Master Hearing Aids: Past and Present

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The term "master hearing aid" may be applied to any amplification system which offers a broad range of electroacoustic characteristics. Laboratory investigations employing master hearing aids typically have been directed toward either determining the frequency response patterns most appropriate for the majority of hearing-impaired listeners or compensating for a particular aspect of an individual's hearing impairment such as his threshold configuration. This paper describes features of master hearing aids used in investigations of both types. In addition, a protocol developed for use in the selection of the optimal characteristics of a wearable master hearing aid is presented.

In the process of selecting amplification for a hearing-impaired individual, the audiologist's primary concern is to insure that the hearing aid offers suitable electroacoustic characteristics, including an appropriate frequency response, adequate gain and sufficient limitation of the maximum power output. Audiologists may choose to recommend a specific hearing aid based on comparative measures of aided performance obtained by using some modification of Carhart's (1946) procedure or to devote themselves to counseling the hearing-impaired listener regarding the general characteristics of appropriate amplification and the criteria to be employed in hearing aid selection (Shore & Kramer, 1963). Independent of the method audiologists employ, they tend to be guided in the selection process by the results of experimental work with "master hearing aids" conducted more than thirty years ago.

In clinical settings, the term "master hearing aid" is generally applied to instruments which offer a broad range of readily manipulable electroacoustic characteristics comparable to those provided by commercially available hearing aids. Use of a master hearing aid is based on the rationale that the instrument permits the audiologist to select the optimum combination of electroacoustic characteristics for a given hearing-impaired listener without requiring maintenance of a large hearing aid inventory (Bergman, 1959). Following determination of the appropriate electroacoustic characteristics, the audiologist presumably can select, from among commercially available hearing aids, the hearing aid whose characteristics are most comparable to those judged appropriate. Berger (1976), in discussing the limited development and application of commercial master hearing aids, noted that hearing aid manufacturers have tended to develop and use such instruments exclusively for the selection of their own products by hearing aid dealers. Contributing to the limited use of master hearing aids by audiologists has been the observation that the amplification provided by those instruments typically is characterized by less distortion and lower internal noise than that provided by hearing aids. Therefore, critics maintain that the benefit to be derived from the use of a hearing aid cannot be assessed adequately using a master hearing aid (ASHA Report, 1967).

In laboratory settings, the term "master hearing aid" may be applied to any amplification system that offers a vareity of frequency responses, variable gain and a number of selectable maximum power output settings. Such amplification systems have found two primary research applications. First, investigators have used master hearing aids in the large scale testing of hearing-impaired individuals to determine, on average, the optimal hearing aid characteristics for individuals exhibiting hearing loss of a particular type, magnitude or configuration (Davis, Stevens, Nichols, Hudgins, Marquis, Peterson & Ross, 1947; Medical Research Council, 1947). Such research has led to the design of hearing aids which offer characteristics that are, in general, appropriate for a large portion of the hearing-impaired population.

Recently, master hearing aids have found a second application in research designed to determine the characteristics of a hearing aid that would be most suitable for a given hearing-impaired listener (Pascoe, 1975; Villchur, 1973). The goal in these investigations has been to compensate, in some way, for the particular characteristics of the individual's hearing loss either with respect to his audiometric configuration or to his responses to suprathreshold stimuli (e.g., loudness recruitment and/or a reduced dynamic range).

The application of master hearing aids to the systematic study of the effects of frequency response on the understanding of speech by hearing-impaired listeners was first pursued by Davis and his colleagues at the Harvard Psychoacoustics Laboratory (Davis et al., 1947) and by Littler and his associates on the Medical Research Council (MedResCo) in England (Medical Research Council, 1947) approximately thirty years ago. The frequent citation of their conclusions by critics of current hearing aid evaluation procedures (Chial & Hayes, 1974; Millin, 1975; Resnick & Becker, 1963; Shore, Bilger & Hirsh, 1960; Wilson & Linnell,

1972) provides evidence of their impact.

The two groups, employing slightly different procedures, reached startlingly similar conclusions. That is, they concluded that the majority of hearing-impaired listeners would receive appropriate amplification from a hearing aid which offered a tone control for selection of either uniform gain or increasing gain (at the rate of 5 or 6 dB/octave) as a function of frequency, with an upper frequency limit of 4000 Hz. The two groups differed only slightly with respect to the recommended low-frequency cutoff of the frequency response. The MedResCo report suggested the frequency response decrease below 750 Hz (at the rate of 12 dB/octave) while the Harvard report recommended the low-frequency cutoff be no higher than 500 Hz.

The similarities in the conclusions drawn by the two groups of investigators are not unanticipated when one considers the rationale underlying their investigative efforts that includes, 1) the patient population selected for study, and 2) the experimental apparatus, 3) the test materials, and 4) the experimental procedures employed. Time does not permit a detailed review of those aspects of the investigations. A critical review of those studies has been prepared for publication (Resnick, scheduled for publication). A brief discussion, however, of the essential features of the master hearing aids employed by the Harvard and MedResCo groups is in order.

The master hearing aids used by both the Harvard and MedResCo investigators offered limited frequency response characteristics. The amplification system employed by the Harvard group provided five "simple and 'smooth' frequency response characteristics" (Davis et al., 1947, p. 23). The laboratory amplifiers, filters and attenuators were arranged to provide frequency responses that were classified as flat, increasing at the rate of 6 dB or 12 dB per octave or decreasing at the rate of 6 or 12 dB per octave. The maximum power output was limited by symmetrical peak clipping and was selectable at approximately 115, 125 and 135 dB SPL. The maximum acoustic gain was 70 dB.

The amplification system employed by the MedResCo investigators was no more flexible than that used by the Harvard group. It offered a flat response to 5000 Hz and various low-frequency limits. After using that system to determine the reduction in the low frequency response below 750 Hz enhanced word identification, the investigators evaluated the effect of high-frequency emphasis using only two frequency response patterns: (a) a response that was flat to 3000 Hz and decreased at 18 dB/octave above that frequency, and (b) a response which offered increasing amplification as a function of frequency to an upper limit of 4000 with a sharp cutoff above 4000 Hz.

In both studies, the master hearing aids circumvented the effects of head diffraction and body baffle encountered with wearable amplification. The investigators at Harvard presented their speech materials live voice via a microphone that was maintained at a distance of 25 inches from the talker's mouth for most of the test conditions. The signal was then shaped, attenuated, amplified and delivered to the listener via supra-aural earphones. In the first stage of the MedResCo study, tape-recorded speech signals were processed by the amplifying system and presented to the listener via supra-aural earphones as well.

The alterations in the spectra of signals delivered by ear level and body aids as a consequence of head diffraction and body baffle have been documented in a number of studies and summarized by Olsen and Carhart (1975) and by Erber (1973). Although the implications of head diffraction, body baffle and real ear resonances have not been explored systematically, modification of the frequency response to compensate for the effects of head diffraction and real ear resonances has been reported to improve the identification of some test materials for some subjects (Pascoe, 1975).

Recognizing the possible significance of head diffraction effects, the MedResCo group used a method of specifying overall acoustic amplification which differed from that employed in the Harvard study and from the method in current use. That is, they incorporated a correction for head diffraction in combination with real ear resonance in specifying the frequency response. One must eliminate the correction in order to make the recommended frequency response of the MedResCo group comparable in form to that of the Harvard group. The frequency responses derived in this fashion suggest that both patterns recommended by the MedResCo group introduce a high-frequency emphasis but at rates of 5 dB/octave and 10 dB/octave as specified in a 3 cc coupler.

The matter is complicated further by the evidence that the frequency response measured in an artificial ear differs from that which is obtained in the real ear for either a supra-aural earphone or an insert receiver (Ewertsen, Ipsen & Nielsen, 1957; Shaw, 1966; van Eysbergen & Groen, 1959; Sachs & Burkhard, Note 1). It is unreasonable to assume that an amplification system which offers a flat frequency response in a 6 cc coupler and a system which delivers a flat response in a 2 cc coupler will produce identical frequency responses as measured at the tympanic membrane. Thus the flat and high-frequency emphasis response patterns recommended by the Harvard group may not be appropriate when the signal is delivered to the ear via an insert receiver coupled to the ear with an earmold of variable dimensions.

Among the number of factors which limit the generality of the conclusions drawn by the two groups of investigators is the basis on which individuals were selected for inclusion in the investigation. Both groups limited subject selection to individuals they believed, according to some unreported criteria, could benefit from amplification. The more than 200 subjects tested in the MedResCo study ranged in age from 10 to 70 years and 78% were over 39 years of age. However, 65% of the subjects were diagnosed as having a hearing loss "due to a disease of the conducting mechanism of the middle ear" (Medical Research Council, 1947, p. 57). In the Harvard study, several of the 18 subjects who participated had both ears tested, resulting in a total of 25 ears tested. The subjects ranged in age from 17 to 70 years; in that group conductive components were reported for 50% of the ears receiving otological examinations.

In the past thirty years, significant advances in the medical and surgical management of the middle ear disorders have reduced the proportion of hearing aid users whose loss is reported to be a consequence of middle ear pathology (Rosenberg, Note 2). Recent research in the area of hearing aids suggests that frequency responses which differ substantially from those recommended by the Harvard and MedResCo investigators may improve the understanding of speech for individuals with sensori-neural hearing loss characterized by a particular audiometric configuration or suprathreshold characteristic. Individuals with normal or near normal thresholds for frequencies below 1000 Hz and steeply sloping losses above that frequency have been reported to benefit from earmold modifications that produce a decrease in the low-frequency response of the hearing aid (Green & Ross, 1968; McClellan, 1967). Listeners with recruitment problems have been shown to benefit from frequency selective compression (Villchur, 1973; Yanick, 1976). Individuals with gently sloping sensori-neural hearing loss have been reported to profit from frequency response modifications which compensate for head diffraction and for changes in real ear resonances accompanying the use of an earmold (Pascoe, 1975).

Basically, the reports prepared by the Harvard Psychoacoustics Laboratory and by the Medical Research Council provide evidence that under conditions in which head diffraction and body baffle effects are eliminated and phonetically balanced word lists are presented monaurally (via supra-aural earphones) to hearing-impaired adults (at least 50% of whom demonstrate conductive involvements), the frequency response patterns resulting in the highest word identification are flat or introduce a high-frequency emphasis of 6 dB/octave (or 10 dB/octave) as specified in a 6 or 3 cc coupler. Under conditions more comparable to those of hearing aid use, the same conclusions may not apply.

Both Villchur (1973) and Pascoe (1975) employed master hearing aids in their individualized approaches to determining the optimal amplification for hearing-impaired listeners. Unlike the amplification systems used by the Harvard and MedResCo groups, the master hearing aids used by Villchur and Pascoe were not limited to simple frequency response patterns but were adjustable on an individual basis.

Villchur sought to compensate for disruptions in the loudness-intensity function (occurring in sensori-neural hearing loss) through the use of compression amplification. Recognizing that the extent of the disruption may vary with signal frequency, Villchur argued that it was theoretically possible to "restore normal loudness relationships to each acoustical element of importance to intelligibility" (1973, p. 1648) by adjustment of the compression ratio in an infinite number of frequency bands. The practical adaptation implemented by Villchur was an amplification system consisting of a two-band compressor followed by a multifilter for spectral shaping. The two-band compressor provided different compression ratios for the low and high-frequency bands into which the tape-recorded speech signal was split. The compression ratios in the two bands were adusted to compensate for the extent of the disruption in the loudness-intensity function.

Villchur estimated the extent of the disruption by determining the span between the hearing-impaired listener's threshold of audibility and a given equal loudness contour. The reference for the equal loudness contour was a 1000 Hz tone whose level placed it .57 of the distance between the listener's threshold of audibility and his threshold of discomfort. The reference was selected because .57 is the "proportionate distance between normal threshold and discomfort of the 1-k Hz, 74-dB peak speech level" (p. 1651). He compared the span for the hearing-impaired listener with the span between threshold and the 74 phon equal loudness contour for normally-hearing listeners. The ratio of those two spans determined the compression ratio for the particular listener. Equalization, or spectral shaping, was introduced to restore the spectrum of the compressed speech to an appropriate suprathreshold level. The shaping served to insure that the spectrum occupied a position with the range between the absolute threshold and the threshold of discomfort comparable to that for normal hearing listeners. Although the speech signals were tape-recorded, they had been recorded originally in a reverberant room using a microphone mounted "at ear position in a pinnaless replica of the human head" (p. 1651). Following processing, the signals were delivered via a TDH-39 earphone housed in a mounting developed by Villchur (1969) which reportedly simulates real ear listening conditions in a free field.

The identification of nonsense syllables by Villchur's six hearing impaired subjects for speech signals that had been subjected to compression in combination with spectral shaping was substantially better than for uncompressed highpass filtered speech. Subsequently, Yanick (1976) reported improved identification of key words in sentences for 24 hearing impaired listeners under comparable conditions of amplification. Drucker, Lawrence and Woodworth (1977) recently reported development of a two-band compression system utilizing a microprocessor which, although too large to be used as a hearing aid, may be used as a training device on a one-to-one basis or time-shared for use as a group amplification system.

Pascoe's master hearing aid employed head-mounted microphones, insert receivers and a multifilter which allowed the investigator to compensate for the amount of hearing loss, for head diffraction effects at the microphones and for alterations in ear canal resonance resulting from the use of an earmold. The frequency response of the system extended from 100 to 6300 Hz. Use of the multifilter permitted production of frequency responses that were defined with respect to gain as measured in a 2 cc coupler (coupler gain) or with respect to differences between the listener's aided and unaided noise-band thresholds in sound field (functional gain).

Pascoe reported that for his eight hearing impaired subjects (between 55 and 75 years of age) with gently sloping sensori-neural hearing losses, maximum word identification scores were not achieved with adjustments of the multifilter to produce coupler responses that were flat or increased at the rate of 6 dB/octave. Instead, he reported a significant improvement in scores on a 50 item closed-response monosyllabic word list (weighted with the voiceless plosives and voiceless fricatives frequently misidentified by hearing-impaired listeners) when the multifilter was adjusted to produce aided thresholds for noise-bands that were a constant level above the thresholds for normals (that is, at a "uniform hearing level").

Both Pascoe and Villchur have demonstrated the superiority of an individualized approach to the adjustment of a master hearing aid for selected subjects listening to specific materials under laboratory conditions.

The Communication Sciences Laboratory of the City University of New York is engaged in a project to develop a practical *clinical* protocol for th prescriptive fitting of a *wearable* master hearing aid. The project, supported under contract from the National Institutes of Health and directed by Harry Levitt, incorporates features of the two types of investigations employing master hearing aids which have been discussed to this point. I was affiliated with the project during the period from September, 1974 to June 1976, and now serve as a consultant. A brief description of the master hearing aid, the test materials employed for its prescriptive fitting and the protocol developed for use with the master hearing aid follows.

The wearable master hearing aid, designed and built by Bolt, Beranek and Newman, under contract to the National Institutes of Health, offers a broad range of readily manipulable hearing aid characteristics. The hearing aid is portable, thus permitting the hearing-impaired listener to use it in his general communication environment.

The hearing aid components, with the exception of the microphone and receiver, are housed in a case which measures approximately 6 inches by 3 inches and weighs less than 6 ounces. The microphone is affixed to a dummy ear level hearing aid, thereby approximating the absorbtion and reflection of sound energy caused by the head with conventional ear level aids. The sound energy impinging on the microphone is transduced to electrical energy, processed by the components in the hearing aid case and is finally transduced to an acoustic signal by a standard receiver. The receiver is coupled to the ear by a custom earmold, thus closely duplicating the ear canal resonance effects present with a conventional aid. Thus, despite its dimensions, the master hearing aid functions as an ear level rather than as a body aid.

Selection of the characteristics of the master hearing aid is affected by changing modules and component cards within the hearing aid case. Thus, selected characteristics of the hearing aid can be changed in a matter of seconds while maintaining all other hearing aid settings, as well as the microphone and receiver, constant.

The electroacoustic characteristics that are variable include the slope of the frequency response, the upper and lower cutoff frequencies, the maximum power output and the gain. The values of the slope of the frequency response range from a low frequency emphasis of -6 dB/octave to a high-frequency emphasis of 12 dB/octave in 3 dB/octave steps. The gain is selectable for values between about 30 and 80 dB. The maximum power output can be set between 110 and 130 dB SPL. The wearable master hearing aid has the capability of operating as an automatic gain control aid. It can be used as a true binaural hearing aid with independent microphones, amplifying systems and receivers for each ear, or as a CROS or BiCROS aid. To this point, evaluation has been limited (with one exception) to monaural fittings on experienced users of monaural amplification.

The number of manipulable hearing aid characteristics and the fact that the hearing aid parameters function in an interactive fashion make selection of the optimum characteristics for each subject a time-consuming task. Furthermore, although the primary interest is in assessing changes in speech understanding as a function of the hearing aid setting, tests of speech understanding in a current use are inadequate for distinguishing among hearing aid frequency response characteristics for a particular listener in a reliable way.

Efforts to develop tests for use in hearing aid evaluations have been directed primarily toward either: (a) increasing the difficulty of pre-existing tests through the simultaneous presentation of competing noise, or (b) developing monosyllabic word lists which are weighted with phonemes that are frequently misidentified by hearing-impaired listeners.

At the Communication Sciences Laboratory interest was directed toward development of a test for use in hearing aid evaluations which would permit analysis of the phoneme errors made by an individual under conditions of hearing aid use. A closed-response nonsense syllable test was developed for that purpose.

The Nonsense Syllable Test consists of consonant-vowel and vowel-consonant syllables organized into seven subtests of seven to nine syllables each. The subtests differ with respect to: (a) the class of consonants represented, that is voiced or voiceless, (b) the position of the consonants, and (c) the vowel context. No attempt was made to phonetically balance the test but a scoring system may be developed which assigns weights to phonemes in accord with their frequency of occurrence in spoken English.

The listener's response to a syllable within a given subtest is limited to syllables within the same subtest; the response foils correspond to all the syllables within the same subtest as the test item and include th most frequent perceptual confusions reported for normal-hearing listeners by Miller and Nicely (1955) and Wang and Bilger (1973) and for hearing-impaired listeners by Owens, Benedict and Schubert (1968). In a current version of the test, errors with respect to place and/or manner of articulation are possible; errors with respect to voicing are not. At Gallaudet we are investigating modification of the response forms and reconstruction of the subtests to permit analysis of voicing errors. The Test consists of 62 items and includes one repeat item in each module. Administration of the test requires approximately eight minutes.

The test has been recorded by a male and female speaker whose speech is without marked regional characteristics. Each syllable is presented in the carrier phrase "You will mark ____________ please." Attenuation was selectively introduced in the original recording in order to equate the level of the word "Mark" in the carrier phrase for each test item. Sixteen forms of the test (eight each of the male and of the female speaker) were produced by randomizing the order of syllables within subtests and the order of subtests within the test. This procedure permitted the production of eight lists for each speaker which are equated in difficulty by virtue of the fact they they contained identical items.

Additional investigation is necessary to determine whether the subtests and response foils are appropriate for a variety of clinical patients. The unpublished results of two investigations employing normal-hearing listeners (Resnick, Dubno, Hawie, Hoffnung, Freeman & Slosberg, Note 3; Resnick, Dubno, Hoffnung & Levitt, Note 4) suggested that the closed response nonsense syllable test is a useful technique as its use does not alter previously reported patterns in phoneme identification. Furthermore, the test has the advantage of being a practical clinical tool for the analysis of errors in phoneme identification by hearing-impaired listeners. Although time does not permit detailed reporting of the experimental data for hearing-impaired listeners, it is worthwhile to note that the error patterns of the hearing-impaired listeners appear to be idiosyncratic and to be differentially affected for the listeners by the various hearing aid settings. That is, the error patterns change in different ways for different listeners as a function of hearing aid setting.

In order to elicit the subjective evaluations of the hearing aid users a questionnaire was developed in which the user was asked to:

1. Report the percentage of time the aid was worn and the conditions under which he was satisfied or dissatisfied with its performance;
2. Rate—on an equal appearing interval scale—the clarity, naturalness and performance of the hearing aid, and, finally;
3. Rate the percentage of speech he believes he understood in a variety of situations.

To this point, I have described the wearable master hearing aid and the materials we have developed. I would like *now* to describe the basic features of the protocol being used. The protocol is currently undergoing revision.

The present protocol has four stages.Stage I is devoted to the acquisition of baseline audiometric data. Audiometric pure-tone and speech tests are administered, otoadmittance measurements are made and loudness discomfort levels as well as most comfortable listening levels are determined. Loudness discomfort levels are determined for ⅓ octave bands of noise centered at 250, 500, 1000, 2000 and 4000 Hz and presented via a loudspeaker in sound field. These estimates of the loudness discomfort levels are made while the listener is using the master hearing aid. For each listener, determination of the maximum power output setting is based on the loudness discomfort levels estimated at this time. Similarly, the most comfortable loudness levels for the noise bands provide the basis for our initial estimates of the gain suitable for the hearing aid user.

During Stage II the hearing aid user is exposed to an experimental test battery. He is tested under eight fixed experimental conditions using the master hearing aid to determine the effects of slope and frequency limits of the frequency response on the identification of nonsense syllables. The second stage has served two purposes. First, it has permitted determination of whether a variety of experimental factors such as signal-to-noise ratio and speaker gender and hearing aid characteristics exert comparable effects for all hearing aid users. Second, it provides an initial estimate of the best setting of the hearing aid with which to begin testing in Stage III.

During Stage III, the testing procedure is individualized as an attempt is made to converge on the best setting for each user. Successive adjustment of the hearing aid parameters are made according to a prescribed adaptive strategy. By an "adaptive strategy" we mean that adjustment of each hearing aid characteristic is dependent on scores obtained on the Nonsense Syllable Test with other settings of those same characteristics. The adaptive strategy takes into account minor daily variations in user performance and his adaptation to the hearing aid. The strategy is aimed at moving away from those settings (or combinations of settings) which produce low scores and toward those producing high scores. The rules for the adjustments are straightforward and are easy to apply. At present, the adaptive strategy is used to adjust only the slope and limits of the frequency response.

After the best setting has been determined, the subject's performance on a variety of tests using his own, clinically-selected hearing aid is compared with his performance using the experimentally selected master hearing aid setting. The electroacoustic characteristics of the two hearing aids are also compared. This is done in the final test session which constitutes Stage IV of the protocol. Aided and unaided noise-band thresholds are measured in an effort to determine whether a relationship exists, for these subjects, between the aided noise-band thresholds and the optimum setting of the wearable master hearing aid. The measurements are also part of an attempt to determine the frequency response of the hearing aid in the real ear.

In summary, the protocol developed for use with the wearable master hearing aid utilized measures of phoneme identification (obtained with a nonsense syllable test) to select from among a number of fixed electroacoustic characteristics those characteristics which are optimum for a particular listener as determined using an adaptive strategy.

Technological advances have made possible the design of master hearing aids for use in the laboratory which offer almost unlimited possibilities for the manipulation of their electroacoustic characteristics. Those advances are reflected in the commercial master hearing aids being developed (Blackledge, Halladay, Holmes, Lawrence & Stearns, Note 5).

Audiologists are, therefore, faced with the challenge of developing evaluative procedures which are sufficiently sensitive to permit the selection of the optimum electroacoustic characteristics.

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