre, University of Strathclyde, Glasgow G4 0NW, UK

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Contact: J.C. Misra, Dept. of Electronics and Communications Engineering, Andhra University College of Engineering, Waltair-530003, India

172. Salvage, with Arthrodesis, in Intractable Diabetic Neuropathic Arthropathy of the Foot and Ankle. Papa J, Myerson M, Girard P, *J Bone Joint Surg* 75A(7):1056-1066, 1993.
Contact: John Papa, MD, Jewett Orthopaedic Clinic, 1285 Orange Ave., Winter Park, FL 32789

173. Vacuum-Compression Therapy for the Treatment of an Ischemic Ulcer. McCulloch JM Jr, Kemper CC, *Phys Ther* 73(3):165-169, 1993.
Contact: Joseph M. McCulloch, Jr., PhD, PT, Dept. of Physical Therapy and Rehabilitation Services, School of Allied Health Professions, Louisiana State University Medical Center, 1501 Kings Hwy., Shreveport, LA 71130-3932
See also 3, 6, 180

WHEELCHAIRS and POWERED VEHICLES

174. Assessment of Need for Special Seating and/or Electronic Control Systems for Wheelchairs Among People with Severe Physical Disabilities. Lachmann SM, Greenfield E, Wrench A, *Clin Rehabil* 7(2):151-156, 1993.
Contact: Eve Greenfield, Research Occupational Therapist, Disablement Services Centre, Addenbrooke's Hospital, Hills Rd., Cambridge CB2 2QQ UK

175. The Model 28B Electric-Powered Outdoor Wheelchair: A Users' Survey. Dudley NJ, McMahon M, *Clin Rehabil* 7(2):147-150, 1993.

Contact: N.J. Dudley, Dept. of Geriatric Medicine, St. Luke's Hospital, Bradford BD5 0NA, UK

176. Physical Performance of Elite Wheelchair Basketball Players in Armcranking Ergometry and in Selected Wheeling Tasks. Hutzler Y, *Paraplegia* 31(4):255-261, 1993.
Contact: Y. Hutzler, PhD, The Zinman College of Physical Education, The Wingate Institute, Netanya, Israel

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Contact: John B. Redford, MD, Dept. of Rehabilitation Medicine, University of Kansas Medical Center, 39th and Rainbow Ave., Kansas City, KS 66103

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Contact: R.O. Ham, Dept. of Medical Engineering and Physics, King's College School of Medicine and Dentistry, Dulwich Hospital Site, East Dulwich Grove, London SE22 8PT, UK
See also 99, 159

WOUNDS and ULCERS

179. Accuracy of Interface Pressure Measurement Systems. Allen V, et al., *J Biomed Eng* 15(4):344-348, 1993.
Contact: Dr. V. Allen, Regional Medical Physics Dept., Freeman Hospital, Newcastle-upon-Tyne NE7 7DN, UK

180. Effect of Total Contact Cast Immobilization on Subtalar and Talocrural Joint Motion in Patients with Diabetes Mellitus. Diamond JE, Mueller MJ, Delitto A, *Phys Ther* 73(5):310-315, 1993.
Contact: Jay E. Diamond, PT, Dept. of Physical Therapy, Irene Walter Johnson Rehabilitation Institute, Washington University Medical School, 509 S. Euclid Ave., St. Louis, MO 63110

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Contact: Dr. V. Allen, Regional Medical Physics Dept., Freeman Hospital, Newcastle-upon-Tyne NE7 7DN, UK

182. Treatment of Chronic Wounds by Means of Electric and Electromagnetic Fields—Part 2: Value of FES Parameters for Pressure Sore Treatment. Stefanovska A, et al., *Med Biol Eng Comput* 31(3):213-220, 1993.
Contact: A. Stefanovska, Faculty of Electrical and Computer Engineering, University of Ljubljana, Trzaska 25, 61000 Ljubljana, Slovenia
See also 11, 98, 155, 167, 173

CALENDAR OF EVENTS

NOTE: An asterisk at the end of a citation indicates a new entry to the calendar.

1993

December 7-12, 1993
American Academy of Neurological and Orthopaedic Surgery: 17th Annual Convention, Las Vegas, NV
Contact: Dr. Michael R. Rask, 2320 Rancho Dr., Suite 108, Las Vegas, NV 89102-4592

December 8-12, 1993
Fifth International Symposium on Neural Regeneration, Pacific Grove, CA
Contact: Office of Regeneration Research Programs (151N), VA Medical Center, Portland, OR 97201; Tel: 503-273-5193; FAX: 503-721-7906

1994

(no date yet), 1994
16th Annual International Conference of the IEEE/EMBS, Baltimore, MD
Contact: Dr. Joshua Tsitlik, Johns Hopkins School of Medicine, Rm 410 Traylor Bldg., 720 Rutland Ave., Baltimore, MD 21205

January 28-29, 1994
Third Annual Symposium on Pathomechanical Conditions of the Human Body, New Orleans, LA
Contact: Deanna Fish, CPO; Tel: 800-866-7522, ext: 23*

January 31-February 4, 1994
Visions in Mobility International Mobility Conference-7, Melbourne, Australia
Contact: Royal Guide Dogs Associations of Australia, Chandler Highway, Kew, Victoria 3101, Australia; Tel: +61-3-860-4444; Fax: +61-3-860-4500

February 17-19, 1994
10th International Seating Symposium, Vancouver, BC Canada
Contact: Seating Symposium, Room 105-2194 Health Sciences Mall, The University of British Columbia, Vancouver, BC Canada V6T 1Z3; Tel: 604-822-4965; Fax: 604-822-4835

February 24-March 1, 1994
Annual Meeting of American Academy of Orthopedic Surgeons, New Orleans, LA
Contact: 222 South Prospect Ave., Park Ridge, IL, 60068*

March 16-19, 1994
CSUN'S Ninth Annual International Conference, Technology and Persons with Disabilities, Los Angeles, CA
Contact: Dr. Harry J. Murphy, Center on Disabilities, California State University, Northridge, 18111 Nordhoff St-DVSS, Northridge, CA 91330; Tel: 818-885-2578; Fax: 818-885-4929

March 22-26, 1994
AAOP Annual Meeting and Scientific Symposium, Nashville, TN
Contact: Annette Suriani, National Office; Tel: 703-836-7118*

March 27-30, 1994
IFAC Symposium on Modeling and Control in Biomedical Systems, Galveston, TX
Contact: Susan George, IFAC Biomedical Symposium, University of Texas Medical Branch, Box 55176, Galveston, TX 77555-5176; Tel: 409-770-6628; Fax: 409-770-6825*

April 6-12, 1994
17th International Conference on Medical and Biological Engineering and 10th International Conference on Medical Physics, Rio de Janeiro, Brazil
Contact: Mr. OZ Roy, Sec Gen Intl, Union for Physical and Engineering Sciences in Medicine, c/o National Research Council, Room 307, Building M-50, Ottawa, Ontario, K1A 0R8, Canada

April 7-9, 1994
BME'94 International Conference on Biomedical Engineering, Hong Kong
Contact: BME'94 Conference Secretariat, c/o Rehabilitation Engineering Centre, Hong Kong Polytechnic, Hunghom, Kowloon, Hong Kong; Tel: 852-766-7683; Fax: 852-362-4365

April 9-16, 1994
IRMA VII—Seventh World Congress of the International Rehabilitation Medicine Association: 25th Anniversary of IRMA, Washington, DC
Contact: IRMA VII, 875 Kings Hwy., West Deptford, NJ 08096

April 9-16, 1994
XIIth World Congress of the Rehabilitation Medicine Association, Washington, DC
Contact: Ms. D. Jones, 1333 Moursund, A-221, Houston, TX 77030

April 16-17, 1994
Thirteenth Southern Biomedical Engineering Conference, Washington, DC
Contact: Jafar Vossoughi, PhD, 4401-A Connecticut Ave., NW, Suite 327, Washington, DC 20008; Tel: 202-282-2388; Fax: 202-282-3677

April 17-22, 1994
11th International Congress of the World Federation of Occupational Therapists, London, UK
Contact: Conference Associates and Services Ltd - WFOT, Congress House, 55 New Cavendish St., London W1M 7RE, UK; Tel: 071-486-0531; Fax: 071-935-7559

April 25-27, 1994
Annual Conference of the American Spinal Injury Association, Philadelphia, PA
Contact: Jane Mulkey, ASIA, 2020 Peachtree Rd., Atlanta, GA 30309; Tel: 404-355-9772*

May 31-June 2, 1994
Annual Meeting of International Medical Society of Paraplegia, Kobe, Japan
Contact: Host Organizer, IMSOP 1994 Annual Meeting, Japan Organizing Committee, Orthopedic Department of Tokushima University 3, Kuramoto-cho, Tokushima-shi, 770, Japan; Tel: 0886-31-3111; Fax: 0886-33-0178

June 2-3, 1994
Improving the Quality of Physical Therapy, International Conference, 's-Hertogenbosch, The Netherlands
Contact: Mr. J. Dekker, PhD or Ms. E. Zoer, PO Box 1568, 3500 BN Utrecht, The Netherlands; Tel: 31-30-319946; Fax: 31-30-319290

June 4-8, 1994
Annual Conference of The American Physical Therapy Association, Toronto, Canada
Contact: APTA, 111 N. Fairfax St., Alexandria, VA 22314; Tel: 703-706-3169*

June 9-10, 1994
Second Annual International Conference, "Virtual Reality and Disabilities," San Francisco, CA
Contact: Dr. Harry J. Murphy, Center on Disabilities, California State University, Northridge, 18111 Nordhoff St.-DVSS, Northridge, CA 91330; Tel: 818-885-2578; Fax: 818-885-4929

June 17-22, 1994
17th Annual RESNA Conference, Nashville, TN
Contact: RESNA, 1101 Connecticut Ave. NW, Suite 700, Washington, DC 20036; Tel: 202-857-1199

June 21-24, 1994
10th Congress of the International Society of Electrophysiology and Kinesiology, Charleston, SC
Contact: ISEK Congress, Dr. Richard Shiavi, Biomedical Engineering, Box 6117, Station B, Vanderbilt University, Nashville, TN 37235

June 29-July 1, 1994
American Control Conference, Baltimore, MD
Contact: Prof. Hassan Khalil, Department of Electrical Engineering, Michigan State University, East Lansing, MI 48823-1226; Tel: 517-355-6689; Fax: 517-353-1980*

July 4-7, 1994
The Second Biennial European Joint Conference on Engineering Systems Design and Analysis (ESDA), London, England
Contact: Dr. Minoo Dabestani or Professor P.S. Walker, Department of Biomedical Engineering, Institute of Orthopaedics, Brockley Hill, Stanmore, Middlesex HA7 4LP, England*

July 5-8, 1994
Dundee '94- International Conference on Clinical Gait Analysis, Dundee, Scotland
Contact: Dundee '94 Secretariat, Dundee Limb Fitting Centre, 133 Queen St., Broughty Ferry, Dundee DD5 1AG, Scotland*

July 10-15, 1994
2nd World Congress of Biomechanics, Amsterdam
Contact: Biomechanics Section, Institute of Orthopaedics, University of Nijmegen, PO Box 9101, 6500 HB Nijmegen, The Netherlands*

August 15-19, 1994
Rehabilitation Ergonomics, Toronto, Ontario, Canada
Contact: IEA '94 Secretariat, c/o JPdL Multimanagement Inc., Toronto Dominion Centre, 55 King St. West, Suite 2550, Toronto, ON, Canada M5K 1EZ; Tel: (416) 784-9396; Fax: (416) 784-0808

August 21-26, 1994
World Congress on Medical Physics and Biomedical Engineering, Rio de Janeiro, Brazil
Contact: Conference Secretariat, Rua do Ouvidor, 60/414 Rio de Janeiro, CEP 20040, Brazil; Tel: +55 21 224 .6080; Fax: +55 21 231. 1492

September 4-9, 1994
6th European Regional Conference of Rehabilitation International, Budapest, Hungary
Contact: Rehabilitation Secretariat, ISM Limited, The Old Vicarage, Haley Hill, Halifax HX3 6DR, UK; Tel: 44(0)422 359 161; Fax: 44(0)422 355 604

September 19-21, 1994
4th IFAC Symposium on Robot Control (SY.RO.CO.'94), Capri, Italy
Contact: Prof. Salvatore Nicosia, SY.RO.CO.'94 Scientific Secretariat, Departimento di Ingegneria Elettronica, Universita' degli Stidi di Roma "Tor Vergata," Via della Ricerca Scientifica, 00133 Roma, Italy; Fax: +39-81-7683186*

October 11-15, 1994
American Orthotic and Prosthetic Association (AOPA), Annual National Assembly, Washington, DC
Contact: Annette Suriani, AOPA, 717 Pendleton St., Alexandria, VA 22314; Tel: (703) 836-7116

November 8-11, 1994
Third International Conference on Automation, Robotics, and Computer Vision, Singapore
Contact: Prof. N. Sundararajan, c/o UCARCV'94 Conference Secretariat, Institution of Engineers, Singapore, 70 Bukit Tinggi Rd., Singapore 1128, Republic of Singapore; Tel: 65-469-5000; Fax: 65-467-1108*

November 18-21, 1994
American Speech-Language-Hearing Association (ASHA), Annual Convention, New Orleans, LA
Contact: Frances Johnston, ASHA, 10801 Rockville Pike, Rockville, MD 20852; Tel: (301) 897-5700

December 7-10, 1994
8th International Conference on Biomedical Engineering, Singapore
Contact: The Secretary, 8th ICBME 1994, Department of Orthopaedic Surgery, National University Hospital, Lower Kent Ridge Rd., Singapore, 0511; Tel: (65) 772-4424; Fax: (65) 778-0720

1995

February 16-18, 1995
11th International Seating Symposium, Pittsburgh, PA
Contact: Elaine Trefler or Jill Bebout, University of Pittsburgh Medical Center, Department of Conference Management, Nese-Barkan Bldg., Suite 511, Pittsburgh, PA 15213-2593; Tel: 412-647-8218; Fax: 412-647-8222

March 27-31, 1995
International Federation of Physical Medicine and Rehabilitation (IFPMR), Sydney, Australia
Contact: Dianna Crebbin Conferences, PO Box 629, Willoughby NSW 2068, Australia; Tel: +61 (02) 417-8525; Fax: +61 (02) 417-8513

April 2-7, 1995
8th world Congress of the International Society for Prosthetics and Orthotics (ISPO), Melbourne, Australia
Contact: Congress Secretariat, PO Box 29, Parkville, Victoria, Australia 3052; Tel: +613-387-9955; Fax: +613-387-3120

July 9-16, 1995
4th World Congress of Neuroscience, Kyoto, Japan
Contact: Host Organizer, Secretariat, 4th World Congress of Neuroscience, c/o International Communications, Inc., Kasho Bldg., 2-14-9, Nihonbashi, Chuo-ku, Tokyo 103, Japan; Tel: 03-3272-7981; Fax: 03-3273-2445

November 17-20, 1995
American Speech-Language-Hearing Association (ASHA), Annual Convention, Cincinnati, OH
Contact: Frances Johnston, ASHA, 10801 Rockville Pike, Rockville, MD 20852; Tel: (301) 897-5700

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