A COMPARISON OF TRADITIONAL VS. FORMULA HEARING AID SELECTION METHODS, UTILIZING PROBE MICROPHONES

by

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INTRODUCTION

One of the more hotly debated topics in the field of audiology is the method of hearing aid selection used by the clinical audiologist. Since Carhart made an attempt to standardize the selection of hearing aids (1946), his methods have been debated, modified, and in some clinics changed completely. In 1972, Burney concluded on the basis of a survey that most clinics still use a selection procedure which is based on Carhart's work. However, other techniques of selective amplification have been developed since that time, and these have gained some popularity. These formula techniques are based on the premises that a person's hearing sensitivity can be quantified, and that a person's hearing can be selectively amplified at the critical frequencies so as to yield optimum performance. These techniques are also based on the assumption that the characteristics of a given hearing aid can be adequately measured and that the client's performance with that hearing aid can be adequately predicted. For most clinics, this involves the use of the 2 cc hard-walled coupler with which the measurements of the frequency response, saturation sound pressure level, and total harmonic distortion of a hearing aid are made. This study was undertaken to look further into the formula techniques, to evaluate the premises upon which they are based, and to evaluate the effectiveness with which clients are fitted using these techniques.

Ear Canal Variance

It has long been established that the ear canal of a person has a significant effect on the hearing sensitivity of that person (Studebaker and Zachman 1970, McDonald and Studebaker 1970). For purposes of hearing aid fitting, the role of the ear canal has usually been estimated using a 2 cc coupler. It has been well established that this estimate is a poor one (Tonnison 1975, Harford 1980b, Pascoe 1974, McDonald and Studebaker 1970). Pollack (1980) pointed out that the 2 cc hard-walled coupler was developed over 30 years ago, not for purposes of yielding a response similar to that of the average adult ear, but instead for quality control purposes only. The underlying cause for the development of the coupler was the need for a standard means to compare a given unit of a hearing aid model with another, and to consistently exchange information concerning hearing aids between laboratories. In fact, Pollack pointed out that the volume of a typical adult ear between the earmold canal tip and the tympanic membrane is closer to 1.2 cc and not 2 cc. In addition, the hard-walled 2 cc coupler does not approximate the acoustic impedance of the human ear. The 2 cc coupler was "never intended for use as a means of selecting a hearing aid that is appropriate for a particular hearing loss." (Pollack 1980). In spite of this knowledge, and numerous studies which show its inadequacy in that role, the 2 cc coupler is more and more widely used clinically as the basis for selective amplification.

Methods of Estimating Canal Volume for Hearing Aid Fitting

The inability of the 2 cc coupler to estimate real-ear gain has been studied by a number of researchers, under a number of different conditions. Jacobson and Krug (1972) measured physical responses (frequency response characteristics derived using a 2 cc coupler), and psychophysical responses (loudness estimated using an alternate binaural loudness balance technique) in seven normal hearing subjects using four different earmolds, vented and unvented. Although the physical characteristics varied for the vented and unvented conditions, no significant changes in loudness occurred due to vent size. The authors suggested that acoustic measurements derived using a 2 cc coupler should not be used as an indicator of listener perception.

Tonnison (1975) suggested that the variables affecting real-ear performance are too numerous to be predictable by a 2 cc coupler estimate. He cited input impedance of the ear, head diffraction, body baffle effect, ear canal resonance, earmold type, depth of insertion of earmold, tubing parameters, microphone location, and other factors. All these suggest the need for a feasible method of measuring real-ear performance of a hearing aid.

Studebaker and Zachman (1969), on the other hand, found a somewhat predictable difference between frequency response curves obtained using a hard-walled 2 cc coupler and those obtained using a probe tube real ear measurement. Despite a high degree of variability in their data, Studebaker and Zachman showed that canal resonance peaks are much smoother when measured with a probe tube in a real ear than when measured in a hard-walled coupler. Their data suggested that although the hard-walled coupler can show resonances very visibly, it cannot show the quantitative effects of earmold modifications on real ear performance. They cited van Eysbergen and Groen (1959) as recommending that the 2 cc coupler should be used for limited purposes only, and concluded that the standard hearing aid frequency response curve obtained using a 2 cc coupler will have only a vague relation to the shape of the signal which reaches the human ear.

McDonald and Studebaker (1970) continued the work of Studebaker and Zachman cited above, with an improved method of mounting the real-ear probe tube and using a modified 2 cc coupler. Again they were looking for a predictable relationship between 2 cc coupler measurements of frequency response and real-ear measurements. They were able to cut down on the variability experienced by Studebaker and Zachman, and predictability seemed to improve with the introduction of the modified coupler. However, the limitations of the 2 cc coupler remained.

Other Estimates of Ear Canal Volume

Several alternate methods of estimating the effects of the individual's ear canal and predicting listener performance have been devised. These include: the Zwislocki coupler, the KEMAR (Knowles Electronic Mannikin for Acoustic Research) mannikin, and "real-ear" measures made using a probe tube placed in the ear canal which is attached to an external microphone.

The inherent problems with the 2 cc coupler and the general dissatisfaction with its clinical usefulness led Zwislocki (1971a and b) to develop an alternate coupler. This coupler was designed to reproduce the eardrum impedance of the typical adult ear. It is closer to 1.2 cc in size, and has 4 side-branch resonators which synthesize the inertance, resistance, and compliance of the adult ear canal. Sachs and Burkhard (1972) verified its accuracy in estimating the characteristics of the average adult human ear. They reported that for frequencies between 800 and 7500 Hz, the mean pressure in real ears measured using a probe tube and that estimated by the Zwislocki coupler differ by no more than 2 dB. Below 800 Hz they reported even greater agreement.

The KEMAR device was designed in 1974 to be used with the Zwislocki coupler. This was designed by Knowles Electronics to account for other variables in addition to ear canal size and impedance, including head diffraction and body baffle effects. KEMAR is an anthropometric mannikin, built of the average size and shape of an adult human, which allows in situ placement of a hearing aid for measurement. Those who advocate its use point out that it is a reproducible test subject which allows for uniform exchange of information between labs, and which is not subject to fatigue or other physiologic changes during lengthy testing. However, certain problems exist which limit the clinical applicability of the KEMAR mannikin. Its use requires an anechoic chamber to minimize sound reflections and standing waves. The anechoic chamber must have a minimum size of a six foot cube. This in itself is prohibitive for many clinics. In addition, at least one researcher has pointed out some limitations in the ability of KEMAR to estimate real-ear performance. (Pollack 1980). Pollack found a great deal of variability among KEMAR measurements when comparing different hearing aids. He also compared the use of a Zwislocki coupler in a test box with its use when placed in the KEMAR mannikin. Again, results were variable, even though certain trends were noted. The test box vs. KEMAR measurements were close (within 6 or 7 dB), and when compared with measurements made by the conventional 2 cc hard-walled coupler, it was noted that the 2 cc coupler can seriously underestimate the gain and output of a hearing aid.

It should also be noted that the Zwislocki coupler and the KEMAR mannikin provide measurements which approach the mean responses of adult human ears; however, they are estimates of an average reading. Measurements made on a given individual may differ significantly from those estimated using even the best available techniques of estimation. Only a real-ear measurement can give information concerning a given person's canal volume, body baffle effect, etc.

"Real-ear" measurements have been attempted for a number of years. Until very recently, these involved the mounting of a probe tube into the person's ear canal through some immovable apparatus, connecting the probe tube to an external microphone, and obtaining readings of real-ear performance from the external microphone. The methods used by various researchers (McDonald and Studebaker 1970, van Eysbergen and Groen 1959, and others) have varied greatly, and the results obtained have been inconsistent. Most have involved the stationary placement of a subject in a chin rest (or other device to restrict movement) while the pinna is pulled back and anchored securely so as to avoid the displacement of the probe tube. The tube was then attached carefully to the external apparatus, again with the possibility for movement minimized. McDonald and Studebaker (1970) varied this somewhat by the use of a helmet from which the probe tube and earmold were suspended, thus allowing the subject a small amount of mobility. Because of the apparatus problems, the probe tube and real-ear measurements were restricted in use for research purposes only, and were not practical for routine clinical use. Therefore, the measurements made were of limited value as they could not be replicated in the individual clinic.

Alternate Suggested Methods for Hearing Aid Fitting

Some authors have expressed dissatisfaction with the available measurement techniques, and have suggested methods for hearing aid fitting which do not involve the traditional measurements. One such example is the method suggested by Tonnison (1975). He suggested that real-ear gain of a hearing aid can be closely approximated based on measurements of aided and unaided acoustic reflex thresholds. Real-ear gain was defined as the difference in decibels between aided and unaided reflex thresholds. Wide individual differences were noted in the real-ear measurements; the author noted that this could be expected due to varying location and orientation of the microphone on the head or body. Based on this study, Tonnison suggested that real-ear measurements be a part of every hearing aid selection procedure, in order to enhance the critical speech frequencies.

The above-mentioned studies involved attempts at accurate measurements of real-ear gain. Pascoe (1974) advanced the process to the next logical step and attempted to study listener performance as the frequency response of a hearing aid was varied in five different ways. He suggested that there may be a more effective method of predicting listener performance than matching frequency response curves measured on a hard-walled coupler to a given person's audiogram configuration. His study involved the use of a master hearing aid which could be continuously adjusted so that a hearing impaired person could receive appropriate amplification which could bring up his/her hearing thresholds to an aided audibility curve which is parallel to normal. Pascoe denoted this as a uniform hearing level (UHL) and noted that listener performance was significantly improved when the listener was fitted according to his UHL. Discrimination scores in quiet and in noise were compared for the following conditions:

1. The listener was fitted with an aid which provided uniform gain at all frequencies, as measured on a 2 cc coupler,
2. The listener was fitted with an aid which provided gain increasing in the higher frequencies, rising at a 6 dB/octave slope as measured in a 2 cc coupler,
3. The listener was fitted with an aid which was adjusted individually

to provide a uniform functional gain across all frequencies,

4. The listener was fitted according to his UHL as described above,
5. The listener was fitted with a simulation of a single commercial hearing aid with functional gain similar to that obtained by the subjects with their own hearing aids.

Pascoe noted significant improvement in speech discrimination scores, particularly in the presence of noise, and recommended the use of uniform hearing level for the fitting of hearing aids. An obvious drawback to the use of this method clinically is the expense of a master hearing aid and the small number of clinics which employ the use of a master hearing aid.

Suggested Formula Approaches

Other authors (Shapiro 1976, Berger 1977, Berger 1979, Berger 1980) suggested that, although 2 cc hard-walled coupler measurements do not exactly match those measurements made in real ears, nevertheless formulae can be applied to listener hearing thresholds and tolerance thresholds to adequately amplify a person's hearing selectively. Shapiro (1976) outlined his suggested methods, which involved the use of narrow bands of noise and perceived most comfortable loudness levels. He pointed out the time required for a comparative hearing aid trial and noted that a simple formula fitting could yield the same listener performance levels as could a fitting by the time-consuming Carhart method. Shapiro's 1980 study compared his formula method, involving direct measurement of most comfortable loudness level using narrow bands of noise, with two other formula methods, including that of Berger (1977). His results indicated that there were no significant differences in listener performance among the methods, though there was a great deal of inter-subject variability.

Perhaps the most well-known formula method of fitting hearing aids is that of Berger (1977). Again, Berger postulated that even though measurement of the frequency response of a hearing aid on a 2 cc coupler is not an accurate measure of real-ear performance, still his formula method is an adequate predictor of listener performance after amplification. Berger's formula for fitting is based on what he calls the "half-gain rule", that a hearing impaired person will tend to keep the gain of his/her hering aid at a level which is approximately half of the amount of hearing loss at a given frequency. The formula he suggested for maximum gain was:

- 500 Hz: HTL/2 +10 dB
- 1000 Hz: HTL/1.6 +10 dB
- 2000 Hz: HTL/1.5 +10 dB
- 4000 Hz: HTL/2 +10 dB

Correction factors must be applied when comparing HTL levels with 2 cc coupler readings which are expressed in dB SPL.

Berger (1977, 1979) attempted to standardize selective amplification processes by setting up several criteria basic to his formula approach. The harmonic distortion of the chosen hearing aid must be less then 5% at all test frequencies. Also, maximum saturation sound pressure level must be set according to the tolerance thresholds of the individual listener. The fitting of a given hearing aid is acceptable if the measured gain of the aid is within ±9 dB of the predicted gain at 1000 and 4000 Hz, within +5 and -9 dB of the predicted gain at 500 Hz, and within +9 and -5 dB of the predicted gain at 2000 Hz.

Berger (1977) reported a high rate of successful amplification applying these criteria and his formula, and pointed out that a successful hearing aid trial can usually be accomplished in one-half hour using his method. However, he made no attempts to compare listener performance when a subject is fitted with an aid through his method to the performance of the same subject when fitted using the modified Carhart technique.

Millin (1980), in his discussion of practical and philosophical considerations in hearing aid fitting, gave an overview of Berger's technique. He noted that despite the fact that Berger cited many "satisfied" hearing aid wearers, Berger gave no basis for assuming that these wearers might not be more satisfied with another hearing aid. Millin (1980) suggested that all formula techniques lack experimental validation to substantiate the claims that these techniques are as effective and that they yield as good or better listener performance. Obviously, formula techniques have certain advantages: only pure-tone thresholds and tolerance thresholds are needed, and the time involved can be a fraction of that necessary for a comparative evaluation. This is a clear advantage when dealing with patients who are difficult to test using speech stimuli. Millin stated, "If formulas could be shown to be as effective as traditional procedures, an important advance in clinical selection would be achieved." (1980). However, he also noted that the formula methods currently available rely on approximations of real-ear performance which have been shown to be unreliable. He concluded that "Only real-ear measurements of some kind will determine what pressures will actually occur in a given patient's ear" (Millin 1980).

Millin also pointed out some other underlying premises of the formula approach to hearing aid fitting, which seem to have little face validity. First of all, the formula approach implies that two people with the same audiogram should automatically be fitted with the same hearing aid. Intuitively, this does not seem to hold true in clinical applications. In addition, the formula approach implies that pure-tone thresholds and tolerance thresholds are the two most important factors predicting speech understanding of a patient. Again, there seems to be no experimental evidence to substantiate this claim.

Problems do exist, and research needs continue to be apparent; still the possibility of establishing a relatively quick and equally effective method of hearing aid selection warrants the need for further systematic study of the formula approaches.

Real-ear Measures

Still another approach to hearing aid fitting has been attempted by Harford (1980a, 1980b). This method involves the use of a miniature microphone to verify the performance characteristics of a hearing aid to be fitted. Real ear measures have been attempted experimentally in the past, using probe tubes and external microphones; however, these methods have not been feasible clinically (Wiener and Ross 1946). Harford suggested that with new technology available, the miniature microphone can be routinely used for effective hearing aid fitting.

His suggested technique involves the use of a probe microphone measuring approximately 4x5x2 mm which can be safely inserted into the patient's canal yielding accurate measures of sound pressure levels reaching that point in the canal. Harford's early work (1980a) established the reliability and replicability of the measures of frequency response obtained through the probe microphone when a conventional ear-level hearing aid and custom earmold are placed in the ear over the microphone. His later work (1980b) pointed out the practicality of using this for the fitting of difficult-to-test patients and suggested the possibility that the probe microphone may have value as a tool routinely used in a clinical setting. He cited ease of insertion, minimal instrumentation needed, ease of calibration, and relative low cost as factors which support further study of this potential tool.

Rationale for this Study

The present study was undertaken with these elements in mind: that the miniature probe microphone is a reliable and useful tool which may be beneficial for hearing aid selection, that further study is necessary to evaluate traditional vs. formula approaches to hearing aid fitting, and that the 2 cc hard-walled coupler is of questionable value for estimating the real-ear gain of a hearing impaired listener. If, in fact, a reliable method for plotting the real-ear performance characteristics of a given hearing aid can be put to use practically in a clinical setting, then perhaps a less time-consuming and still accurate method of hearing aid fitting can be devised.

The purpose of this study is to compare listener performance when a given hearing-impaired listener is fitted with a hearing aid by three different selection methods:

1. the formula method advocated by Berger, involving the fitting of a person's hearing loss with a hearing aid the frequency response of which is measured conventionally (with a 2 cc hard- walled coupler)

2. the same formula method, but involving the measurment of the frequency response of the hearing aid using the probe microphone inserted in the listener's ear, and
3. the modified Carhart selection technique, involving comparisons of listener performance and preference.

Subjects involved in this study were fitted essentially three times: once by each of the methods mentioned above. The subjects were then tested with each of the aids selected. Testing included Spondee Reception Threshold, speech discrimination in quiet, and speech discrimination in noise. Listener performance on each of the tasks was evaluated, and significant differences in performance were noted. Significant differences in listener performance were reported which were attributable to the hearing aid selection procedure used.

METHODS AND MATERIALS

Subjects

Five adult hearing impaired subjects were involved in this study, with ages ranging from 49 to 83 years. All subjects had sensorineural hearing losses of varying configurations (see figure 1). Each subject expressed an interest in being fitted with a monaural, ear-level hearing aid. Only one subject had previously worn a hearing aid.

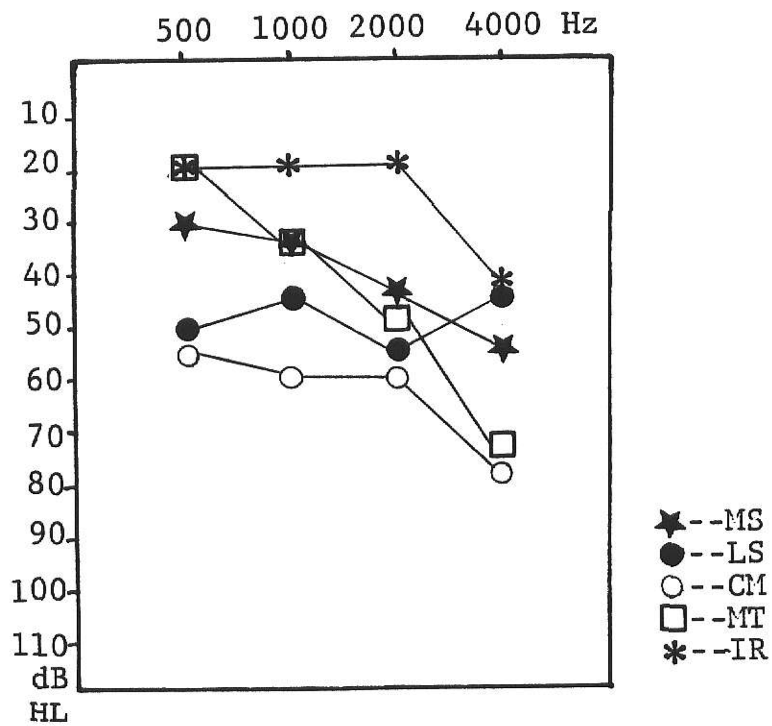

Figure 1. Audiograms of five experimental subjects.

Subjects were individuals who came to the KSU Speech and Hearing Center requesting a hearing aid trial, either after having been evaluated at this center or having been referred for a hearing aid trial from another source. All adults requesting a hearing aid trial during a 3-month period were given the option of participating in the study, until the desired number of subjects was obtained. All potential subjects opted to participate in the study, and all completed the entire testing procedure.

All subjects who were evaluated at the KSU Speech and Hearing Center were fitted with a Killion style fully occluding earmold which best suited their hearing loss. Those referred from other sources obtained their custom earmold prior to the beginning of testing. In two of these cases, it was necessary to make earmold modifications prior to testing.

Equipment

Pure-tone air- and bone-conduction hearing thresholds, Spondee Reception Thresholds, speech discrimination scores in quiet and in noise, and pulsed tone tolerance thresholds were obtained using a Grason-Stadler Model 1702 manual audiometer. Word lists used included CID W-22 Spondee words, and NU-6 phonetically balanced mono-syllabic words, all recorded by Auditec of St. Louis, and presented using a stereo cassette tape recorder (Sony #TC-136SD).

Frequency response, saturation sound pressure level, and total harmonic distortion of hearing aids used in the study were measured on a Phonic Ear HC 2000 hearing aid test box and were plotted on the attached plotter model HC 2200. For real ear measurements of hearing aid performance characteristics, the output of the Phonic Ear equipment was fed to the desired speaker within the sound treated chamber so that the sweep of the 60 dB SPL pure tone could be accomplished. The sound chamber consisted of a double walled, single room sound treated test environment, which satisfied existing ANSI 1969 ambient noise level standards.

Real-ear measurements were made using a Starkey Series RE 4 Real Ear Probe Microphone System. The test microphone was placed approximately 1 cm into the subject's ear canal, with the custom earmold placed over the microphone. The regulator microphone was placed directly outside the same pinna, as close to the ear as possible without touching it. The probe microphones were covered with an acoustic damping screen and a disposable plastic cover, which were changed after each insertion into a new subject, according to the manufacturer's specifications. The probe microphones were coupled to the Phonic Ear equipment with a Starkey RE 4 interface system. (See block diagram, figure 2.)

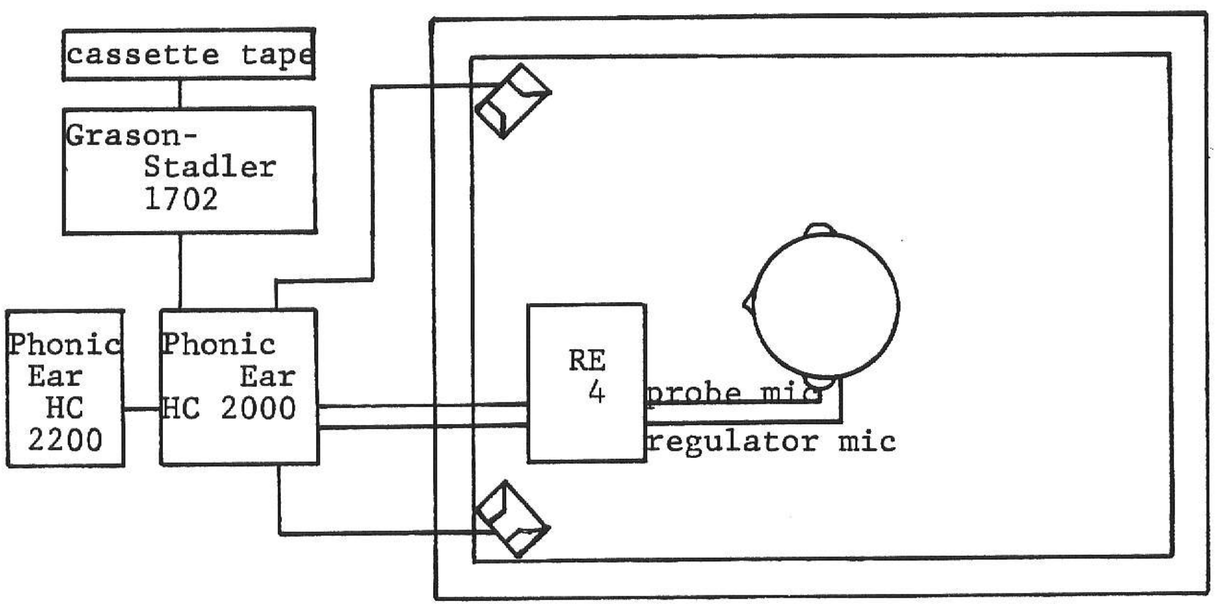

Figure 2. Block diagram of experimental situation.

All equipment used was calibrated periodically throughout the duration of the study. Calibration equipment included a Bruel and Kjaer sound level calibrator, Type 4230; a Hewlett Packard 132A dual beam oscilloscope; a Bruel and Kjaer Microphone Amplifier, Type 2603; and a Bruel and Kjaer Band Pass Filter Set, Type 1615. Calibration of the probe microphones was accomplished according to the manufacturer's specifications. The linearity of the microphones was established prior to testing for both the closed field and the open field conditions. (See figures 3 and 4.)

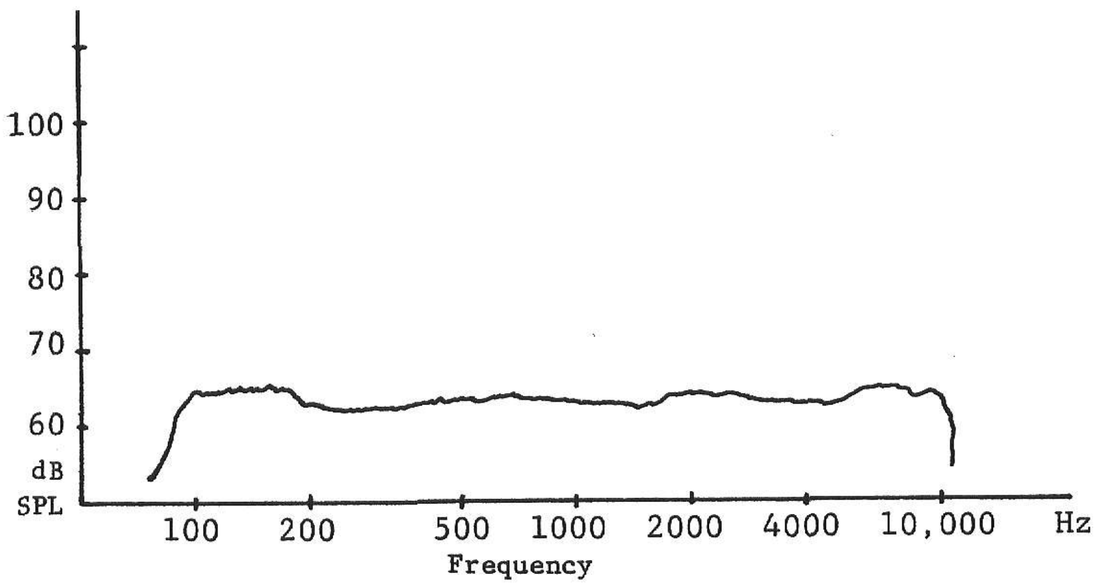

Figure 3. Output of probe microphone with 60 dB SPL input, measured within Phonic Ear HC 2000 test box.

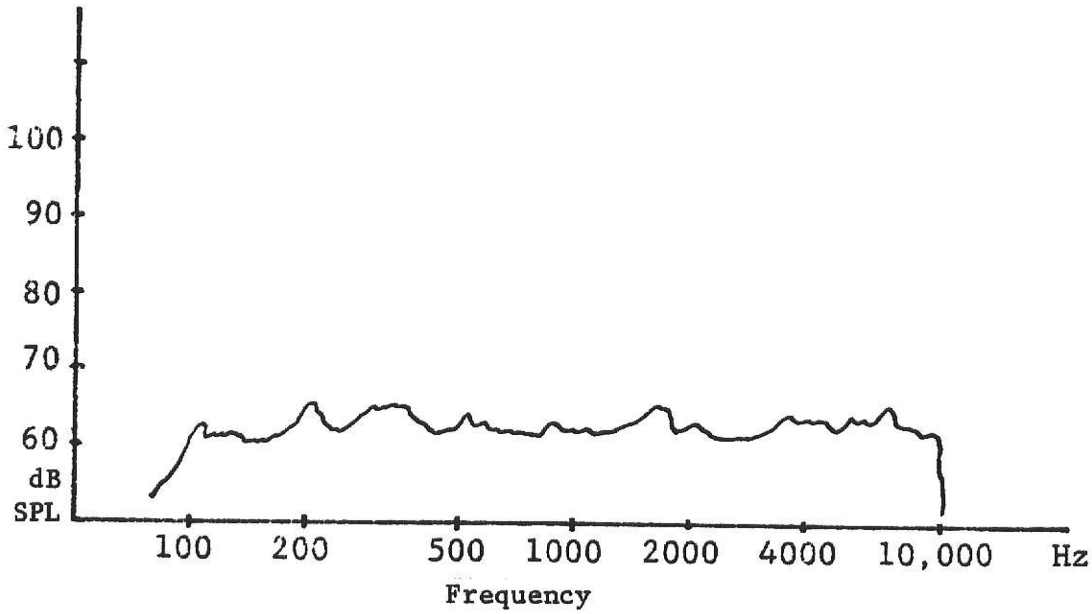

Figure 4. Output of probe microphone with 60 dB SPL input, measured in sound treated test environment (sound field).

Hearing Aid Selection

The hearing aid stock of the Kansas State University Speech and Hearing Center (approximately 50 hearing aids) was screened initially to select those hearing aids which met Berger's criteria (Berger 1977). These criteria included:

- The aid must be a monaural hearing aid.
- The aid must be an ear-level hearing aid.
- The aid must have a front-facing microphone.
- The aid must have acceptable total harmonic distortion.

In addition, those aids which also had variable tone control and power control and which had no undesirable peaks and/or valleys in frequency response, were singled out. Those aids became the pool from which the experimenter randomly chose for fitting by the formula methods. They were:

1. Phonic Ear PE 801 AGC
2. Phonic Ear 840
3. Siemens 274-PP-PC
4. Widex F7+H
5. Widex F8+H
6. Widex A12+H
7. Oticon E19VF
8. Qualitone DWA
9. Qualitone DAD
10. Bosch 55 AGC-ES
11. Audiovox PA 64

For each subject, the above aids were assigned a random number, and a fitting was attempted beginning with the hearing aid having the lowest number. Formulae were applied to the listener's audiogram. If the aid could be adjusted to meet the desired gain requirements within the criteria established by Berger (1977), the aid was selected. If it could not be adjusted to meet the criteria, it was abandoned and the next hearing aid was tried. This process was continued until a suitable fit was found. All subjects were successfully fitted in this manner.

The preselection of hearing aids for the conventional modified Carhart method for hearing aid trials was done as follows:

All hearing aids were organized according to manufacturer, and the lists of manufacturers were randomly sequenced. With the first subject, the experimenter began with the first manufacturer and continued through the list until four satisfactory hearing aids had been selected. Aids were judged satisfactory in a subjective manner, based on reference test gain, high frequency emphasis, low harmonic distortion, and availability of appropriate compression circuits. With the second subject, the sequence was begun with the second manufacturer, continuing through the list of manufacturers until four satisfactory hearing aids were preselected. With the third subject, the selection process began with the third manufacturer, and so on. Thus experimenter bias was minimized.

Procedure

Following selection of a subject and the completion of all routine unaided scores (pure-tone thresholds, SRT, WDS in quiet, and WDS with a S/N ratio of +10 dB), the subject's ear to be fitted was determined. This was determined through Berger's criteria:

1. greatest dynamic range
2. absence of recruitment
3. degree of loss in range of greatest satisfaction

This ear was fitted with a custom mold, as previously described. All subjects were counseled as to the procedures to follow, questions answered, and consent obtained. The tolerance threshold of that ear was then tested using pulsed pure tones presented via closed field at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz (Berger 1977).

A hearing aid was then selected by the random method described, until one was found which met Berger's specifications for gain at each frequency (.5k, 1k, 2k, and 4k Hz), for SSPL, for harmonic distortion, and for compression (if needed). The first aid to meet Berger's criteria was selected and labeled B1, with all adjustments noted and gain control set according to Berger's formula for operating gain. The B1 aid was then fitted on the subject. The subject was instructed to make no adjustments to the aid, regardless of loudness perceived. The subject's SRT was then obtained by a descending method. Speech discrimination in quiet was obtained at 30 dB SL re: SRT. Speech noise was introduced at a level 10 dB below signal level and the speech discrimination score in noise was obtained.

The probe microphone was then inserted into the subject's test ear, and the chosen hearing aid (B1) was re-fitted on the subject. No adjustments were made, and the real-ear frequency response of that hearing aid was plotted using a 60 dB SPL pure tone input fed through the appropriate speaker. The amount of functional gain at each test frequency was measured, and any discrepancies from the desired operating gain noted. Adjustments were then made to the hearing aid to attempt to bring the real-ear functional gain to within the criteria established by Berger (1977). As adjustments were made, additional real-ear frequency response curves were generated to verify the acceptability of the fit. If the chosen aid was successfully adjusted and the criteria satisfactorily met, this new set of conditions was labeled B2. If, on the other hand, that chosen aid could not be adjusted satisfactorily, that aid was abandoned, and another hearing aid was randomly chosen from the pool listed above. Real-ear measurements were run, and adjustments made until a satisfactory fit was accomplished. This aid with its appropriate adjustments was labeled B2. The B2 aid was placed on the subject, who was again instructed to make no adjustments to the aid. The subject's SRT and discrimination scores in quiet and in noise were then obtained. Throughout the testing process, the word lists were randomly varied so as to avoid any order effect of list presentation.

In most cases, this marked the end of the first session, and the subject was asked to return at a later date for the final portion of testing. The final session consisted of a modified Carhart comparative hearing aid trial. Preselection of four appropriate aids was accomplished (as described above) prior to the testing session. During testing, each aid was fitted on the subject using his or her custom earmold. Running speech was presented at a level of 40 dB HL by the experimenter, and the subject adjusted the gain control to a comfortable loudness. The subject's SRT and discrimination scores in quiet and in noise were then obtained, along with the aided tolerance threshold and aided most comfortable loudness level. These scores were obtained for all four aids, unless one or more proved to be unsatisfactory.

Following this procedure, the scores for the three different fittings were visually compared. Those hearing aids which produced the best listener performance were selected, and the subject was asked to use the aids for a short time in the clinic to express any listener preference. A hearing aid was then prescribed on the basis of listener performance and preference.

All scores were tabulated and analyzed using a two-way analysis of variance. Results of this analysis are included in the following section.

RESULTS AND CONCLUSIONS

The following table (table 1) shows the raw scores for each of the five subjects on the three measurements: Spondee Reception Threshold, word discrimination score in quiet, and word discrimination score in the presence of noise. Spondee Reception Thresholds have been converted from dB HL to Pascals in order to make linear comparisons in the analysis. Word discrimination scores are given as raw scores rather than as percentage scores, again for purposes of analysis.

Table 1. Table of raw scores comparing listener performance across three methods of hearing aid selection: Berger's formula method (B1), a modified formula method using probe microphones (B2), and the modified Carhart technique (C).

Subject	Method	SRT in dB HL	pressure in Pa	WDS-Q raw	WDS-Q %	WDS-N raw	WDS-N %
IR	B1	22	2.518	45	90	36	72
	B2	17	1.416	50	100	33	66
	C	17	1.416	46	92	14	28
LS	B1	35	11.247	36	72	15	30
	B2	20	2.000	40	80	17	34
	C	17	1.416	42	84	8	16
MS	B1	25	3.556	48	96	25	50
	B2	25	3.556	47	94	22	44
	C	22	2.518	49	98	19	38
CM	B1	15	1.125	46	92	16	32
	B2	15	1.125	43	86	25	50
	C	10	0.632	41	82	18	36
MT	B1	32	7.962	42	84	33	66
	B2	20	2.000	41	82	28	56
	C	7	0.448	31	62	--	--

A two-way analysis of variance was run on each of the three sets of scores, using the Statistical Analysis System's Analysis of Variance and General Linear Models procedures, in accordance with the repeated measures design of this experiment. The analysis of variance tables follow.

Table 2. Analysis of Variance table for SRT scores.

Source	df	SS	F
Subject	4	.00000028	1.15
Method	2	.00000045	3.71 **

** An F-ratio of 3.71 is significant at the .0724 level.

Table 3. Analysis of Variance table for WDS-Q.

Source	df	SS	F
Subject	4	238.4	4.48*
Method	2	14.933	0.56

* An F-ratio of 4.48 is significant at the .0341 level.

Table 4. Analysis of Variance table for WDS-N.

Source	df	SS	F
Subject	4	482.429	4.34 *
Method	2	210.042	3.78 **

* An F-ratio of 4.34 is significant at the .0444 level.
** An F-ratio of 3.78 is significant at the .077 level.

Table 2 showed that there is a difference in means that is attri butable to the method of selection used, and that this difference is significant at the .0724 level. Though this level of significance allows for a certain amount of Type I error, nevertheless, in light of the fact that only five subjects were involved, this trend is notable.

Duncan's Multiple Range Test run on the Statistical Analysis System at the .05 level shows that the significant difference between means occurs between methods B1 and C. That is, there is a significant difference (at the .05 level) between the SRT scores of subjects when fitted by Berger's formula method. and the SRT scores of the same subjects when fitted by the modified Carhart method. Comparing the means of scores of listeners obtained by these two methods, it can be seen that the Carhart method yielded significantly lower SRT scores.

Table 3 showed the comparison of word discrimination scores in quiet and revealed no significant differences attributable to method of fitting. There is a significant difference between subjects on this measure; however, this inter-subject variability may be expected.

Table 4 showed a difference among the means which is attributable to method of selection, significant at the .077 level. The mean scores obtained from methods B1 and B2 were equal. However, Duncan's Multiple Range Test showed that these two means are significantly different from the mean of the subjects when fitted by Carhart's procedure. Thus, the subjects when fitted by a formula method (either Berger's method or the modified formula method based on a real-ear measurement) scored better on the word discrimination task in noise than they did when fitted by the modified Carhart method.

The following table shows the differences measured between the 2 cc hard-walled coupler measurements and real-ear measurements obtained during the study. These differences appear here in dB SPL and in Pascals for purposes of linear comparison. More than five comparisons appear because this process was repeated on two subjects using different hearing aids. The dB SPL values were converted to Pascals by the following formula:

dB SPL = 20 log (P1/0.0002 Pa). (Acoustic zero = 0.0002 Pa.)

Table 5. Comparison of 2 cc coupler gain and real-ear gain, by subject and by frequency.

Subj	Freq in Hz	2 cc gain in: dB SPL	2 cc gain in: Pa	real-ear gain in: dB SPL	real-ear gain in: Pa	difference in Pa
CM	500	34	.0100	38	.0159	-.0059
	1000	48	.0502	46	.0399	.0103
	2000	47	.0448	41	.0224	.0224
	4000	50	.0632	42	.0254	.0378
MA	500	16	.0013	16	.0013	.0000
	1000	34	.0100	24	.0032	.0068
	2000	39	.0178	35	.0112	.0066
	4000	35	.0112	24	.0032	.0080
MS	500	13	.00089	12	.00079	.0001
	1000	33	.0039	22	.0025	.0064
	2000	38	.0159	31	.0071	.0088
	4000	39	.0178	27	.0045	.0133
LS	500	28	.005	24	.0032	.0018
	1000	41	.0224	41	.0224	.0000
	2000	42	.0254	39	.0178	.0078
	4000	32	.008	21	.0022	.0058
MT	500	14	.001	4	.0003	.0007
	1000	27	.0045	22	.0025	.002
	2000	39	.0178	30	.0063	.0115
	4000	39	.0178	35	.0112	.0066
IR	500	5	.00036	12	.00079	-.00043
	1000	16	.0013	27	.0045	-.0032
	2000	25	.0036	31	.0071	-.0035
	4000	31	.0071	28	.005	.0021
IR	500	13	.00089	13	.00089	.0000
	1000	20	.002	31	.0071	-.0051
	2000	30	.0063	33	.0089	-.0026
	4000	35	.0112	45	.0356	-.0244

The differences between the 2 cc coupler reading and the real-ear reading are plotted by subject and by frequency, and are shown in figure 5. These curves are superimposed upon each other in figure 6 to demonstrate the random dispersion of the differences in gain. Though the average difference between the 2 cc coupler measurements and the real-ear measurements is not great, as shown in figure 7, the dispersion of the scores is wide, and therefore discussion of average differences becomes meaningless.

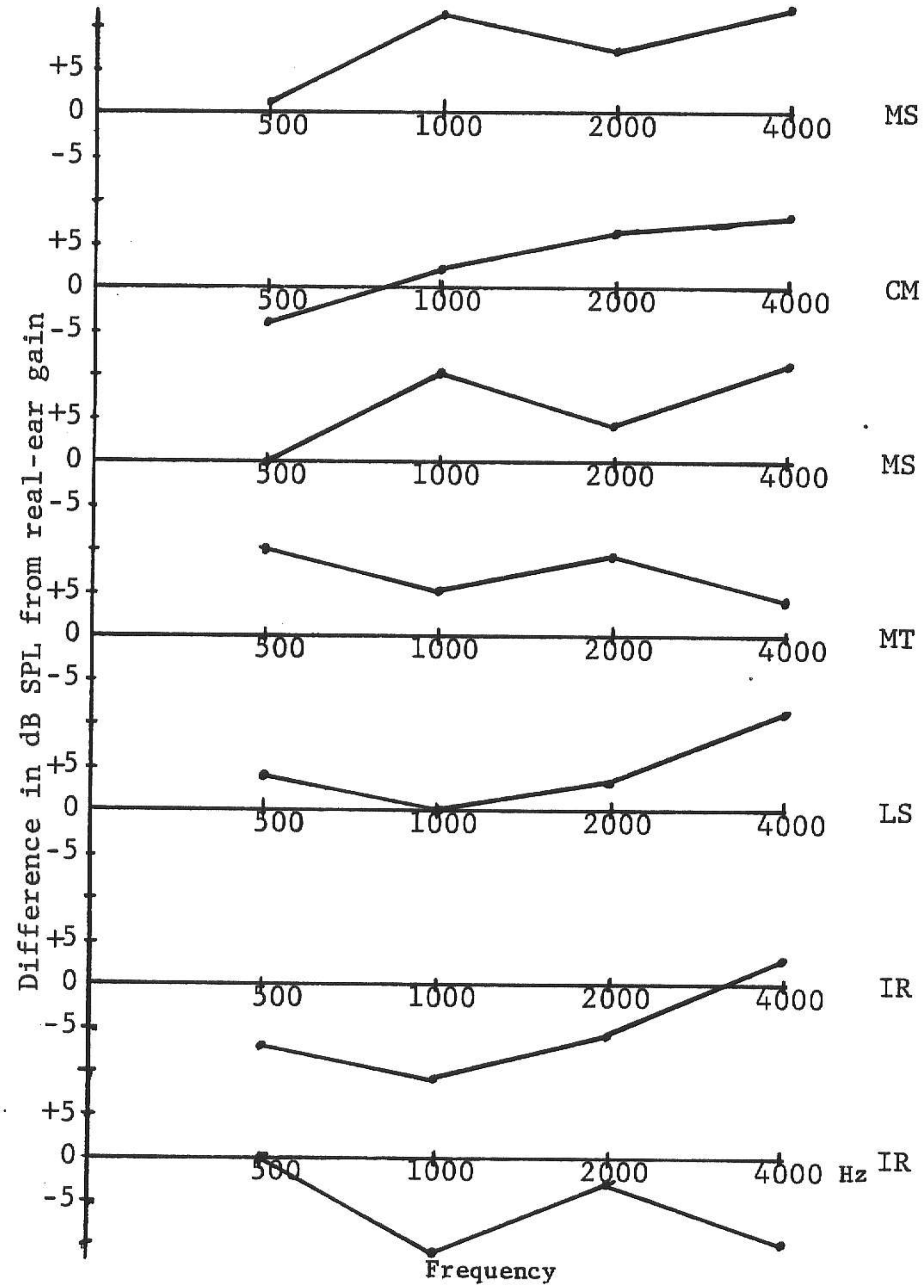

Figure 5. Differences between 2 cc coupler gain and real-ear gain, by subject.

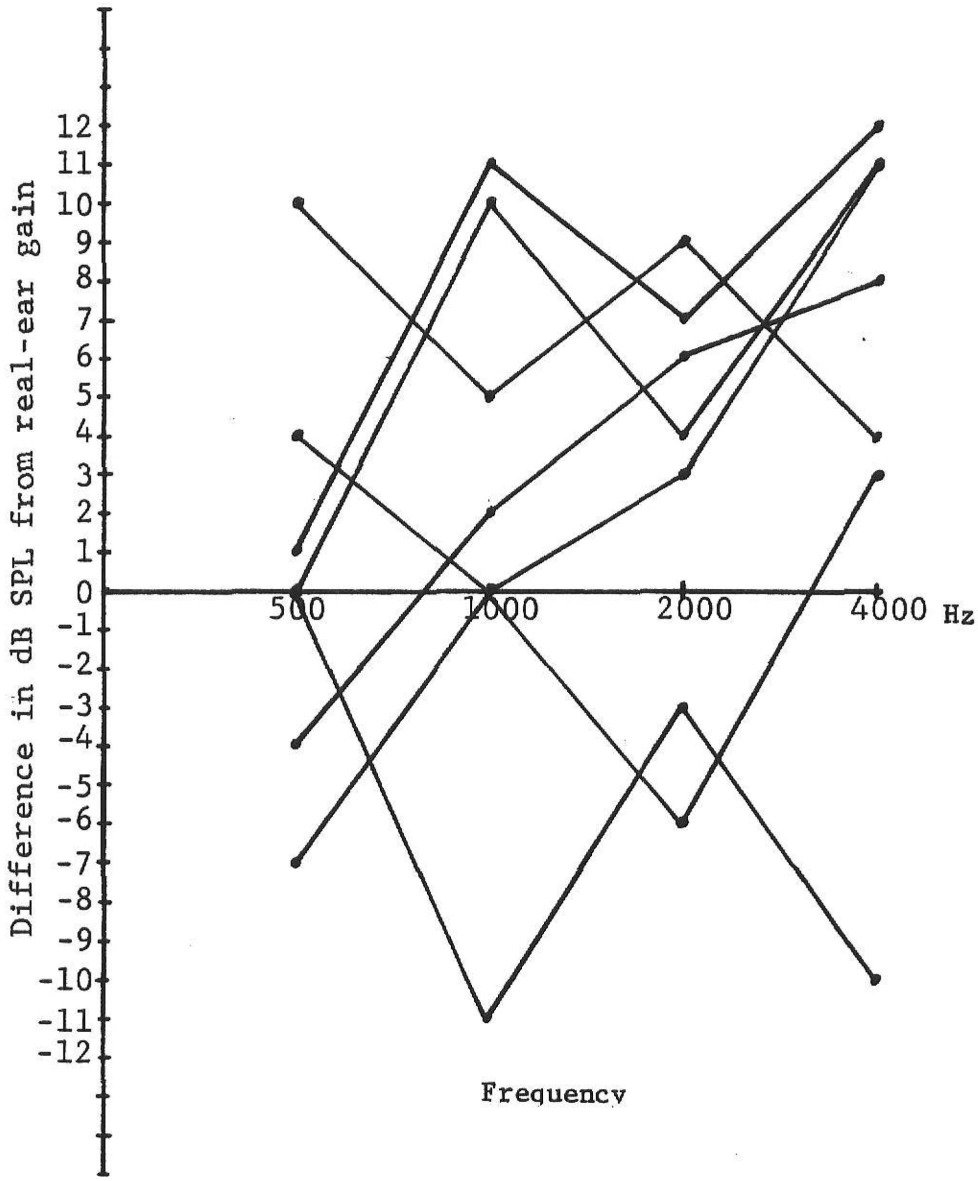

Figure 6. Superimposed plots of differences between 2 cc coupler gain and real-ear gain, by subject.

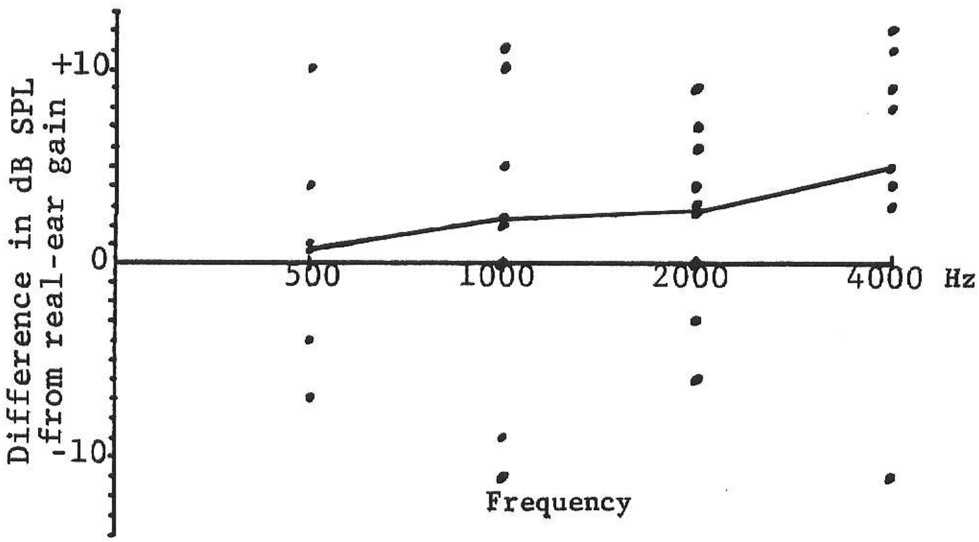

Figure 7. Average difference between 2 cc coupler gain and real-ear gain across subjects, with scatter plot of range.

Individual plots of real-ear gain vs. 2 cc coupler gain are shown in Figures 8, 9, and 10. Sizable differences in gain can be noted.

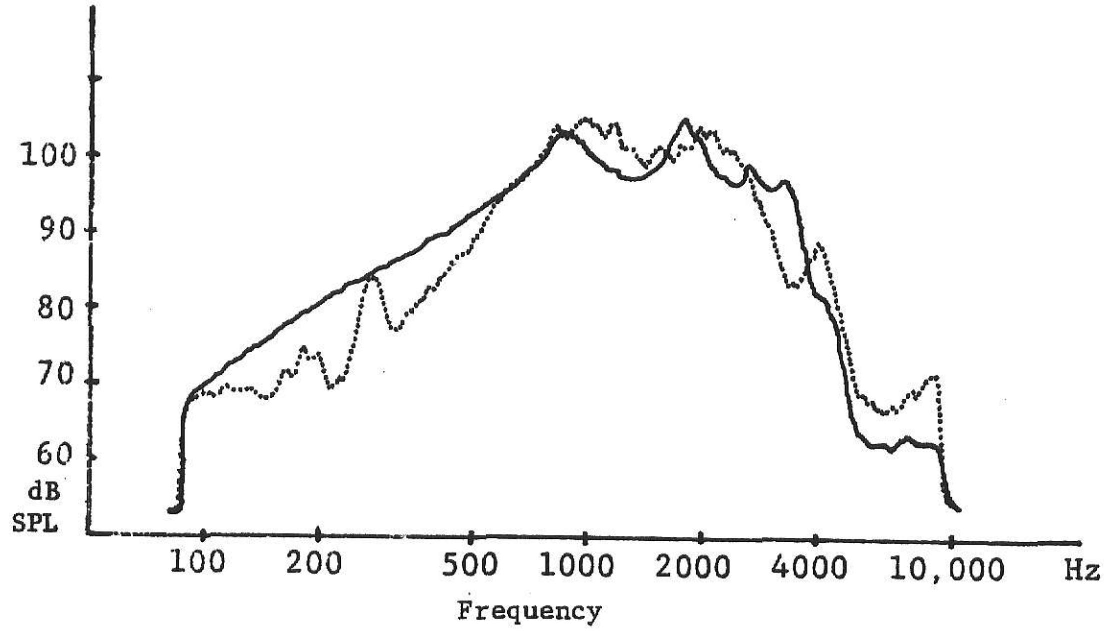

Figure 8. Plot of 2 cc coupler gain vs. real-ear gain, subject LS.

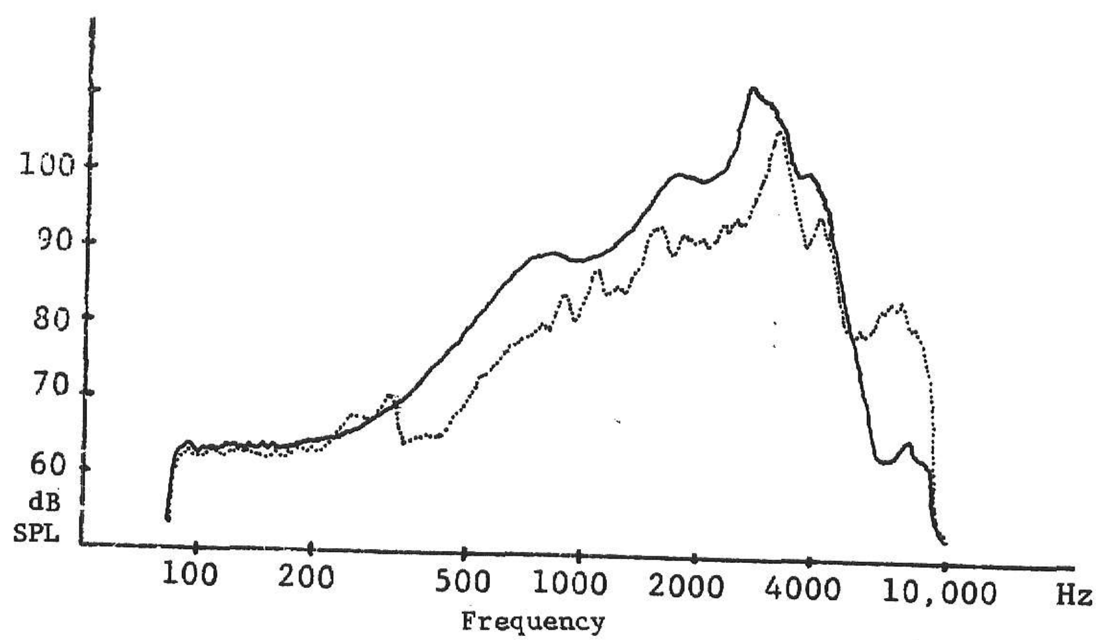

Figure 9. Plot of 2 cc coupler gain vs. real-ear gain, subject MT.

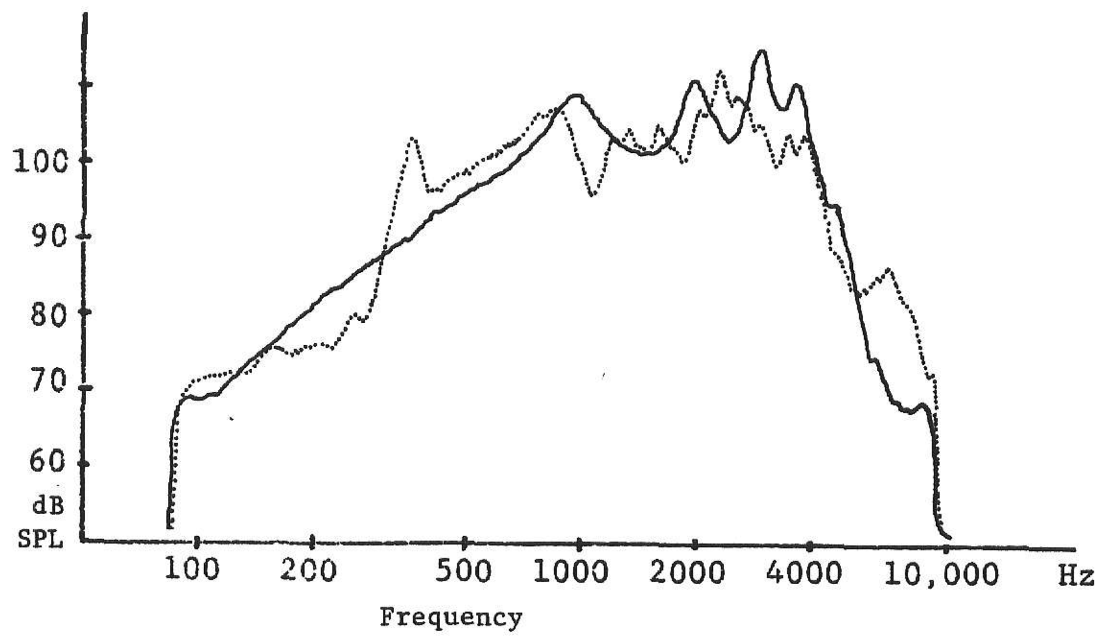

Figure 10. Plot of 2 cc coupler gain vs. real-ear gain, subject CM.

The data analyzed above were limited by the fact that only five subjects were involved in the study; and, due to this fact, levels of significance can lead one to conclude only trends that the data suggest. However, these trends are of interest:

- that the modified Carhart method of hearing aid selection may be able to fit a person with a hearing aid which yields a lower, and therefore better, Spondee Reception Threshold than can Berger's formula method based on a 2 cc coupler measurement or than can an alternate formula method based on real-ear measurement of gain, and
- that subjects fitted by the modified Carhart selection procedure may score lower on word discrimination tasks in the presence of noise than when those subjects are selectively fitted by a formula method.

In addition, in the process of this experiment, it became apparent that the 2 cc coupler measurement of gain of a hearing aid is a poor and inconsistent predictor of the real-ear gain of that hearing aid as measured with a probe microphone. No consistent differences were apparent by frequency; and despite the fact that the average differences across subjects was insignificant, the wide dispersion of differences renders this average meaningless when compared to an individual subject's reading.

DISCUSSION

It was the purpose of this experiment to determine if the miniature probe microphone could offer for the clinician a quick-and-easy method of effective hearing aid fitting. It was hoped that this method would be financially feasible for most clinics, would be less time-consuming than conventional hearing aid trials, and would produce equally good listener performance scores on conventional tests.

From the data described in the previous section, this superior method was not found. Instead two interesting trends appeared:

1) The *traditional modified* Carhart method of hearing aid trial yielded significantly lower SRT scores than those obtained using Berger's formula technique. The modified formula technique yielded scores which were not significantly different from either of them.

This was a surprising trend, and possible explanations can only be speculative. The possibility exists that this difference occurs because in the Carhart procedure, the subject is allowed to adjust the gain setting of each hearing aid while running speech is presented to him at 40 dB HL. It is possible that the subject may adjust the gain to a higher setting than the operating gain level that Berger *predicts* in his formula. We have no empirical evidence to suggest that this was the case in our study. Further study would be needed to determine if, in fact, the Carhart technique does result in client hearing aid fittings with lower SRT scores.

2) The two formula techniques yielded significantly higher word discrimination scores in noise than did the modified Carhart hearing aid trial. The two formula techniques employed in the study had identical means on this measure (see table 4), and therefore showed no

differences. There were no significant differences among any of the three methods on the test of word discrimination in quiet.

The word discrimination task in noise is assumed to be affected most by the presence or absence of high frequency information. It was noted in several cases in this study that the two formula methods called for greater amplification at 4k Hz than was present in the preselected aids used in the Carhart procedure. In fact, it was at times difficult to find a hearing aid which provided sufficient 4k Hz amplification to meet the criteria for the formula approaches.

Of note are two cases in which the formula approaches suggested the prescription of hearing aids with greater 4k Hz amplification than did the Carhart procedure. In these two cases, the increased high frequency information was demonstrated to the subject by verbally presenting the five phonemes /a/, /o/, /i/, /ʃ/, and /s/ to the subject at distances of 2 yards and 5 yards (Ling and Ling 1978). These two subjects were unable to detect the /s/ phoneme at either distance with the aid prescribed by the Carhart method (labeled hearing aid C), yet were able to detect the /s/ phoneme with the aid selected by a formula approach (hearing aid B). However, these two subjects stated that they preferred hearing aid C, the aid with less high frequency amplification. They described the other hearing aid (B) as "harsh," "causing voices to sound whistly," and "letting in more sharp, high sounds." These two subjects were strong in their preference for the aid with less high frequency amplification, and in fact purchased hearing aid C despite the demonstration that their word discrimination scores in noise and ability to detect the /s/ phoneme were greater with hearing aid B.

Listener preference was not a controlled factor in this study; this observation is made from interest only. Perhaps further research should be conducted which includes listener preference as an experimental factor in the design of the study.

It was in evaluating the real-ear high frequency gain of a hearing aid that the miniature probe microphone was often found to be a most useful tool. Figure 8 shows the example of one of the subjects involved in this study. This subject was fitted with a hearing aid according to Berger's formula technique, which measured the gain of the aid using the 2 cc hard-walled coupler. According to that measure, sufficient gain was present at 4k Hz. This aid was then placed in the subject's test ear, with the probe microphone in place, and a real-ear measurement was made. Figure 8 shows first the frequency response as plotted using the 2 cc coupler and hearing aid test box, and then the real-ear measurement of frequency response. A decrease in gain of approximately 10 dB at 4k Hz can be noted. At other times, the real-ear plot showed unwanted peaks in the frequency response of a hearing aid, as in figure 9. In at least one case, the presence of too much low frequency amplification was detected by the probe microphone, causing potential masking of the important high frequencies (see figure 10). These various examples demonstrate the clinical usefulness of the miniature probe microphone. Through its use, the clinician may be made aware of what earmold modifications might be most beneficial for a given hearing impaired listener.

It is this experimenter's conclusion from this study that the miniature probe microphone is a fairly practical and useful clinical tool. The cost of the entire microphone system was not prohibitive (approximately $1,000.00) and the two miniature microphones could be replaced for approximately $100.00 per pair. The method for insertion was learned easily, and was accomplished without client complaint. Once inserted, the placement of the custom earmold was straightforward. It was mandatory that the custom earmold fit very well to avoid leaks around the probe microphone wire. Calibration of the microphone system was carried out without difficulty. In addition, as Harford (1980a) demonstrated, this study found that the readings of the probe microphone were replicable over a number of insertions.

Harford (1980b) suggested that the probe microphone might be most useful when fitting difficult-to-test clients. This study involved only cooperative adult subjects; however, insertion of the probe microphone was easily accomplished in all cases. It can be presumed that the microphone could be successfully inserted in the ears of difficult-to-test clients. In these cases the real-ear information would be highly valuable for successful hearing aid fitting. In any case where a hearing aid trial is not feasible, the probe microphone could offer quick and valuable information.

One problem with the probe microphone was encountered. After testing four subjects and removing the plastic sheath from the test microphone after each subject's trial, the wires at the base of the microphone became disconnected, presumably from removing and replacing the sheath. Within a week, the Starkey company replaced the pair of microphones and no delays were caused. No further problems of this type occurred during the remainder of the study. However, this could be a weak point in the probe microphone system, and it is uncertain if repeated clinical use could cause this problem to arise again.

In addition to comparing listener performance across method of hearing aid fitting, this study also included a comparison of 2 cc coupler measurements and real-ear measurements of frequency response. These results were charted in the previous section. As was stated, no trends of any type could be noted which could describe a predictable relationship between the 2 cc coupler reading and the real-ear plot. It is true that the average difference curve shows fairly good agreement of the two in the low frequencies and a tendency of the 2 cc coupler to overestimate gain in the high frequencies, and a t-test for related samples showed no significant differences between average gain measurements. Nevertheless, the very wide dispersion of scores demonstrates that to a specific listener this very small "average" trend means very little.

Again, very few subjects were involved in this comparison, and so this lack of predictability should be interpreted with caution. A total of seven comparisons were made on five different subjects. For one of these subjects, the 2 cc coupler measurement greatly underestimated the real-ear gain at virtually all frequencies; in all other cases (except at one frequency for one subject) the 2 cc coupler overestimated real-ear gain. This particular subject was tested with two different hearing aids, and the 2 cc coupler underestimated real-ear gain with both aids. It is not clear as to why this particular subject did not fit the pattern. Perhaps 20% of all hearing impaired persons would show this same trend. The data are not conclusive on this point.

The most useful conclusion which can be drawn from these data is that the individual real-ear readings varied so greatly from the 2 cc coupler readings (an overestimation by as much as 12 dB and an underestimation of as much as 13 dB) that even a coupler which gives an excellent average measurement of real-ear gain will be of limited use to the individual. It is of questionable value to fit a person with a hearing aid based on an estimate of gain which may fit that person no better than this.

It has already been pointed out that a major drawback of this study is the small number of subjects tested. The levels of significance, therefore, were higher than is desirable, and it can only be concluded that further study is warranted.

Another potential drawback occurred because of the desired order of experimental procedure. For all subjects, the same order of presentation was used for purposes of comparison. The subject was first fitted by Berger's technique, then by the modified formula method using the probe microphone so that these two could be immediately compared for each subject. The traditional Carhart hearing aid trial followed, usually on a subsequent day. This could cause a possible order effect, including either a learning effect or a fatigue effect, which could compound the results. In order to minimize learning effect, a sufficient number of word discrimination lists were used (12) so that no subject was tested on the same word list twice in the same day. To minimize fatigue effect, frequent breaks were taken as necessary, and a long break was taken between the fitting by Berger's method and the probe microphone fitting, when both were done on the same day.

Further study involving a greater number of subjects would perhaps reveal more about the trends noted here. Decisions concerning hearing aid fitting are complex, and it cannot be stated that any one single performance score is the single most important factor in hearing aid fitting. Further research may reveal more about how well subjects are able to function in daily life when fitted with hearing aids by either formula techniques or by the conventional procedures. It would seem the next logical step would be to evaluate listener performance on more complex tasks other than the word discrimination tasks. Perhaps with a more complex listening task, "successful" hearing aid fitting can be better defined, and perhaps a single method of fitting can be found which produces more highly successful fitting.

One element in successful fitting is listener satisfaction, and to achieve listener satisfaction the listener preference step must be included. A hearing aid may seem to the clinician to fit a hearing impaired person's needs, but a dissatisfied listener will not use the hearing aid optimally. If, in fact, high frequency amplification provides greater information necessary for discrimination of speech in noise, but causes harshness and unwanted quality of sound, then this must be studied further. It would seem, therefore, that listener preference should be included systematically in any further research concerning hearing aid fitting.

Finally, the basic premises underlying the formula approach to hearing aid fitting need additional study and questioning. The basic underlying philosophy of any formula approach assumes that any two hearing impaired persons with the same audiogram will be best fit with the same hearing aid. This premise is being questioned by a number of authors, including Millin (1980). He pointed out that persons with identical audiograms do not necessarily perform identically on speech tasks and that they do not perform equally well in the same listening environments. Millin cited Ward (1978) and Yanick (1978) in hypothesizing the wide variety of parameters other than intensity and frequency response which contribute to a hearing impaired person's understanding of speech. These would seem to negate the concept of formula fitting. Still, until more reliable and successful methods of hearing aid fitting are designed, the formula methods seem to be as successful as the tedious and time-consuming traditional method. For this reason, further comparative study is warranted, and it is this author's opinion that the miniature probe microphone should be included as a factor in this research.

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A COMPARISON OF TRADITIONAL VS. FORMULA HEARING AID SELECTION METHODS, UTILIZING PROBE MICROPHONES

by

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ABSTRACT

Listener performance of five subjects was compared when each listener was fit with a hearing aid by three different methods: 1) Berger's (1977) formula method based on gain measured with a 2 cc coupler, 2) a modified formula method based on real-ear gain measured using a Starkey RE 4 probe microphone inserted in the subject's ear canal, and 3) the modified Carhart selection procedure. Listener performance in aided and unaided conditions was measured on three tasks: 1) Spondee Reception Threshold (W-22 list A), 2) word discrimination in quiet, WDS-Q (NU-6 lists A, B, and C), and 3) word discrimination in noise, WDS-N, (NU-6 lists A, B, and C) presented at a S/N of +10 dB . Listener performance on these three tasks was obtained using all hearing aids involved in the three selection procedures. Significant differences on two tasks (SRT and WDS-N) were found when the three selection methods were compared. Differences were attributable to method of fitting. The modified Carhart method yielded a lower SRT but a poorer word discrimination score in noise than either of the formula methods.

In addition, gain measured using the 2 cc hard-walled coupler was compared to real-ear gain measured using the probe microphone. The correlation between the 2 cc coupler measurement and the real-ear measurement was low at each frequency across subjects, and the dispersion of differences was wide.