The Need for Better Understanding of the Electroacoustical Characteristics of Hearing Aids by the Clinical Audiologist

Gregory W. Salyer
Gorgas Army Hospital
William J. Brown
University of Louisville

It has been our experience that hearing aid users are subject to differences in quality and performance of hearing aids which are not predictable on the specification data provided by the manufacturers. Various publications and research reports concerned with the technical performance of hearing aids are in only partial agreement as to the specific performance indices of value in predicting the superior electroacoustic characteristics. In the belief that the clinical audiologist must be aware of technical hearing aid performance and in order to provide the best care in his rehabilitative effort we have established a philosophy that all hearing aids kept in stock for hearing aid evaluation purposes must have a performance review in our laboratory. It is presently undetermined whether the hearing aid features being measured are the optimum for predicting help to the client. So the present report must be considered as a pilot study.

Another feature of the present topic has to do with cost and performance analysis which can be helpful to private or state agencies engaged in the provision of hearing aids for medically indigent people. In the state of Kentucky there are three state agencies with an established policy of providing hearing aids for individuals meeting the requirements of that particular agency. These are the Kentucky Bureau of Rehabilitation Services, the Kentucky Commission for Handicapped Children, and the Kentucky Medical Assistance Program (medicaid). These agencies are purchasing several hundred hearing aids annually and need facts regarding the efficacy of their respective hearing aid programs. The selection of hearing aids on the local market is different from the national sample as analyzed by the very excellent Veterans Administration Program. Necessity demands that the individual clinic or local groups in some way develop a hearing aid technical analysis program.

The Veterans Administration considers price as one of the determining factors for hearing aid selection (Veterans Administration, 1971, p. 26) and hearing aid cost is considered at other clinics (Shore, et al., 1960). It is not certain that the more expensive hearing aid has better electroacoustical features than the less costly aid. The present paper will present preliminary data on the performance of more and less expensive aids on three electroacoustical measures. This information is from an unpublished thesis by Salyer (1973).

The hearing aid evaluation exists today as a very controversial aspect of clinical audiology. This same statement was made in 1950 (Carhart, 1950) which means the problem has been the center of controversy for about the entire time audiology has been a profession. The conventional hearing aid evaluation consists of having hearing impaired clients listen to speech test materials with a number of different aids. Speech reception thresholds, discrimination scores for monosyllabic words, most comfortable listening levels, and tolerance levels are obtained for the client with each aid, and the aid with which the best performance is achieved is usually recommended for purchase. The controversy attacks the basic premise of the hearing aid evaluation, questioning whether the procedure is necessary, even the accuracy of the tests. Some audiologists advocate reserving the conventional hearing aid evaluation for the problem case type of client (Shore, et al., 1960) (Davis, et. al., 1946). Others recommend the test for all clients who need amplification (McConnell, et. al., 1960) (Berger and Millin, 1971) (Jeffers, 1960). However, both groups agree on one issue, that being the awareness of the electroacoustic characteristics of the hearing aid that the client eventually wears.

At the WHAS Crusade Audiology and Speech Pathology Center in Louisville, Kentucky, conventional hearing aid evaluations are employed for the selection of aids with which the Clinic's hearing impaired clients are fitted. Measurements are made of the electroacoustic features of the recommended aids, and these measurements checked for changes when clients return for annual re-evaluations. Advocates of the hearing aid evaluation recommend this knowledge of the physical performance of hearing aids as a supporting element for the test procedure and rehabilitation program. Other audiologists not only recognize the electroacoustical meausres to be important, but believe them to be so valuable that their realization may be substituted for the conventional hearing aid evaluation. Shore, Davis, and their associates feel an awareness of the exact physical performance of each hearing aid available to a clinical setting will allow the audiologist to match a client's audiogram with an appropriate aid. All the audiologist need do is describe the general electroacoustic characteristics needed in the hearing aid and send the "prescription" with the client to the hearing aid dealer. Both sides of the controversy do recognize the value of electroacoustical measurements of hearing aid performance. Research shows disagreement as to exactly how influential electroacoustical characteristics are to the intelligibility os speech achieved with an aid.

Three specific measurements emerge as being significantly important to the success achieved with a hearing aid by a hearing impaired person. These physical characteristics are (1) the smoothness of the frequency response curve, (2) the distortion level, and (3) the influence of hearing aid gain control rotation on acoustic gain. The thesis by Salyer (1973) measured these three electroacoustic characteristics in two groups of hearing aids, one being more expensive in retail cost than the other. Comparisons were made between the two categories of aids on only these three measures. No attempts were in-tended at establishing one group to be superior to the other in overall performance.

Kasten, Letterman, and Revoile (1967) examined variability in full-on gain versus frequency-response curves of 15 samples of each of 10 different hearing aid models (150 aids) and compared the average full-on gain measurements they obtained with specifications published by the manufacturers. A Bruel and Kjaer audio-frequency analyzer was used to perform all measurements. Results of this study show that wide discrepancies sometimes exist in both gain and output configuration between response curves of aids used in the study and response curves provided by the manufacturers. About one-half of the aids showed good intragroup consistency across the entire amplification range, while the other half demonstrated a large degree of variability of gain characteristics. The variability found in the aids of a model was independent of how closely the mean gain versus frequency curve obtained in the study approximated the data published by the manufacturer.

Kasten and Revoile (1965) had earlier compared the actual response characteristics of specific aids to manufacturers' specifications. Hearing aids tested included fifteen aids of each model under test and the types of aids consisted of eyeglass, behind the ear, and body models.

Considerable variation was noted in the performance characteristics of the fifteen samples of each model tested. The performance of some aids closely agreed with the manufacturers' specifications whereas some differed to the extent that the manufacturers' specifications were not at all descriptive of the actual performance of the aid.

The need for electroacoustical measurements also exists because new aids are on occasion found to be defective performance-wise. Zink (1972) conducted a two-year longitudinal electroacoustic hearing aid evaluation program in which new hearing aids obtained through hearing aid dealers were analyzed. During the school year 1970-71, seventy-five hearing aids were analyzed, after which forty (53 percent) were classed as acceptable and thirty-five (47 percent) were classed as unacceptable. The primary reason for unacceptability was distortion, which affected thirty-two aids (91 percent). Distortion was followed by frequency response (19 aids or 54 percent), then gain/MPO (8 aids or 23 percent), and gain control variability (2 aids or 6 percent).

During the 1971-72 school year, a smaller sampling of new aids (26) was evaluated. The results indicated that 19 (73 percent) were acceptable and 7 (27 percent were unacceptable). Two (29 percent) of the unacceptable hearing aids were unacceptable because of frequency response limitations, two (29 percent) were unacceptable because of gain/MPO limitations, and only one aid (14 percent) was unacceptable because of distortion. An increased acceptance rate of 20 percent was found in the 1971-72 sampling of new hearing aids. It was Zink's impression that the cause of the 20 percent increased acceptance rate in the 1971-72 sampling was due to dealers being more selective in the aids they supplied for the study and because the aids were from more current hearing aid inventories.

Hearing aids available on the market today differ substantially in the fidelity with which they make speech louder. These differences among the aids are of course the electroacoustical variations from aid to aid. Just how important to the intelligibility of hearing aid amplified speech are these electroacoustic characteristics? One means of investigating this question is to employ aids with a wide range of electroacoustic characterists and record speech through the different aids, then have subjects compare the fidelity of the hearing aids. Jerger (1967), used such a method and concluded from his research the following:

1. There are behavioral correlates of hearing aid performance.
2. The electroacoustic characteristics of hearing aids affect the intelligibility of speech for normal listeners as well, much as for hearing impaired listeners.
3. Behavioral performances by the subjects indicate that no significant interaction exists between aids and type or degree of hearing impairment, so the best aid for one person is the best for anyone.
4. Just because a person is an ideal candidate for amplification (mild, flat conductive loss) does not mean the electroacoustical differences between aids are less important than for the problem case (severe, sloping sensori-neural loss).
5. The use of a behavioral task based on intermodulation distortion as a substitute for speech materials may be employed in the hearing aid evaluation.

The effects of electroacoustic characteristics of hearing aids on speech understanding was the subject for a research study conducted at the Houston Speech and Hearing Center by Jerger and Thelin (1963). The frequency response, effective bandwidth, and the distortion in twenty-one sample hearing aids was measured with Bruel and Kjaer equipment. Ten of the aids were body type and ten were ear-level aids. One hearing aid was of the eye glass nature. The aids were felt to be representative of the commercially available aids on the market. They possessed frequency responses ranging from smooth, flat traces to jagged, falling configurations. Differences in effective bandwidth and distortion also existed among the aids composing the sample.

Subjects receiving the synthetic sentence identification (SSI) listened to the taped sentences, with the competing message test for speech understanding being presented 12 dB louder at the same time, then attempted to identify the test sentence from a group of ten sentences written on a panel before them. The percentage of correctly identified sentences played through each of the 21 sample aids determined the person's SSI scores for that particular hearing aid. Three separate experiments were conducted employing the SSI method for determining the relationship between electroacoustical characteristics and behavior test results.

Normal hearing subjects participating in the first experiment achieved SSI scores for the 21 hearing aids which, when analyzed, revealed which electroacoustic parameters were most important for speech intelligibility achieved with a hearing aid. The smoothness of the response curve was most highly correlated with the SSI score obtained by the listener. The index of frequency response irregularity (IRI) of a hearing aid determined the ability the normal hearing listeners achieved in speech understanding with the aid. Jerger and Thelin concluded from research that the difference in IRI values among hearing aids may be so important to speech understanding that it "effectively obscures the effects of variation in other physical dimensions" (p. 183).

The smoothness of the frequency response curve is also considered important to speech intelligibility achieved with a hearing aid by the Veterans Administration. Their measurement of smoothness is performed at discrete frequencies however, and irregularities between measured points are missed. Jerger's IRI value is concerned with irregularities in the response, not just the uniformity of slope.

The discovery of the importance of the IRI value was actually made while examining the influence bandwidth had upon speech intelligibility. Positive correlations were found between high SSI scores and effective bandwidths below 1000 Hz. Not only were lower correlations found for the bandwidths above 1000 Hz, an actual negative correlation was disclosed. This finding initiated a search for the reason for the negative correlation and the investigators found that the response curves above 1000 Hz were jagged in those aids with the negative correlations. The bandwidth above 1000 Hz, even with a smooth response curve, did not help the subject attain a high SSI score. In many cases, because of the poor IRI value, the upper bandwidth hurt the subject's SSI score.

Jerger and Thelin's research disclosed evidence that distortion in hearing aids is not a significant source of degradation in speech intelligibility. Correlation coefficients between distortion and the SSI were actually negative for practically every case. This finding by Jerger and Thelin was in direct contradiction to earlier research conclusions by Jerger himself (Jerger, Speaks, and Malmquist, 1966) and others (Kasten, Lotterman, and Burnett, 1967; Harris, Haines, Kelsey, and Clack, 1961). Jerger explained the contradiction by saying that the distortion measurements made in earlier studies were not performed under comparable circumstances for all aids. Jerger and Thelin subjected all 21 sample aids to the same input signals after each aid's gain had been set by a common rule.

The importance of frequency response to speech intelligibility for hearing aid produced speech was realized as early as 1946, evidenced by the emphasis it received in the often mentioned "Harvard Report." The results of the investigation led the researchers to make certain recommendations for standards of hearing aid electroacoustical performance (Davis et al., 1946). Among their recommendations were suggestions concerning frequency response and slope.

These were:

1. Frequency Response
   a. The lower limits of the range be between 200 and 400 Hz, preferably at 300 Hz.
   b. The upper limit should be no lower than 3000 Hz, and 4000 Hz is preferable.
   c. The cut off at the lower limit should be at least 10 dB per octave.
   d. The frequency response can fall off as abruptly as possible at the upper limits.
   e. There should not be sharp peaks or valleys in the frequency response.
2. Frequency Slope
   a. The slope of the response curve should be smooth without jagged, irregular traces.
   b. The frequency response should be flat or a gradual rise of not more than 1 dB per octave, with an alternative slope having a smooth rise of 6 or 7 dB per octave toward the high frequencies.

Acoustic gain is one of the most important electroacoustical characteristics of a hearing aid. Natural speech must be made louder if the hearing aid subject is to have his hearing sensitivity improved. Manufacturers usually make gain specifications for their aids at a full-on control setting with a 50 dB SPL input level and this does not represent the actual gain a client will achieve with his aid (Lotterman, Kasten, and Revoile, 1967). Carhart pointed out the need for reserve gain, and high levels of distortion in the upper half of the gain control have been shown by research. These two findings encourage the hearing aid user to select a hearing aid for use which will have a most comfortable listening level that is located somewhere in the middle of the dial rather than at the top. Lotterman, Kasten, and Revoile (1967) found that there is usually about 10.4 dB difference in the amount of gain of the hearing aid and the threshold improvement of the hearing aid user. Thus, an aid with 40 dB of gain at the most comfortable listening level of a client will provide that person with about 29.6 dB of threshold of improvement.

Reserve gain refers to the amount of gain potentially left in the hearing aid, or that amount of gain that is still available to the wearer. Carhart (1946a) emphasized the necessity of having some reserve gain that could be used by the hearing aid wearer in certain listening situations. The volume control potentiometer should have a range of at least 40 dB (Davis et al., 1946). The hearing aid user should be able to set the volume control at a most comfortable listening level, which would not correspond to the complete rotation of the volume control dial. In the clinical test situation, the audiologist may assume that the client can accurately determine the most comfortable listening level on the dial himself. Carhart (1946b) checked for test-retest reliablility for the comfort level method for hearing aid settings, and concluded that it was a justifiable procedure of setting gain control on a psychophysical basis.

It is important that the audiologist realize how much reserve gain is available to the hearing aid client after the subject has selected his most comfortable listening level. In order to achieve this knowledge of the hearing aid, the exact range of the potentiometer and the percentage of total gain represented by different gain control dial positions must be realized.

Sixteen manufacturers of hearing aids donated a total of 33 aids to a study of the influence of hearing aid gain control rotation on acoustic gain (Kasten and Lotterman, 1969). The aids were catergorized as either average gain (between 25 and 45 dB) or high gain (over 45 dB). Thirteen aids composed the former group, and 20 hearing aids formed the latter group. Gain was determined as the mean of 500, 1000, and 2,000 Hz. Bruel and Kjaer hearing aid test equipment was employed by the examiners. The aids were placed individually in the Hearing Aid Test Box 4112 and a 70 dB SPL input signal was introduced and maintained throughout the spectrum. Eight different gain control settings were measured. Each setting represented 12 1/2 percent of the maximum rotation. These settings were examined at 500, 1000, and 2000 Hz. In both the average and high gain groups there was much less change in gain in the upper half of the rotation dial than in the lower half. For the 13 aids in the average group, the median acoustic gain for a full-on setting was 42 dB. With the gain control setting at 50 percent on, the median acoustic gain was 31 dB (74 percent of the total gain), and when the gain control was set at 25 percent, 21 dB or 50 percent of the total gain was achieved. Kasten and Lotterman found the median full-on gain value to be 60 dB for the high-gain aids. At 50 percent rotation, only 13 dB of reserve gain remained as the median. Positioning the gain control dial at 25 percent on left 26 dB of reserve gain, or 43 percent of the total gain. So for the 20 sample aids with more than 45 dB of gain, practically all (78.4 percent) of the gain was achieved the the lower half of the gain control dial.

A considerable amount of variability in taper characteristics for both groups was disclosed. Part of the reason for this was the difference in the range of the potentiometers used for the volume controls. If an aid has 60 dB of gain, there is no practical reason for a gain control position to equal the minumum amount of gain. Kasten and Lotterman found however, that in some of the aids used in their study, the bottom of the potentiometer range was equivalent to too much gain, leaving plenty of control dial to be maneuvered but little reserve gain to be manipulated. Consequently, an aid might have 60 dB of gain, but the potentiometer a range of only 20 dB, thus the hearing aid user could only choose between 40 dB and 60 dB for such an aid. Kasten and Lotterman recommended that audiologists be aware of the exact range of their hearing aids volume control dial. Also recommended was a familiarization by the audiologist of the taper characteristics of the hearing aids on hand.

Lotterman and Kasten (1967) employed Bruel and Kjaer equipment to investigate the relationship of gain control setting to nonlinear distortion. Thirty-five different hearing aids, (17 of which were body type aids and 18 of which were eyeglass or ear level aids) were randomly selected from over 300 aids. The total possible amount of rotation of the gain control knob of each hearing aid was divided into eight equal sections, each representing 12.5 percent of the total possible rotation. Frequencies at which measurements were made were 500, 800, and 900 Hz as stated by the American Standards for the measurement of hearing aid characteristics (ASA S3.3-1960) and at 70dB SPL.

The HAIC Standard Method of Expressing Hearing-Aid Performance (1961) makes no recommendations for the methods to measure or report distortion levels in hearing aids, so even though some hearing aid manufacturers do publish distortion figures for their hearing aids, seldom are the conditions or methods of the measurements included. The need for standards can thus be realized.

A study was undertaken by Lotterman and Kasten (1967b) to examine nonlinear distortion in new modern hearing aids. The hear-aids were tested by the Sound Section of the National Bureau of Standards. The gain of the hearing aid was set by placing the aid in an anechoic chamber and presenting sweep frequency pure tone input signals held at 62.5 dB SPL at the face of the microphone of the hearing aid. The gain control was set at the highest point at hich harmonic distortion would not exceed 10 percent at any frequency. The signal input level was then increased to 75 dB SPL while the gain of the aid was held constant, and harmonic distortion was read at 500, 700, and 900 Hz. The frequency of maximum distortion and its magnitude were also determined for each hearing aid.

Body type hearing aids, or hearing aids with external receivers, generally displayed greater distortion values than ear level hearing aids, or instruments with internal receivers. The frequency of maximum distortion generally fell below 1000 Hz for body type aids, with a range from 5 percent to 62 percent. The frequency of maximum distortion generally fell above 1000 Hz for earlevel aids, with a range from about 5 percent to 80 percent.

At the present time, manufacturers provide sample hearing aids to most university and hospital clinics for hearing aid evaluations of clients under the assumption that the performance of the hearing aid actually purchased will be nearly identical to the sample aid upon which the recommendation is based. In a study to determine the validity of this assumption, Lotterman and Farrar (1965) examined nonlinear distortion in 150 new hearing aids obtained from eight manufacturers. Ten ear and body level hearing aid models were chosen for the study. In testing each hearing aid, high gain settings carried considerably more distortion than lower gain settings and it was not uncommon to find extreme levels of nonlinear distortion in aids at high gain settings relative to low gain settings. Lotterman and Farrar found a great deal of variability among not only the different models but also among various samples of the same model. Therefore, nonlinear distortion present in one aid does not truly represent distortion present in other aids of the same model.

Kasten and Lotterman (1967) examined the distortion levels in 1170 new hearing aids over a period of six years, from 1962 to 1967. All the hearing aids had been submitted for contract evaluation to the Veterans Administration. The aids were divided into three categories, mild (32 to 53 dB average gain), moderate (42 to 63 dB), and strong (more than 59 dB average gain). The investigators used 62.5 dB SPL input and set the gain control of each aid so that distortion was less than 10 percent at all amplified frequencies.

The results of the study revealed more distortion in the mild category of hearing aids than the other two groups. This mild category was composed of mostly ear level hearing aids. The moderate category possessed the second highest level of distortion, and this group of aids was composed of about equal number of ear level and body type aids. The strong category of aids was made up mostly of body type hearing aids. Another finding of the study was that distortion levels for the hearing aids submitted in 1967 were no better than those levels found in the 1962 hearing aids, suggesting little improvement in the quality of the aids in terms of elimination of distortion. Distortion levels were essentially greater at 500 Hz than 700 or 900 Hz for each year's submitted hearing aids.

Research has disclosed the presence of distortion in new hearing aids. In the study by Jerger and Thelin reviewed earlier, the importance of distortion as an influence of speech intelligibility was minimized. Not all investigators in the field of hearing aid research agree with Jerger and Thelin.

Bode and Kasten (1971) conducted an experiment to examine the effects of hearing aid distortion on speech discrimination, especially consonant identification in noise. Consonant identification scores were objectively obtained from 34 normal hearing college students who listened and responded to material that had been processed through a body type hearing aid placed under realistic input conditions. Arbitrary distortion levels were specified by the average harmonic distortion acquired by separate input signals of 500, 700, and 900 Hz. By systematic rotation of the aid's volume control until desired levels of nonlinearity were achieved, distortion levels were obtained. After the hearing aid was adjusted to arbitrary harmonic distortion levels, tape recorded speech in noise was played through the hearing aid to the listeners during listening trials at constant sensation level of 70 dB SPL simulating conversational intensities. Volume control rotation during the five experimental hearing aid conditions (high fidelity, A, B, C, D) was 60 to 100 percent. The first hearing aid condition was high fidelity which was the measurement system without a hearing aid and in which the average harmonic distortion was less than 1 percent. Other types of distortion, such as harmonic distortion, intermodulation, transient, and spectral changes were possibly operating during the measurement and test procedures and were labelled A, B, C, D. Measured distortion under hearing aid condition A was 5 percent, B was 15 percent, C was 25 percent, and D was 35 percent. By comparing the frequency response tracings for each distortion condition, it was seen that as gain was increased the aid was driven to saturation with resulting slight changes in the spectrum shape. Frequency responses of hearing aid distortion condition A (harmonic distortion) and D (spectral changes) showed that with an increase in output, there was a relative increase in low-frequency response and a decrease in high-frequency response. Harmonic distortion increased considerably as a function of hearing aid distortion conditions A through D, while the frequency range decreased slightly, especially at the high-frequency limits.

Harris, Haines, Kelsey, and Clack (1961) investigated the influence of electroacoustic characteristics of hearing aids and the speech intelligibility achieved with the aids. They also attempted to rank the electroacoustic characteristics in order of importance. The specific electroacoustic characteristics investigated included distortion, frequency range, frequency response, and signal to noise ratio. Twenty normal hearing and 20 hearing-impaired people served as subjects. One hundred colloquial sentences, representing the general phonemic content of English, were distorted in three ways, then fed through 10 sample hearing aids and tape recorded. The resulting tapes were listened to by 40 subjects. The investigators concluded from their research that there is dependence of intelligibility on some of the electroacoustic characteristics of hearing aids. Distortion was disclosed as being most closely associated with intelligibility. The authors concluded that the frequency range of a hearing aid is significantly associated with intelligibility. The frequency responses of all the sample aids used in the study were flat enough to provide adequate intelligibility.

Another study which disclosed distortion as being directly related to unintelligibility of speech produced by a hearing aid was performed by Jerger, Speaks, and Malmquist (1966). Sentences were tape recorded through three different hearing aid conditions and then played to both normal hearing and hearing-impaired subjects. Both groups were able to identify the sentences played through the less distorted hearing aid condition best. The percentage of correctly identified sentences for the subjects was inversely proportional to the amount of distortion in sentence condition. Thirty-six hearing-impaired subjects, representing all types, degrees, and configurations of losses, then listened to the taped sentences. Once again the hearing aid conditions were ranked inversely proportional to the amount of distortion. The researchers concluded that distortion in a hearing aid will reduce the efficiency of that aid to reproduce clear, intelligible speech.

Electroacoustical measurement of hearing aids is necessary because of the inadequacies in manufacturer-supplier data sheets and faulty performances in many new hearing aids. Electroacoustical differences among hearing aids can be determined by behavior tasks assigned to subjects as well as by electronic measurements. The literature reviewed here points out the direct relationship between the intelligibility of speech achieved with hearing aids and three specific characteristics: (1) the smoothness of the frequency response curve (measured by the IRI), (2) total distortion, and (3) the influence of the volume control rotation on acoustic gain.

METHODS AND PROCEDURES

The criterion for selection of hearing aids, classification of hearing aids, equipment used, and procedures for measurements are presented.

Criterion For Hearing Aid Selection. The hearing aid sample used for this study consisted of the total population of hearing aids available to the Center. Twenty-two ear-level, 19 body-type, and three eyeglass-mounted aids made up the sample. This selection of aids was felt to be representative of the supply of aids usually on hand. All the hearing aids were employed as clinical test instruments and were on loan from local hearing aid dealers. All of the hearing aids had been serviced within the year and were judged to be in good working condition.

Classification of Hearing Aids. The retail price for each aid used in the study was obtained from the hearing aid dealer who had placed the aid at the Clinic as a sample test instrument. The hearing aids were rank ordered according to price. Two categories of hearing aids were established by finding the median price of the aids ($349.50), and terming those aids which cost more than the median, "Category A" and those aids which cost less than the median, "Category B". The mean price of the aids in Category A was $377.96 and in Category B the mean price was $296.46. The mean price of the total population was $337.21. Category A consisted of two eyeglass, 12 ear level, and eight body type hearing aids, while one eyeglass, 12 ear level, and nine body aids were in Category B.

Equipment. A Bruel and Kjaer hearing aid test system was used to perform the electroacoustical measurements for this study. The various components were a Type 1022 beat frequency ocsillator, Type 4212 hearing aid test box, Type 2606 measuring amplifier, Type 2107 frequency analyzer, and Type 2305 graphic level recorder.

Frequency Response. The Index of Response Irregularity (IRI) as defined by Jerger and Thelin (1968) was calculated for each hearing aid. This measure of the smoothness, or regularity of the response curve, was judged by its developers to be the most significant electroacoustical characteristic influencing speech understanding.

Distortion. A 1000 Hz input signal of 75 dB SPL was introduced into the anechoic chamber, and the gain adjusted to the hearing aid so that the output of the aid was 80 dB, or as close to this level as possible. The 1000 Hz frequency was eliminated from the hearing aid's output by the filter in the Type 2107 analyzer. The sound pressure level of the remaining tone at the output of the aid was read in dB directly from the meter scale of the analyzer. This total distortion measurement was done at 500, 700, and 900 Hz (Lybarger, 1961). The distortion levels for these three frequencies were averaged, providing the "Total Distortion" for the hearing aid.

Influence of Volume Control on Acoustic Gain. The third electroacoustic characteristic measured in the study was linearity of change in gain. As previously mentioned, a problem in the area of hearing aid "fitting" that the audiologist often experiences is the lack of change in acoustic gain when the volume control dial is moved from one setting to another. Sometimes most of the gain has been utilized by the wearer of an aid when the gain rotation is only positioned at half-on, leaving little reserve gain to be manipulated, even though a great deal of the volume control dial is left. This study measured the gain versus volume control linearity in the following manner:

1. An input signal of 50 dB was fed to a hearing aid stationed in the anechoic chamber.
2. The gain control was set at full-on and the resulting frequency response charted.
3. The average gain at 500, 1000, and 2000 Hz was computed.
4. The same precedure was performed with the volume control set at three-fourths, one-half, and one-fourth on.
5. The resulting average gain for each volume control setting was compared.

RESULTS

The more expensive hearing aids (Category A) were compared to the less expensive aids (Category B) in terms of their performance on the three electroacoustical characteristics. Body and ear level aids were compared in the same manner.

No significant difference (t=-.17) on IRI occurred between the two price categories of hearing aids (Table I). In addition, the product moment correlation (Table II) between IRI and price was .24 for the ear level hearing aids, and was -.45 for the body aids. The correlation for the body aids was almost significant at the .05 level.

TABLE I

t Values for Total Distortion and IRI Comparisons Between Category A and Category B Hearing Aids.

Total Distortion:

Group	Number	Mean	Variance	St. Deviation	t
Category A	22	4.50	6.39	2.53	-2.6808*
Category B	22	7.80	25.25	5.03	

IRI:

Group	Number	Mean	Variance	St. Deviation	t
Category A	22	17.59	249.02	15.78	- .1737**
Category B	22	18.45	269.78	16.43	

* Significant at .05 level
** Not significant at .05 level

Table I shows a significant t value of -2.68 ($p<.05$) between the two price categories on mean total distortion scores. This finding is further supported by a significant correlation ($r=-.42$, $p<.01$) between price and total distortion, indicating that the more expensive hearing aids had less distortion. A significant correlation ($r=-.60$) also occurred between price and total distortion for the body aids, but no significant relationship ($r=-.12$) between price and distortion occurred for the ear level aids.

Table II shows there was no significant correlation (r=-.09) between the IRI values and total distortion scores of the hearing aids.

TABLE II

Correlation Matrix for Price, IRI, and Total Distortion of the Fourty-four Hearing Aids used in the study, and Separate Matrixes for the Fourty-four Aids as Body and Ear Level Types.

Total Population (All 44 Aids):

	Price	IRI	Total Distortion
Price	1.0	.069*	-.409**
IRI		1.0	-.087*
Total Distortion			1.0
Mean	337.20	18.02	6 15
Standard Deviation	57.19	15.92	4.36

Body Aids (17 Hearing Aids):

	Price	IRI	Total Distortion
Price	1.0	-.4488*	-.6024***
IRI		1.0	.1441*
Total Distortion			1.0
Mean	325.88	9.47	6.88
Standard Deviation	7.186	8.40	5.12

Ear Level Aids (24 Hearing Aids):

	Price	IRI	Total Distortion
Price	1.0	.2431*	-.1193*
IRI		1.0	-.1807*
Total Distortion			1.0
Mean	343.67	25.38	5.93
Standard Deviation	48.25	17.30	3.83

* Not significant at .05 level
** Significant at .01 level
*** Significant at .05 level

The percentages in Table III show very poor linearity of change in gain for both price categories. The only significant difference between the two categories occurred at the one-fourth volume setting. The most expensive hearing aids provided 60 percent of their total gain while the less expensive aids offered a more linear 40 percent at the first setting. The remaining three settings failed to show any significant difference between the categories. Both categories of hearing aids provided too much gain in the lower half of the volume control dial.

Comparisons were also made between body and ear aids on IRI, total distortion, and linearity of change in acoustic gain. Eyeglass aids were not included in the comparison because of the small sample. There was a significant difference ($t=3.42$, $p<.01$) between body and ear level aids on IRI, with body aids having better IRI values than

TABLE III

Mean Percent of Total Gain at Four Volume Control Settings for Various Groupings of the Forty-four Hearing Aids Used in the Study.

	Total Population	Category "A"	Category "B"	Body Type	Ear Level Type
1/4	52.86%	60.53%	40.04%	53.85%	47.42%
1/2	73.88%	78.05%	70.19%	74.65%	67.69%
3/4	88.72%	90.76%	86.91%	88.91%	85.79%
Full-on	100.00%	100.00%	100.00%	100.00%	100.00%

ear level aids (Table IV). The mean IRI of the body aids was 9.49, compared to a mean of 25.38 for the ear aids. However, on total distortion there was no difference between body and ear level hearing aids (Table IV). No significant difference occurred between body and ear level hearing aids on the linearity of change in acoustic gain. Table III reveals that both types provided nearly half of their total gain at only one-quarter volume setting.

TABLE IV

t Values for Total Distortion and IRI Comparisons Between Body and Ear Level Type Hearing Aids Used in the Study.

Total Distortion:

Group	Number	Mean	Variance	St. Deviation	t
Body	17	6.88	26.19	5.12	.6706*
Ear Level	24	5.92	14.68	3.83	

IRI:

Group	Number	Mean	Variance	St. Deviation	t
Body	17	9.47	70.63	8.40	-3.422**
Ear Level	24	25.38	299.20	17.29	

* Not significant at .05 level
** Significant at .01 level

There was a positive relationship between price and total distortion for the body aids, but not for the ear level aids. The body aids possessed better IRI values than the ear level type hearing aids.

SUMMARY AND CONCLUSION

The present study was designed to investigate a comparison of higher versus lower priced hearing aids. Three electroacoustical measurements were employed in making the comparisons. The irregularity of the frequency response curve, total distortion, and the relationship of volume control setting to acoustic gain were selected as measures on which the comparisons could be made. Literature in the hearing aid research field names these three electroacoustical characteristics as being some of the most influential amplification characteristics on speech intelligibility achieved with a hearing aid.

Specific questions examined were: (1) Given some difference in price of a hearing aid, will there be a significant difference in the irregularity of the response curve (IRI), total distortion, or relationship of volume control to acoustic gain? (2) Given some difference in the IRI of a hearing aid, will there be a significant difference in total distortion? 3) Is there any significant difference between body and ear level type hearing aids for IRI, total distortion, or volume control-acoustic gain relationship?

A significant relationship was found to exist between the price of a hearing aid and its total distortion. The amount of total distortion tended to become less as the price of the aid went up. No such relationship existed between price and IRI or linearity of change in gain. The correlation between price and IRI for body aids was close enough to being statistically significant at the .05 level to indicate a significant correlation might occur if a larger sample was studied. No significant correlation was discovered to exist for IRI and total distortion relationships. Body aids were found to be significantly better than ear level aids for IRI, but no difference between the two types occurred for total distortion and volume control-acoustic gain influence.

The conclusions lead to several implications. Given, from the literature, that the IRI, total distortion, and relationship between volume control and acoustic gain do affect the intelligibility of speech achieved with a hearing aid, the audiologist should be aware of the exact performance of each hearing aid in the clinic on these three electroacoustical characteristics. Price cannot always be used as an estimate of the aid's performance, for cheaper hearing aids often display equality of performance for IRI and linearity of change in gain. Neither can the manufacturer-supplied hearing aid spec sheets be followed faithfully, because of incomplete, and often inaccurate data. Thus, the audiologist must himself be able to measure hearing aid performance.

Following such performance measurements, the audiologist should be able to scientifically identify the hearing aids with the superior electroacoustic characteristics. According to hearing aid research literature these "superior" aids should provide better speech intelligibility for the hearing aid user than the aids with the poorer electroacoustic features. The IRI, total distortion, and linearity of change in gain characteristics of the hearing aids in a clinic's available supply should be leading factors to be considered by the audiologist when he is determining which aid to recommend to a hearing impaired client.

There are audiological cases, such as some children and mentally retarded individuals, in which conventional hearing aid evaluations cannot be successfully performed. The examiner may be unable to condition such a client to the test procedure. Instead the audiologist may be forced to select a hearing aid for the client on the basis of an audiogram. This selection will of necessity involve consideration of the IRI, total distortion, linearity of change in gain, and other electroacoustical characteristics belonging to each hearing aid available to the audiologist. Following the recommendation for a certain hearing aid possessing particular amplification features determined desirable by the audiologist, the hearing impaired client will obtain the suggested aid from a dealer. Since this particular client may not be able to have his listening performance with the newly purchased aid conventionally evaluated, the aid's electroacoustical features must be measured to assure their agreement with these "prescribed" characteristics.

When the audiologist must select four or five hearing aids with which to perform a hearing aid evaluation for a client, or make a recommendation on judgment, he may make his selection or selections on the basis of such electroacoustic measures as the three examined in this study; IRI, total distortion, and linearity of change in gain. If the audiologist has available several aids with similar electroacoustic characteristics, he may justifiably use price as a determining factor.

REFERENCES

A Guide to the Care of Adults with Hearing Loss: A Manual Prepared for the Use of Graduates in Medicine. American Academy of Ophthamology and Otolaryngology, 1965.

American Standard Method for Measurement of Electroacoustical Characteristics of Hearing Aids, S3.3-1960. New York: American National Standards Institute, 1960.

Berger, Kenneth W. and Joseph P. Millin. "Hearing Aids" *Audiological Assessment,* Darrell E. Rose, ed. Englewood Clifts, New Jersey: Prentice-Hall, Inc., 1971.

Bode, Daniel L. and Roger N. Kasten. "Hearing Aid Distortion and Consonant Identification." *Journal of Speech and Hearing Research,* 14 (2): 323-331, June 1971.

Carhart, Raymond, "Hearing Aid Selection by University Clinics." *Journal of Speech and Hearing Disorders,* 15 (2): 106-113, February 1950.

Carhart, Raymond. "Test for Selection of Hearing Aids." *Laryngoscope,* 56: 780-794, 1946a.

Carhart, Raymond. "Volume Control Adjustment in Hearing Aid Selection." *Laryngoscope,* 56:510-526, 1946b.

Carver, William F. "A Historical and Technical Review." *Handbook of Clinical Audiology,* Jack Katz, ed. Baltimore: The Williams and Wilkins Co., 1972.

Corliss, Edith L., Edwin D. Burnett and J. T. Priestly. "Development of Test for Evaluating the Performance of Hearing Aids." *Journal of the Acoustical Society of America,* 38 (7): 922-923, July 1965.

Corliss, Edith L., Michael Kobal and Susan E. Burghorn. "Reduction of Signal-to-Noise Ratio Induced by Distortion in Speech Transmission Systems." *Journal of the Acoustical Society*,32 (11): 1502, November 1960.

Davis, H., C. V. Hudgins, R. J. Marquis, R. H. Nichols, Jr., G. Hearing Aids." *Laryngoscope*, 56: 85-115, 135-163, 1946.

Gaeth, John H. and Evan Lounsbury. "Hearing Aids and Children in Elementary Schools." *Journal of Speech and Hearing Disorders*, 31 (3): 283-389, August 1966.

HAIC Standard Method of Expressing Hearing Aid Performance. New York: Hearing Aid Industry Conference, 1961.

Harris, J., H. Haines, R. Kelsey and T. Clack. "The Relation between Speech Intelligibility and the Electroacoustic Characteristics of Low Fidelity Circuitry." *Journal of Auditory Research*, 1: 357-381, 1961.

Haug, Olaf, Frederick R. Guilford, R. Ray Battin and Paul Baccaro. "A Comparison of Hearing Aids Evaluation Test Instruments and Aids Purchased from Dealers." *Volta Review*, 65 (1): 26-29, January 1963.

"Hearing Aids." *Consumer Reports*, 36: 310-317, May 1971.

Jeffers, Janet. "Quality Judgement in Hearing Aid Selection." *Journal of Speech and Hearing Disorders*, 25 (3): 259-266, August 1960.

Jerger, James and James Thelin. "Effects of Electroacoustic Characteristics of Hearing Aids of Speech Understanding." *Bulletin of Prosthetic Research*, 10 (10): 159-197, Fall 1968

Jerger, James. "Behavioral Correlates of Hearing Aid Performance." *Bulletin of Prosthetic Research*, 10 (7): 62-75, Spring 1967.

Jerger, James, Carolyn Malmquist and Charles Speaks. "Comparison of Some Speech Intelligibility Tests in the Evaluation of Hearing Aid Performance." *Journal of Speech and Hearing Research*, 9 (2): 253-258, June 1966.

Jerger, James, Charles Speaks and Carolyn Malmquist. "Hearing Aid Performance and Hearing Aid Selection." *Journal of Speech and Hearing Research*, 9 (1): 136-149, March 1966.

Jerger, James and Carolyn Malmquist. "Evaluating Hearing Aid Performance." *Journal of the American Speech and Hearing Association*, 7 (10): 364, October 1965.

Kasten, Roger N. "Body and Over the Ear Hearing Aids." *Handbook of Clinical Audiology*, Jack Katz, ed. Baltimore: The Williams and Wilkins Co., 1972.

Kasten, Roger N. and Stephen H. Lotterman. "The Influence of Hearing Aid Gain Control Rotation on Acoustic Gain." *Journal of Auditory Research*, 9: 35-39, 1969.

Kasten, Roger N. and Stephen H. Lotterman. "A Longitudinal Examination of Harmonic Distortion in Hearing Aids." *Journal of Speech and Hearing Research*, 10 (4): 777-781, December 1967.

Kasten, Roger N. and Sally G. Revoile. "Variability of Electroacoustic Characteristics of Hearing Aids" *Journal of the American Speech and Hearing Association,* 7 (10): 364, October 1965.

Kasten, Roger N., Stephen H. Lotterman and Sally G. Revoile. "Variability of Gain Versus Frequency Characteristics in Hearing Aids" *Journal of Speech and Hearing Research* 10(2): 377-383, June 1967.

Kelsey, Patricia A. "Intelligibility of Natural and Distorted Speech Led Through Ten Hearing Aids to Normal and to Deafened Individuals." *Journal of the Acoustical Society of America,* 31 (11): 1585, November 1959.

Leckie, Doris and Daniel Ling. "Audibility with Hearing Aids Having Low Frequency Characteristics." *Volta Review,* 70 (2): 83-86, February 1968.

Ling, Daniel. "Implications of Hearing Aid Amplification Below 300 CPS" *Volta Review* 66(10): 723-729, December 1964.

Lotterman, Stephen H., Roger N. Kasten and Sally G. Revoile. "Acoustic Gain and Threshold Improvement in Hearing Aid Selection." *Journal of Speech and Hearing Research,* 10 (4): 856-858, December 1967.

Lotterman, Stephen H. and Roger N. Kasten. "The Influence of Gain Control Rotation on Nonlinear Distortion in Hearing Aids." *Journal of Speech and Hearing Research,* 10(3): 593-599, September 1967a.

Lotterman, Stephen H. and Roger N. Kasten. "Nonlinear Distortion In Modern Hearing Aids." *Journal of Speech and Hearing Research,* 10 (3): 586-952, September 1967b.

Lotterman, Stephen H., Roger N. Kasten and Diane M. Majerus. "Battery Life and Nonlinear Distortion in Hearing Aids." *Journal of Speech and Hearing Disorders,* 32 (3): 274-278, August 1967.

Lotterman, Stephen H. and Norman R. Farrar. "Nonlinear Distortion in Wearable Amplification." *Journal of the American Speech and Hearing Association,* 7 (10): 364-365, October 1965.

Lybarger, Samuel F. "A New Standard for Measuring Hearing Aid Performance." *Journal of the American Speech and Hearing Association,* 3 (3): 121, March 1966.

Lybarger, Samuel F. "Standardized Hearing Aid Measurements." *Audecibel,* 10: 10-18, 1961.

McConnel, Freeman, Eileen Find Silber and Douglas McDonald. "Test-Retest Consistency of Clinical Hearing Aid Tests." *Journal of Speech and Hearing Disorders,* 25 (3): 273-280, August 1960.

Miller, Maurice. *Hearing Aids,* New York: The Bobs-Merrill Co., 1972.

Millin, Joseph P. and Anthony Snyder. "Human Acoustics Seminar, July 1972" Bruel and Kjaer Instruments, Inc. Cleveland, Ohio.

Niemoeller, A. F., S. Richard Silverman and Hallowell Davis. "Hear-Aids." *Hearing and Deafness,* 3rd Edition, Hallowell Davis and

S. Richard Silverman, editors. New York: Holt, Rinehart and Winston, 1970.

Salyer, Gregory W. "A Comparison of Higher Versus Lower Priced Hearing Aids Utilizing Measurements of Three Electroacoustical Characteristics." Unpublished Master Thesis, University of Louisville, 1973.

Shore, Il, Raymond G. Bilger and Ira Hirsh. "Hearing Aid Evaluation: Reliability of Repeated Measurements." *Journal of Speech and Hearing Disorders*, 25 (2): 125-170, May 1960

USA Standard Method of Expressing Hearing Aid Performance, S3. 8-1967. New York: American National Standards Institute, 1967.

Veterans Administration. Hearing Aid Performance Measurement Data and Hearing Aid Selection Procedures Contract Year 1972. Washington: Author, 1971.

Wallenfels, Herman G. *Hearing Aids on Prescription*. Springfield, Illinois: Charles C. Thomas, 1967.

Zerlin, Stanley and Edwin D. Burnett. "Effects of Harmonic and Intermodulation Distortion on Speech Intelligibility." *Journal of the Acoustical Society of America*, 32 (11): 1501-1502, November 1960.

Zink, G. David. "Hearing Aids Children Wear: A Longitudinal Study of Performance." *Volta Review*, 74 (1): 41-51, January 1972.