69-18,456

McDONALD, Frank Douglas, 1932-
EFFECTS OF EARMOLD ALTERATION UPON SOUND PRESSURE LEVELS GENERATED IN THE HUMAN AUDITORY MEATUS.

The University of Oklahoma, Ph.D., 1969
Health Sciences, general

University Microfilms, Inc., Ann Arbor, Michigan

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

EFFECTS OF EARMOLD ALTERATION UPON SOUND PRESSURE LEVELS GENERATED IN THE HUMAN AUDITORY MEATUS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

FRANK DOUGLAS McDONALD

Oklahoma City, Oklahoma

1969

EFFECTS OF EARMOLD ALTERATION UPON SOUND PRESSURE LEVELS GENERATED IN THE HUMAN AUDITORY MEATUS

APPROVED BY

DISSERTATION COMMITTEE

ACKNOWLEDGMENTS

The author wishes to express his gratitude to the following:

To Dr. Gerald A. Studebaker, for his guidance and encouragement through out the preparation and conduct of this experiment.

To Dr. Joseph Barry, for his technical advice during the preparation of the experimental apparatus.

To Dr. William A. Cooper, for allowing use of Veterans Administration Audiology facilities for the purposes of screening of subjects and preparation of earmolds used in this study.

To the dissertation reading committee and final examination committee, comprised of the aforementioned and Doctors John E. Allison and Howard B. Ruhm.

To the Veterans Administration Hospital, Oklahoma City, for providing funds to support this study through their traineeship program in Audiology, and for providing the services of their ENT staff for the otological examination of subjects used in this study.

To the Speech and Hearing Center, University of Oklahoma Medical Center, for furnishing instrumentation and testing facilities for this study.

To my wife, Betty, for her patient, understanding and inspirational attitude, and for skillful management of the household and our four children during my studies.

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CHAPTER I

INTRODUCTION

The earmold is a retentive-coupling device which channels sound from a hearing-aid receiver to the tympanic membrane of the wearer's ear. At various times this device has been referred to by names such as ear-insert, ear-piece, ear-stopple, ear-retainer, retentive auditory prosthesis, aural prosthesis and earmold. The term earmold, because it is the most widely used and accepted term, will be used in this study.

The first need for the earmold as a device which couples the hearing-aid receiver to the ear arose in the 1920's with the development of the miniature-type receiver (12). Dentists and dental laboratories were closely associated with the early efforts in earmold fabrication because of the necessity for knowing how to work with impressions and how to process these impressions into permanent earmolds (88) (97) (99). Even today, the fabrication process used by earmold laboratories closely parallels that used in the production of certain dental prostheses (54) (60) (104).

Earmolds are available in a variety of hard or soft materials and may be classified into two broad categories, i.e., custom and stock types. The custom earmold is fabricated from an impression of the individual user's ear, while the stock earmold is mass produced in various sizes which presumably represent "average" ears. For a variety of reasons which have been discussed elsewhere (13) (29) (52) (59)(62) (74) (97) (98) (99), custom earmolds are generally preferred over stock earmolds.

Both the custom and stock types, may be obtained in a number of different styles. The different earmold styles, or forms, have developed in an attempt to reduce the visibility of the earmold while in place in the ear, or in an attempt to modify the frequency response of a hearing aid, or both. This study is concerned with the influence of earmold modifications on the frequency response of a hearing-aid receiver.

In 1941, Schier (100, p. 53) stated,

> Any commentary on hearing aids must note the tremendous discrepancy between the amazing amount of energy invested in all things pertaining to the instrument proper, and the mere casual thought alloted to the one connecting link that can readily disrupt all calculations and instrument, the earpiece.

More recently certain writers have expressed concern over the fact that little has been written relating to the earmold as a part of the hearing-aid system. For example, it has been referred to as the "Black Sheep of Audiology" (22), and the "Orphan of the Hearing Aid Industry" (31). That this concern is well founded is manifest when one reviews the literature in this area. There are few articles which deal directly with the earmold and its acoustic effects. Even though the earmold is an important part of the hearing-aid acoustic system, it is usually found that in articles dealing with hearing aids the earmold is only casually mentioned or is ignored completely.

The literature reveals that studies have been made of the effects of changes in earmold sound-channel length and diameter (19) (21) (28) (37) (65) (71) (73) (79) (96) (101) (105) (107), of snap-ring recess volume effects (19) (21) (65) (71) (73) (107), of certain effects caused by varying the length and diameter of sound-input tubing used in certain earmold styles (15) (19) (28) (68) (71) (74) (106) (109), of effects of volume changes between the eardrum and the earmold tip (65) (71) (73) (107), of venting, or leakage, effects upon the earmold acoustic system (6) (15) (19) (21) (28) (61) (71) (82) (114), and of earmold effects upon the ability of subjects to discriminate speech stimuli in environments of quiet and/or noise (26) (45) (53) (63) (76) (78) (80) (87) (90) (91) (113). The most comprehensive investigation regarding the effects of earmold alteration on the hearing-aid frequency-response curve was accomplished with the earmold coupled to a 2-cc (two cubic centimeters) cavity constructed of metal (65) (71). Only a few investigators have studied acoustic effects of earmold alteration on real ears (28) (96) (107) (114). Ewertsen, Ipsen and Nielsen (28) measured SPL's (Sound Pressure Levels) on a 2-cc coupler and on the human ear as well, investigating the effects of earmolds with long and narrow sound channels with those having short and wide sound channels. They also studied the effects of long versus short tubing, and the leakage effect caused by loosening the earmold in the ear canal. Wandsdronk (107) measured the effect on frequency response when altering either the snap-ring recess, the sound-channel dimensions, or the volume between the eardrum and the earmold tip. Sandberg and Nielsen (96) compared responses obtained with two earmolds, one with a receiver coupled to it in the "normal way" and the other with a smaller receiver incorporated into its canal tip. Zachman (114) compared the SPL's obtained with vented and unvented earmolds both on a 2-cc coupler and in the human auditory meatus. To date, no study of SPL's in real ears has been reported which compares the acoustic effects of a standard-style earmold with those of drastically modified earmold styles which have recently been made available commercially.

This study is intended to contribute needed information about the acoustical effects of certain earmold alterations upon the total ear-earmold-receiver-hearing aid acoustic system. The sound pressure levels produced in the external auditory meatus were measured at selected fixed-frequencies with signals channeled into the meatus through four different earmold forms. This was accomplished utilizing a probe-tube microphone system to measure SPL's within the ear canals of human subjects with the earmolds positioned in the ear.

CHAPTER II

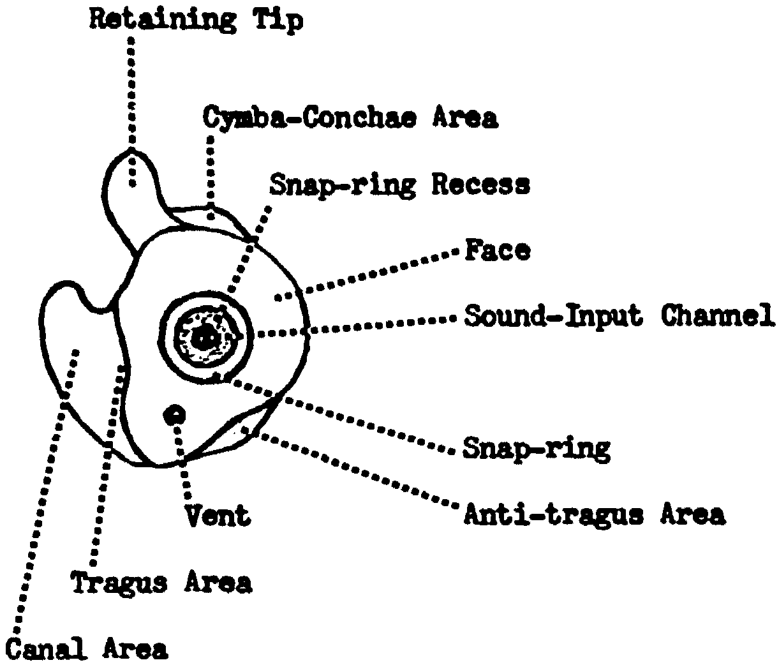
REVIEW OF THE LITERATURE

Introduction

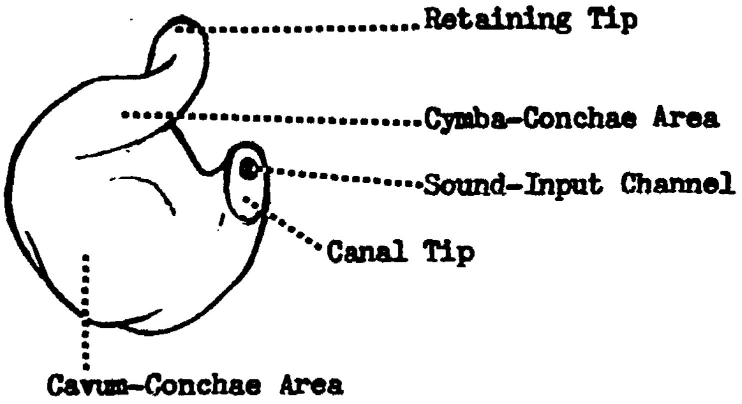
The hearing-aid earmold has the basic function of holding the hearing-aid receiver to the ear. In addition to this fundamental purpose the earmold, depending upon its physical dimensions, may be used to produce changes in the acoustic response of a total hearing-aid system. In this chapter historical and experimental information regarding the earmold is discussed. A short history of hearing-aids is presented first because it chronologically precedes and includes the history of earmolds. A review of the literature relating to acoustic coupling effects as determined in couplers and in human ears follows. In order to avoid confusion regarding terms relating to various parts of an earmold, Figure 1 shows the earmold nomenclature to be used throughout this dissertation.

Hearing Aids and Earmolds

Various devices to aid hearing have been used over the centuries, e.g., the cupped hand, conch shells, animal horns, man-made horns, speaking tubes, sound-conducting fans, and other mechanical devices. Jackson (51) credits Ferdinand Alt of Vienna with conceiving and producing the first amplified electric hearing aid in 1900. Hayden (43)



Face View



Canal View

Figure 1 — Earmold Nomenclature of a Conventional Earmold for the Left Ear.

however states that Alexander Graham Bell invented the first electric hearing aid in 1875 for his deaf mother. He further adds that Bell perfected the telephone from this hearing aid two years later. In 1902, the first commercially available hearing aids were manufactured in the United States (109). These were referred to as carbon aids because carbon granules were basic to their operation. In addition to a number of other limitations, the amount of amplification provided by the carbon-type hearing aids was very small, i.e., hardly 10 to 15 decibels (10 to 15 dB) over a frequency range from 1000 to about 1800 Hertz (Hz) (109).

The first hearing aid to offer significant amplification was the vacuum-tube type which became available in the early 1920's (109). Hanson (40) devised such an instrument in 1921, and gave credit to a number of people for making the vacuum-tube hearing aid possible. He related that Bell invented the telephone, Blake, Edison and Berliner improved the telephone transmitter, Fleming improved Edison's two-electrode vacuum tube which grew out of the incandescent lamp, and DeForest inserted the third electrode in the Edison-Fleming tube thereby making it an amplifier. Vacuum tubes initially were large and hearing aids utilizing them varied from console-sized units to portable units which could be carried around like a suitcase (109).

A custom earmold which attached to a cornet-type hearing device was manufactured by F. C. Rein and Son of London in the 1870's (12). Schier (97) recalls his having made an individually molded earpiece in 1920 which had a "hollowed-out" body and a "wide-open canopy vulcanized on to it." These earlier applications for earmolds are of interest only from the standpoint that they preceded the use of the earmold with the electronic hearing aid. The wide demand for hearing-aid earmolds grew directly from Hugo Lieber's introduction, in 1922, of the midget air-conduction receiver for use with electronic hearing aids (43). Earlier transducers were held at the ear either by hand or by headband due to their relatively large size; however, the small size of the midget receiver allowed it to be held near the ear by connecting it to an earmold which fit into the ear canal of the user.

In the United States, earmolds were first produced on a wide commercial scale in 1925 when the Western Electric Company licensed the S. S. White Dental Company to make custom and stock earmolds for their hearing aids (12). Dentists and dental laboratories, both civilian and military, have played a large part in the development of the earmold, particularly as related to impression techniques, fabrication processes, and the materials used in both (52) (77) (98) (100). Schier (100) investigated over 50 different earmold materials, and introduced the widely used methyl methacrylic resin as a result of his investigation. He credits Rohm with the discovery of the material in 1909. A wide variety of earmold materials have been and are being used both in the making of ear impressions and in the fabrication of the finished earmold. Discussions of these materials can be found elsewhere (1) (9) (14) (30) (48) (62) (64) (74) (93) (99) (100) (103) (115).

There are two fundamental approaches to earmold fabrication. The first, and older, way to obtain an earmold is to make an impression of the hearing aid user's ear and mail that impression to an earmold laboratory for production of the finished earmold. The second way is to use a material for making the ear impression which can be worked directly into the finished earmold. The first approach requires only the skill of making an accurate ear impression. The second requires, in addition, the skill necessary to work the impression into a wearable earmold form, a skill which appears to have received no attention in the literature. The process of making an ear impression, however, is described by many authors (14) (23) (25) (47) (48) (60) (84) (102) (104) (115).

The demand for earmolds has continued. The development of miniature vacuum tubes by the Thomas Houston Company of England in 1934 made possible the first wearable vacuum-tube hearing aid in this country three years later (109). The invention of the transistor by John Bardeen, William Shockley and Walter Brattain in 1948 (18) made possible the first transistor hearing aid, a body-worn instrument which was produced in 1952 (5). Further miniaturization of hearing-aid transistors and transducers made possible the introduction of head-worn instruments in 1955 (75). With head-worn aids the possibility of audible acoustic feedback at high gain settings became greater because of the close proximity of the microphone and the receiver's output point. Therefore, a tight and accurate fit of the earmold became especially important (46).

A drastically modified earmold known as the "Acoustic Modifier" was introduced late in 1963 and patented several months later by the Zenith Corporation (104). In the literature, the term "vented earmold" is commonly used to refer to an earmold which is similar to the Acoustic Modifier in design. According to McGee (78) the Acoustic Modifier is made in the following manner: The canal portion of the earmold is shortened to its limit, then the remaining sound transmission canal is hollowed out and one or more vent holes is drilled into the hollowed-out interior from the flat outer surface (face) of the earmold. McGee states that the Acoustic Modifier was originally designed to help a particular type of hearing impairment, viz., a sensorineural impairment characterized by normal or near-normal hearing sensitivity for low frequencies up to about 1000 or 2000 Hz, and a high frequency drop in hearing sensitivity above that region.

In 1965 Harford and Barry (42) introduced a new approach to the treatment of persons with certain types of unilateral hearing loss by routing sound from the vicinity of the impaired ear, across the head, and presenting the sound to the relatively good ear using an "open", or nonoccluding, earmold. They referred to this principle as "contralateral routing of signals", or "CROS." CROS is accomplished by placing the hearing-aid microphone near the impaired ear, and the amplifier, receiver and an open earmold on the good-ear side of the head. Five years earlier Fowler (31) had suggested the benefit of bringing the signal arriving on the impaired-ear side of the head around to the good-ear side, although he did not mention the use of an open earmold. According to Harford and Barry (42) the function of the open earmold is to hold the sound-input tubing firmly in the ear canal. In some instances shaped-tubing has been successfully substituted for the open earmold.

The CROS hearing aid was originally designed to be used on unilateral hearing-loss cases, but it has recently been suggested that persons having either sensorineural impairments of a precipitous nature or bilaterally-symmetrical sensorineural impairments displaying slightly sloping audiometric patterns can also benefit from the use of CROS hearing aids (27) (33) (34) (41) (69). Since the introduction of the initial CROS type hearing aid other types of modified CROS aids have appeared on the scene, e.g., the BiCROS (41), the UniCROS (27) and the Power CROS (27). Of these modified CROS aids, only the UniCROS employs an open earmold.

In 1966, Lybarger (68) stated, "Body aids have been halved in weight about every 6 years, to a current typical weight of some 1½ ounces. Ear-level aids are being halved in size about every 3½ years to a current typical value of ¼ to ½ ounce." The trend toward even smaller aids continues today, with all-in-the-ear instruments being widely available commercially. A more detailed account of the historical development of hearing aids up to the 1940's has been presented by other writers (109). Various types of instruments used to aid hearing over the years may also be found elsewhere (5) (12) (13) (16) (17) (24) (27) (32) (36) (40) (42) (43) (44) (68) (72) (75) (83) (95) (109) (112).

Development of the 2-cc Coupler

A coupler is defined by Beranek (10, p. 18) as "a cavity of predetermined shape used in the testing of earphones. It couples the earphone to a microphone."

The early development of couplers, including the 2-cc coupler, in this country was due primarily to research efforts at the Bell Telephone Laboratories and the wartime Electro-Acoustic Laboratory at

Harvard (11). According to Beranek (11), the first successful attempt at developing an artificial ear was described in 1932 by Inglis, Gray, and Jenkins (49). Their artificial ear consisted of a special coupling device designed to present the same acoustic load to a receiver as does the "typical human ear," a small condenser microphone, and a means for amplifying and measuring the voltages generated by the condenser microphone. The cap of the receiver under test rested upon "a molded soft rubber insert" which had the "internal contour of the auricle." These experimenters aimed "to overcome previous objections" to the use of such substitutes for the human ear so that they could "be used with confidence in general testing and physical measurement of telephone transmitters and receivers"(49). The coupler used with this artificial ear was designed for supra-aural type receivers, but had a definite influence upon the design of couplers intended for use with the miniature-type receivers.

In 1940, Ballantine (7) described the "Type 505" artificial ear which was designed to test "the acoustic output of a telephone receiver or hearing aid reproducer." It was meant to simulate the human ear's acoustical properties and provide an "unvarying standard for testing." Its dimensions were determined after taking into consideration measurements of acoustical impedances of the ear made by W. West, by J. Troeger, by Inglis, Gray, and Jenkins, and by Ballantine himself. Although the actual dimensions of the artificial ear were not given, Ballantine did give the dimensions of an adapter which could be fitted into the rubber auricle of the artificial ear and simulate the "acoustic condition" which exists when a hearing-aid receiver with "eartip" attached is worn on the ear. The adapter had a duct approximately 5/8 inch long and 3/32 inch in diameter. Ballantine stated that the frequency-response characteristic obtained would enable one to estimate the tested instrument's "fidelity of reproduction."

Romanow (92) in 1942 offered dimensions for a 2-cc coupler that could be used to measure the response of a "small air-conduction receiver," and stated that the technique for measuring hearing aids could be "very much simplified by the use of a closed coupler." He recommended that the coupler have a cavity with a volume of 2 cc, and a tubular entrance to the cavity with a length of 0.710 inch and a diameter of 0.120 inch. A condenser microphone was suggested for terminating the 2-cc cavity, to serve the purpose of measuring the sound pressure in the cavity. The 2-cc cavity was chosen "to simulate the average volume which obtains in the human ear after the insertion of an earpiece." The dimensions of the tubular entrance were chosen to correspond to the "representative size of the holes in earpieces." The earpiece "holes" in Romanow's statement may also be identified as sound-input channels (see Figure 1) or earmold "bores."

In 1944, Sabine (94) coupled a receiver-earmold combination to a 2-cc cavity for the purpose of measuring hearing-aid frequency response. He positioned the earmold adjacent to and feeding into the 2-cc cavity, and kept it in place by using a wax material around it. As a result of his experimentation with the cavity he concluded that the 2-cc cavity would yield reliable measures for hearing aid comparisons.

In 1945, a committee of the American Hearing Aid Association suggested dimensions to be used in the construction of couplers which are utilized in determining hearing-aid response. These dimensions, as set forth in a tentative code for the measurement of performance in hearing aids by Kranz in 1945 (57), correspond with the entrance tube and cavity dimensions suggested earlier by Romanow (92). These dimensions were incorporated into the 1949 American Standard Method for the Coupler Calibration of Earphones (3), and into the 1953 American Standard Method for Measurement of Characteristics of Hearing Aids (2). The American Standard S 3.3-1960 is the current standard offering methods for measurement of the electroacoustical characteristics of hearing aids (4). In this standard only slight changes have been made in the Type 2 coupler, now referred to as the Type HA-2 Coupler, i.e., the tubular entrance now is to have a length of 0.709 inch, or 18 millimeters (mm), and a diameter of 0.118 inch (3 mm), while the cavity retains the same 2-cc volume. According to Lybarger (67) two new coupler forms, Type HA-1 and Type HA-3, were added to take care of newer earphone designs employed in eyeglass and behind-the-ear hearing aids.

The 2-cc Coupler Frequency Response

Nichols, et al.(86), as reported by Beranek (10), compared responses obtained on a 2-cc coupler with responses obtained or the real ear using the probe-tube microphone technique. They used one dynamic, three magnetic, and two crystal earphones coupled directly to the 2-cc coupler, and coupled to a conventional earmold which was seated in the ear canal. Three subjects were used for the real-ear tests. the earphones were "sealed to the ear with a mixture of beeswax and lanolin." Differences between the real-ear and coupler responses were greatest for one of the two crystal earphones. It showed no difference at 800 Hz, 7.5 dB difference at 200 and 1400 Hz, and 7 to 12.5 dB difference from approximately 2100 to 4700 Hz. For the dynamic and magnetic earphones differences were no greater than approximately 3.5 dB below about 1100 Hz, but were as great as 8 to 10 dB above that point. As the Nichols, et al. (86) report was not made available to the public, and is presented only in part by Beranek (10), the conclusions of the author are not known. However, others (105) state that the Nichols, et al. study showed that the 2-cc coupler "represents approximately the same load to the earphone as the human outer ear canal . . . up to about 3000 or 4000 c/s, as measured with probe technique."

Wiener and Filler (111) compared response curves obtained on real ears with those obtained on a 2-cc coupler, using HS-30 magnetic-type earphones with "semi-insert tips." They found that the agreement between the real-ear and coupler responses was good. The frequency response range was from 100 to approximately 4800 Hz. No differences greater than approximately 3 dB were noted from 100 to about 2300 Hz, or above about 3200 Hz. No differences greater than 5 dB were found in the range 2300 to 3200 Hz.

Jonkhoff, according to van Eysbergen and Groen (105), compared real-ear and coupler responses and found that below 3000 Hz the two response curves have "the same trend for all practical purposes," but that beyond 3000 Hz "the coupler curve falls off too sharply and too far with respect to the human overall performance."

Ewertsen, Ipsen and Nielsen (28) state, "Measurements by means of a specially constructed probe tube have shown the same frequency response characteristic for an earphone, measured on a human ear and on a 2-cc coupler." They found, however, that an earmold having a sound channel length of 22 mm and a diameter of 2.4 mm agreed best with the coupler response.

Lybarger (68) utilized both ears of one subject to compare responses obtained when using earmolds in real ears with those obtained on a 2-cc coupler. One of his subject's ears had a "pathological condition, possible otosclerosis," that was "indicated by an almost uniform hearing loss of about 30 to 35 dB (ASA-1959)." A "custom-molded ear insert that was placed in position just as it would normally be worn" was used while making the real-ear tests. Neither the type of earmold nor the type of receiver used is described. On the subject's normal ear it was found that "the differences between the sound pressure developed in the 2-cc coupler and in the actual ear canal are relatively small except in the region below 500 cps where the sound pressure developed in the actual ear canal drops off materially because of leakage around the earmold." Testing the pathological ear he found that the real ear and the 2-cc coupler agreement was "good up to about 1000 cps except for the falling off below 500 cps due to leakage around the earmold," but the agreement was "very poor at the higher frequencies." Lybarger stated that the same hearing aid placed on the pathological ear of this subject would develop some 15 dB more SPL than would be developed on the normal ear. He concluded,

> It would thus appear that on some types of ears, possibly those with conductive losses, the 2-cc coupler does not realistically simulate the situation. For normal ears, and probably for ears with sensorineural involvement only, the 2-cc coupler based on the above measurements and on others that have been reported appears to be a very good simulation of the situation.

He added, however, that more ears must be tested before generalized conclusions can be drawn.

van Eysbergen and Groen (105) studied coupler responses as compared with real-ear threshold determinations converted to SPL's. Measurements were made with two stock-type "nipple" earmolds, neither of which met the requirements of the standard-sized bore as used in the 2-cc standard coupler. They found poor agreement between the real-ear response and that of the 2-cc coupler. They recommended that the 2-cc coupler be used only to provide information for international exchange. For the purpose of obtaining "information on the useful frequency range of the receiver (hearing aid)" they recommend the use of a 0.5 ml (.5 cc) coupler of their own design.

In 1947, Nichols (85) proposed that it is not always safe to apply data taken in the physical laboratory to the problem of "fitting" a hearing aid. He pointed out that the cavity of the artificial ear is only an approximate simulation of an "average" human ear, and its walls are rigid, whereas in the human ear the walls are softer and more yielding, and as a result there is considerable acoustic damping in the human ear. He states that many earphones exhibit response characteristics which are highly peaked at some frequency or frequencies when measured on the artificial ear; however, when these earphones are used on the human ear, these peaks may be absent or greatly diminished. Further, leakage between the coupling of the receiver to the artificial ear and the coupling of the receiver to the earmold may differ.

Others have also questioned the value of drawing conclusions about real-ear response from tests on a coupler, e.g., Krarup and Nielsen (58) used individually-molded earmolds for making probe-tube microphone measurements, and compared these measurements with the response of a 2-cc coupler. They found considerable variation between the response obtained on the coupler and the responses obtained in the real ear.

Briskey, Greenbaum and Sinclair (15) compared probe-tube measurements made in the real ear with measurements made on the 2-cc coupler. They found that "the 2cc coupler records a redistribution of sound energy at higher frequencies than that indicated by the probe sound pressure measurements made in the subject's ears." The coupler measurement had a resonant frequency of the "last peak" (presumed to be the highest peak frequency-wise) of approximately 2800 Hz; however, in the probe-tube measurements they found that the resonance of the last peak occurred at approximately 2100 Hz, and that the response curve decayed at higher frequencies. The authors conclude that the 2-cc coupler does not give the same response that occurs in the real ear as determined by probe-tube measurements. In an attempt to evaluate what the real ear "perceives" as compared with hearing-aid performance on a coupler, they made measurements using narrow bands of noise centered at third-octave intervals as presented to "normal hearing" subjects in a sound field. Thresholds for the noise were traced by the subjects on a "Bekesy audiometer." Body-type hearing aids were then tested independently in the same ear and set at a "low gain" level, after which thresholds were re-run using the same Bekesy threshold technique and the same sound source. When the two conditions were compared the real ear frequency responses had a "wider band" than those recorded with the coupler, and they had "more gain in the low frequencies." Also the real ear responded to bands of noise out to "7 and 8 Hz, although they were somewhat reduced in gain." On the basis of these findings the authors conclude that "subjective loudness as a free-field measurement does not correlate with the standard hearing-aid frequency response" (15).

Zachman (114, p. 87) states,

> The metal 2cc coupler is not adequate for the evaluation of the changes in frequency response of hearing-aid-receiver-earmold systems produced by modifications in the earmold. Results obtained on a 2cc coupler give a false picture of what is taking place in the real ear. This is probably due to the differences in damping between the real ear and this coupler.

The International Electrotechnical Commission (IEC) Publication 126 (50) specifies a 2-cc coupler which has the same recommended dimensions as the American 2-cc standard coupler. This publication clearly states that the use of the 2-cc coupler "does not allow the actual performance of a hearing aid on a person to be obtained; however, the IEC recommends its use as a simple and ready means for the exchange of specifications and of physical data on hearing aids."

Acoustic Effects of Earmold Modification

Early Observations

Early writers urged the use of individually made earmolds not only for comfort and retentive purposes, but for prevention of sound leakage as well. Lederer and Hardy (62) reported that a poorly fitting ear insert could lessen the "efficiency" of a hearing aid by as much as 20 dB; however, they did not elaborate on the effects across the frequency range, nor did they cite research in support of their remark.

In 1933, Schier (99) suggested that "advanced cases of auditory deficiencies" must have an accurately fitting earmold with a lengthy auditory tip, and stated that this "increased sound conduction and induced greater stimulation of the middle ear structures."

Halsted and Grossman (39) in 1942 recommended that patients with middle ear impairments should have an earmold with a "long tip" and a sound canal of approximately 3 mm in diameter, while persons with impairment due either to "pathology of the organ of Corti" or due to "insufficiency of the neural acoustical pathways" should have a "short tip" and the sound-conveying channel should be "as wide as possible." No data was cited to support these recommendations.

Grossman (35) did an experiment in 1943 using three different earmolds with an unspecified number of subjects who rated the earmolds as to their rendering speech "more or less bright" and intelligible when used with a hearing aid. The study was performed in a "normal office room." The examiner spoke into the microphone of the hearing aid from a distance of 10 feet, and the unaided ear was masked by the subject's moving his index finger rapidly in the external canal. The three earmolds used had sound channels which were 22 mm long, and diameters of 1.5, 3.0, and 5.0 mm respectively. The subjects judged the earmold having the 5.0 mm diameter channel as best, and the 1.5 mm diameter channel as poorest. Grossman explained the results on the basis of the best mold's offering more "naturalness" because it interfered less with normal dimensions of the aural canal and also because it lacked the "filter action" found in the other earmolds. He recommended that an earmold for a middle-ear impairment should have a long tip and a sound channel of no less than 3 mm in diameter, while the earmold for a perceptive impairment should have a short tip and sound channel as large and straight as possible.

SPL Observations on Earmolds After Standardization of the 2-cc Coupler

The following criteria have been suggested for judging the merits of an earmold (81): Comfort, freedom from irritation, adequate retention, prevention of acoustic feedback, and acoustic coupling. This section and this study deal with the acoustic coupling criterion, which refers to the acoustic conditions which exist between the diaphragm of the hearing-aid receiver and the eardrum of the listener when the receiver has been attached to the earmold and the earmold has been seated in the ear canal of the listener. Interest in determining these acoustic effects has resulted in studies which measure SPL's in couplers and in real ears as a function of earmold alteration, and studies which look at the effects these alterations produce upon subjective pure-tone thresholds and scores obtained with speech stimuli. Unless otherwise stated, the articles referred to in this section are based primarily upon measurements made with a 2-cc coupler.

Sound Channel - Guttner and Starke (37) have stated that it is possible to extend the upper limits of the hearing-aid frequency-response curve through the use of earmolds having shortened and hollowed sound channels. They referred to this type mold as an open mold, but this term will only be used by this writer to refer to the nonoccluding earmold described earlier.

Ewertsen, Ipsen and Nielsen (28) used probe-tube microphone measures on real ears as well as measures using a coupler to study the effects of the earmold's sound channel dimensions on SPL. They compared an earmold having a sound channel 22 mm long by 2.4 mm in diameter with an earmold having a sound channel 17 mm long by 3 mm in diameter. The earmold having the shorter and wider sound channel yielded SPL's which were lower by one to three decibels from 100 to approximately 2500 Hz, and higher in both amplitude and frequency range above 2500 Hz, i.e., its range was extended to 4000 Hz, whereas the earmold with the longer and narrower sound channel had an upper range of only 3100 Hz.

Lybarger (71) reported an extensive study of the effects of earmold alterations upon hearing-aid receiver frequency response. Two types of receivers were used in the study. One was the miniature receiver used with the conventional earmold and the other was the small balanced-armature receiver used with a "short length of tubing, such as is employed in most eyeglass hearing aids." He found that if the sound channel is the "same diameter but longer than the one used in the standard 2-cc coupler, the primary peak of the response curve will be lower in frequency; if shorter it will be higher in frequency. Similarly, if it is the same length but smaller in diameter the peak frequency will be reduced; if larger it will be increased." He defines the primary-peak region as being from 800 to 2000 Hz. The region 200 to 800 Hz is referred to as the low-frequency region, while frequencies 2000 to 4000 Hz fall in the secondary-peak region. Lybarger also reports that neither the roughness of the sound channel's walls nor the material of which they are made affects SPL to any important degree.

van Eysbergen and Groens (105) compared findings on two stock-type canal eartips, one with a short, wide sound channel and the other with a long, narrow sound channel. They concluded that the high frequency range will be reproduced better when an insert with a "shorter and wider" should channel is used.

Mehmke and Tegtmeier (79) contend that a more favorable energy exchange between the hearing aid and the ear can be achieved by altering the acoustic coupling with an earmold that has a sound channel which is 25 mm in length by 2.4 to 3.0 mm in diameter.

Coogle (19) states that a lengthened sound channel "improves lows slightly." He reports that a small diameter for the sound channel has no effect in the low frequency range, but lowers the frequencies of the primary and secondary peaks and the high-frequency cut-off. His definitions of the low-frequency, primary and secondary peak regions are identical to those of Lybarger (71).

Dalsgaard, Johansen and Chisnall (21) used a constant tube length of 18 mm to study the response curves obtained with 1.5, 3 and 6 mm diameters. Their plotted response curves indicate, relative to the 3 mm diameter that the 1.5 mm diameter caused both the primary and secondary peaks to shift toward lower frequencies, while the 6 mm diameter caused both peaks to shift toward higher frequencies.

Schmitt and Zehm (101) used a 2.5-cc coupler to study the effects of earmold modification. They report that it is possible to improve low-frequency gain by approximately 10 dB through the use of an "extra long mold," and that the use of a very narrow bore causes a "sharp cut-off of the high frequencies." No difference was found between a straight channel and a bent channel. They reported that a "concave drilled" channel in an earmold was found to be "most advantageous", as compared with other channel forms, "when pointing with its largest diameter towards the eardrum."

Wandsdronk (107) made SPL measurements while receiver-earmold combinations were in place in the auditory meatus. He found that an increase in the length of the sound channel causes a shift toward the low frequencies for the primary and secondary peaks, with a very slight (one to two decibels) increase in the amplitude of the primary peak and a slight decrease (three decibels) in the amplitude of the secondary peak.

Sandberg and Nielsen (96) compared findings using an "ordinary" earmold coupled to a miniature receiver with those found using a specially constructed earmold. The special earmold had a small miniature receiver "incorporated into its canal tip," which fed directly into the air cavity between the eardrum and the tip of the earmold. The earmold dimensions were not presented, nor were the two different receivers used in the two different earmolds identified. Comparisons were made on the basis of SPL curves obtained by probe-tube microphone measurements in the auditory meatus and on threshold tracings obtained by Bekesy audiometry. Their eight subjects, from which 13 ears were used, had large ear canals and "normal" eardrums. A "slight dip" at 4000 Hz was noted in "a few cases." The earmold with the transducer at the tip was found to exhibit a loss of "a few dB" at frequencies below 500 Hz, in comparison with the other earmold-receiver combination, and an increase in amplitude in the higher frequencies, especially above 3000 Hz.

Major (73) reports that a "shorter" sound-input channel in a "regular" (conventional) earmold raises the frequency of both the primary and secondary peaks, while a "longer" channel lowers the frequency of those peaks. Channel length is said to have no effect on the high-frequency cut-off point. He states that a "smaller" sound-input channel diameter lowers the frequency at which the response curve's high-frequency cut-off point occurs, and that a "larger" channel diameter raises the high-frequency cut-off point. The smaller channel diameter is also reported to cause the primary and secondary peaks to shift toward lower frequencies.

<u>Tubing</u> - The use of tubing with an earmold as a part of the sound-input channel is commonly seen with eyeglass and over-the-ear type hearing aids, and may also be used to hide the miniature receiver of the body-type hearing aid. This gives the sound-input channel dimensions which differ from those found in the tubular entrance of the standard 2-cc coupler, which are intended to represent the channel dimensions of the typical conventional earmold.

Several writers have mentioned that the hearing-aid response in the high frequencies is reduced when tubing extensions are used with the hearing-aid receiver (20) (59) (74) (75).

Kranz (56) reported that long extensions of tubing on an earmold "would attenuate the sound to some extent" depending on the length and size of the tubing. Watson and Tolan (109) wrote that the most dramatic attenuation takes place in the frequency range 400 to 3000 Hz when tubing extensions of six and twelve inches are used. They did not report the diameter of the tubing.

Mandl (74) states that extension tubings, because of their length, generally produce resonances and anti-resonances which are undesirable. He adds, however, that in some cases such modifications can be used to advantage.

Ewertsen, Ipsen and Nielsen (28) compared the response obtained in the real ear using a tube 300 mm long and 1.7 mm in diameter with the response of a receiver measured on the coupler. Their plotted results indicate that the primary peak of the response curve was shifted to approximately 200 Hz with the tubing, whereas the coupler curve showed a primary peak at about 1400 Hz. The tubing response yielded four resonant peaks of very nearly the same amplitude and falling within the frequency range of 200 to 1800 Hz, whereas the response obtained on the coupler showed a smooth curve up to 1000 Hz and resonant peaks consisting of a primary peak at about 1400 Hz and a secondary peak at about 2700 Hz, both of greater amplitude than the peaks representing the response obtained when the tubing was utilized.

Lybarger (71) suggests that the length of the sound channel is important in determining the frequency of the primary peak. In the case of sound channels lengthened by the use of tubing, the primary peak region may extend into what is usually considered the low frequency range, i.e., below about 800 Hz. He further states that increasing the diameter of the sound channel while keeping its length constant raises the frequency of the primary peak, and because of the lower damping in the channel usually increases the height of the primary and secondary peaks.

Victoreen (106) compared four-inch, two-inch, and ten-inch long tubing effects upon response with the response of a receiver seated directly upon the 2-cc coupler. The direct coupling produced a curve which rose toward the highs and peaked at about 3000 Hz. The four-inch tubing yielded a curve which had several peaks, the highest amplitude of which was at about 500 Hz. The two-inch tubing gave a response with two peaks, one at about 750 Hz, and a less intense peak at about 3000 Hz. The ten-inch tubing caused a general decrease in the over-all amplitude of the response curve, with five peaks occurring between the frequencies 500 and 3000 Hz.

Coogle (19) reports that the shortening of tubing raises the primary- and secondary-peak frequencies, while reduction in the diameter of the tubing lowers the primary-peak frequency.

Briskey, Greenbaum and Sinclair (15) investigated tubing lengths and diameters relative to their effects upon hearing-aid frequency-response curves. They used eight different tubing diameters ranging from .042 to .095 inch, while the length remained constant at 1½ inches. They found that the low-frequency response of a hearing aid is "significantly reduced as the diameter of the tubing is decreased." They studied the effects of length of tubing using 14 different lengths varying from .25 to 3.25 inches and having an unspecified diameter.

They found that the first resonant peak moves to the higher frequencies in an "orderly and predictable pattern as the tubing is shortened; however the second resonant peak does not." They noted that there are two patterns which occur in the higher frequency region. One pattern has a "gradual buildup of energy at 3000 Hz, while the second pattern of curves diminishes in size. The resonant properties of one family of curves actually acoustically obscure the other." Briskey, Greenbaum and Sinclair also put an experimental "kink" in a tubing of unspecified dimensions and found that it caused a drastic reduction in the over-all response curve's amplitude and range, with the most severe reduction occurring in the low frequencies.

Damping Plugs - Lybarger (71) has stated that damping plugs have a controlling effect on the height of both the primary and secondary peaks of the response curve. His plotted findings indicate that the damping plug used in tubing near the receiver reduces the height of both the primary and secondary peaks, and thereby makes the over-all response smoother. He points out that damping plugs do not always produce the same response changes in a complete hearing aid as they do on receivers alone, and that the effects of tubing length and diameter are definitely related to the receiver type used. Others (19) (61) (73) also report that a damping insert in the sound channel reduces the height of both the primary and secondary peaks.

Wax in an earmold's sound channel can also act as a damping plug, but in an unpredictable manner. Briskey, Greenbaum and Sinclair (15) compared the response obtained on an earmold partially occluded by the user's wax with the response obtained when the earmold was unoccluded. The curves which they plotted for the conditions show that the wax caused a drastic change in the form of the response curve. There was a loss of amplitude in the high-frequency range above about 1500 Hz, which amounted to as much as 10 to 15 dB, depending on the frequency.

Snap-ring Recess - Lybarber (71) has reported that the sound channel of an earmold may resonate with the stiffness of the air in the cavity in front of the receiver diaphragm and thereby determine to a "great extent" the response of the "lower secondary peak." He also stated that diaphragm constants can affect frequency response in that a stiff diaphragm will reduce the low-frequency response, whereas a compliant diaphragm will raise the low-frequency response.

Wandsdronk (107) made probe-tube measurements with earmolds in the real ear. He found that an increase in the size of the cavity between the earphone diaphragm and the entrance to the earmold's sound channel causes a downward shift in the secondary peak of the response curve with a consequential lowering of the cut-off point in the high frequencies. This increase in cavity size has only a slight effect (no more than about one decibel of reduction) over the remainder of the frequency range.

Coogle (19) states that a "great enlargement" of the size of the cavity underneath the receiver nub will "raise the peak frequency and height" and eliminate the secondary peak. He did not define or quantify "great enlargement."

Dalsgaard, Johansen and Chisnall (21) found that an increase in the depth of the snap-ring recess will cause "attenuation of the higher frequencies."

Major (73) reports that moderate increases in the snap-ring recess volume "generally will reduce the high frequency 'cut-off'" and that "extremely enlarged" cavities (not defined) produce "unusual curves."

Volume Between the Earmold Tip and the Eardrum - The amount of air volume between the eardrum and the tip of the earmold is determined by the length and form of the canal portion of the earmold. Relative to this cavity, Lybarger (71) has stated:

> The larger the cavity . . . the lower will be the sound pressure developed in it at low frequencies for a given movement of the receiver diaphragm. Conversely, a long tip, that effectively reduces the size of [the] cavity . . . may produce a small improvement in the low-frequency output, probably not exceeding 3dB unless the longer tip also reduces the effect of leakage.

Wandsdronk (107) used the probe-tube microphone technique to study SPL's in the human auditory meatus as a function of increasing the size of the cavity between the earmold tip and the eardrum. He found that an increase in the size of the cavity decreases the level of the over-all frequency-response curve.

Dalsgaard, Johansen and Chisnall (21) obtained response curves of a hearing aid receiver connected to a tube of 3 mm in diameter and 18 mm in length terminated by volumes of 2.2 cc and 4.2 cc respectively. They found that the effect of changing the volume of the coupler cavity results only in a change in the level of the response curve, with the larger cavity showing a lower level of response.

Major (73) reports that a larger cavity between the earmold tip and the eardrum, as determined on a 2-cc coupler, results in a decreased level of the over-all frequency response curve.

Vents and Leaks - An opening drilled from the face of an earmold to its sound-input channel, or to the air cavity between the earmold tip and the eardrum, is an intentionally produced leak which is referred to as a "vent." A vent, depending upon its length and diameter and whether obstructed or unobstructed, can produce acoustic conditions which alter the hearing-aid response (65) (114).

Several writers have reported that the venting of an earmold can cause a reduction in the gain of a hearing-aid system for the low frequencies (15) (71) (94) (97) (108) (114).

Lybarger (71) states that an earmold vent can be drilled in such a way that it does not have much resistance and acts somewhat as a fairly free "vibrating slug or mass of air." He explains that such a vent can "cause a reduction in the extreme low frequencies while causing an increase in more important lows."

Coogle (19) reports that vents can cause a reduction in the low frequency response below 600 Hz, and that a leak tends to affect the same region in the same way.

Langford (61) states that a vent creates a second path for sound energy, and "The larger the venting hole, the lesser will be the energy reaching the eardrum." In comparing vent diameters of .016, .032, .048, .062, and .083 inch diameter he found that an earmold with the .016 diameter vent showed a 33 dB response at 1000 Hz, while an earmold with the .083 diameter vent showed a response of 18 dB at 1000 Hz, a reduction of 15 dB. Reductions due to increased venting effects were noted across most of the testing range of frequencies, viz., 100 to 4000 Hz. The effects above 4000 Hz were difficult to visualize in the plotted results, but it appears that the larger vent caused an extension of the high-frequency range amounting to about 600 Hz when compared with the findings on the earmold with the smallest vent. Langford states that the use of two or more vents in an earmold is "superfluous" because two vent holes with diameters of .032 inch vent off the equivalent of one .064 inch vent, and three .032 inch holes are equivalent to one .096 inch hole. He also says that one or more venting holes being filled with some porous material is similar to an open vent of smaller diameter. There was no mention of the effects of vent hole length.

Dalsgaard, Johansen and Chisnall (21) compared a vented with an unvented earmold and found that an earmold vent of unspecified dimensions produced reductions in SPL of approximately 26 dB at 100 Hz, 12 dB at 200 Hz, and from one to five decibels reduction in the 700 to 3000 Hz region, while increases of eight decibels and four decibels were noted at 400 and 500 Hz respectively. There were no differences between the vented and unvented earmold responses at 300 and 600 Hz.

Briskey, Greenbaum and Sinclair (15) used probe-tube measurements on real ears and found that the following changes occur in an earphone's response due to its being used with a vented earmold (of unspecified dimensions): "The pressure within the ear canal is reduced by approximately 6 dB per octave below 1000 Hz," and "the frequency range is significantly extended from approximately 4000 to 7000 Hz." The authors questioned the validity of their measuring technique above 7000 Hz and therefore chose not to comment on their findings in that region. The low-frequency limit of their investigation was 300 Hz according to their plotted findings.

Zachman (114) measured SPL's using four standard-sized earmolds, three of which were vented, both on a 2-cc coupler and in the human auditory meatus. All four earmolds had sound channels 18 mm long and 3 mm in diameter. The vents of the three comparison earmolds were drilled from the face of the earmold to the sound channel. Vent channels were unobstructed and had lengths of about 11 mm and diameters of 3, 1.5 and .75 mm respectively. After comparing results found using vented earmolds with those found using unvented earmolds Zachman stated that four principal features were evident in their frequency-response curves: "The low-frequency filtering; the low-frequency resonances; the downslope above the low-frequency resonances; and the high-frequency resonant peaks." The low-frequency filtering effect was progressive with increased vent diameters. The progressive drop in the mid-frequencies reached a minimum in the 3000 Hz region, and the magnitude of this drop was "increased with larger vent diameters." He also remarked that the unvented as well as the vented earmolds showed resonant peaks in the 3000 to 3500 Hz region.

Lybarger (65) states that leaks between the earmold and the skin of the auditory meatus affect low-frequency response, i.e., this type leak causes a reduction in the low-frequency response of a hearing aid when compared with the condition where no leak exists. His plotted findings indicate that the frequencies below 500 Hz are primarily influenced by such leakage.

Morton and Jones (82) report that in ordinary use acoustical leaks occurring between the earmold and the ear often have a powerful, though variable, influence upon impedance at frequencies up to 1000 Hz.

Ewertsen, Ipsen and Nielsen (28) dislodged a conventional earmold slightly in the ear canal to produce a leak, then studied the effects of the leak on the sound pressure in the ear canal using a probe-tube microphone. They found the leak caused reductions of 10 dB at 100 Hz, 5 dB at 200 Hz, 3 dB at 300 Hz and 2 dB at 400 Hz, with no differences noted at 500 Hz and above.

Aspinall, Morton and Jones (6) used a 1.5-cc coupler to study the effects of an acoustical leak between a hearing-aid receiver's nubbin and the snap-ring of an earmold. They found that such a leak may cause a reduction in the level of the frequency response curve across the entire frequency range. Their plotted results for one such leak indicate, however, that the low frequencies below about 500 Hz are affected more drastically than higher frequencies. Aspinall et al. also reported that an acoustical leak through the socket holes of a receiver may be troublesome when attempting to repeat objective measurements of receiver characteristics, and that "changes of the order of 1 dB in earphone sensitivity have been observed between the conditions with sealed and unsealed plug."

Lybarger (65) studied response curves obtained on couplers while using vented and open earmolds. His procedure and equipment for measuring the vented earmold is not explained. However, his plotted findings indicate that the vented earmold is effective in cutting the low-frequency amplification of a hearing aid. His response curve was plotted from 400 to 4000 Hz, and showed a progressive drop toward the low frequencies starting at 2000 Hz when compared with an unlabeled response curve which this writer presumes was obtained using a standard 2-cc coupler. Differences were approximately 14 dB at 400 Hz, 12 dB at 500 Hz and 4 dB at 1000 Hz. To "roughly approximate" the acoustic situation that an open earmold presents, Lybarger devised an "open-meatus coupler" consisting of an open tube 0.276 inch in diameter and 0.875 inch deep, with an acoustic resistance material at its inner end. The open coupler utilized a condenser microphone for measuring SPL's. He compared the levels found using a CROS hearing aid on the open coupler with those found on a closed standard 2-cc coupler. For measuring the effect of the open earmold he used a plastic tube 2 3/4 inches long by 0.077 inches in diameter, and inserted this tube 3/8 inch into the open end of the open coupler. His plotted results indicate that he tested from 250 to 5000 Hz, and that the open-coupler condition (open earmold) showed a relative amplitude decrease in the frequencies below 1400 Hz and a relative increase above that point when compared with the closed-coupler condition. The relative reduction in amplitude amounted to about nine decibels at 1000 Hz and 12 dB at 500 Hz, and the relative increase was approximately 18 dB at 2000 Hz and 11 dB at 4000 Hz.

Green and Ross (33) used one hearing-impaired subject to compare the effects on threshold of a conventional earmold with the effects of a nonoccluding earmold having a three-inch tubing and with a nonoccluding earmold having a 14-inch tubing. The subject traced his threshold on a sweep-frequency audiometer which was also used to drive a loudspeaker in a sound-field testing environment. When the three earmold test conditions were compared the nonoccluding earmolds showed" no significant differences" between them, but when the nonoccluding earmolds were compared with the regular earmold a low-frequency reduction of from 25 to 40 dB was noted for the frequency range 250 Hz (the lowest frequency tested) to 1750 Hz.

Effects of Drastic Earmold Modification on Speech-Stimuli Scores

Vented Earmold - According to Dodds and Harford (26) speech discrimination ability using vented and unvented earmolds was tested by Lewis and Plotkin and reported in 1962 (63). The unvented earmold was the conventional type. In this unpublished study Lewis and Plotkin compared the performances of 15 patients with high-frequency sensorineural hearing impairments. They found that patients with very poor unaided speech-discrimination scores (under 70%) showed an average gain in speech-discrimination ability of about 19% when using the vented earmold in conjunction with a hearing aid.

Menzel (81) cited a single case with high-frequency hearing impairment who benefited markedly from the use of a vented earmold. He stated that the aided speech-discrimination score with a conventional earmold was only 60%, but when the vented earmold was used with the same hearing aid the patient's score was improved to 92%.

McGee (78) has stated that aided speech-discrimination tests showed impressive improvements over unaided scores when vented earmolds were used, but failed to show improvements when conventional earmolds were used. He did not cite the research upon which his remarks are based, but added that "improvements of 20% were not uncommon" in speech-discrimination scores.

McClellan (76) tested aided and unaided speech discrimination in noise and quiet conditions using vented earmolds and unvented conventional earmolds. He evaluated results found on five patients having the type of hearing impairment the vented earmold was designed to help. The vented earmolds were of a stock type rather than individually molded. He reported an improvement of about 15% in speech-discrimination scores in noise when the vented earmold was used as opposed to the unvented earmold.

Jetty and Rintelmann (53) found that vented earmolds improved speech-discrimination scores by 17.8% when compared with the unaided findings on subjects having precipitous sensorineural hearing losses. For these same subjects an improvement of 10.4% was noted when the vented earmold was used as compared with the conventional earmold. Using subjects with gradually-sloping, sensorineural hearing impairments they noted an improvement of 5.4% for the vented earmold results when compared with unaided findings, and an improvement of 10% when vented-earmold results were compared with those of the conventional earmold. No significant differences in speech-discrimination scores were noted when conductive hearing-impairment cases were compared as to relative differences between unaided and aided conditions utilizing vented and unvented earmolds. However, they did find that conventional earmolds yielded better SRT's for the conductive loss cases than did the modified earmolds.

Revoile and Causey (91) reported that they obtained no significant differences between scores found with vented earmolds, hard conventional earmolds, and soft conventional earmolds. A questionnaire (90) was sent to their subjects, all of which had sensorineural hearing impairments, asking them to subjectively evaluate the three earmolds after having worn each for equal periods of time. It was found that 66% of the subjects evaluated the vented earmold as providing better hearing than the two conventional earmolds. Revoile (89) later concluded that the "judgment of the hearing aid wearer in the choice of his ear insert may be the most realistic index of the improvement in hearing which the individual will derive."

Using subjects with high-frequency hearing impairment, Hodgson and Murdock (45) compared a vented earmold with a conventional earmold in both quiet and noise and found no significant difference between the speech-discrimination scores obtained with each. Nor was any significant difference found between scores obtained with vented earmolds and scores obtained with open earmolds.

Dodds and Harford (26) also used high-frequency, sensorineural hearing-impaired patients to compare conventional with vented earmolds. They found no significant difference between aided speech-discrimination scores obtained with the conventional earmolds and those found with the vented earmolds.

Northern and Hattler (87) utilized speech stimuli in comparing four different earmold forms: Conventional; conventional with "hollow body;" conventional-vented; and a vented, large-bore earmold with a shortened canal. Mean sound-channel diameters of these earmolds were 3, 5.6, 3, and 7.7 mm respectively. The sound-channel length of the shortened canal earmold was about 1.5 mm, and the sould channels of the other three earmolds were about 9.5 mm long. They used five normal-hearing subjects with "mild-to-severe sloping audiometric configurations bilaterally." None of the subjects had prior experience with a hearing aid. The earmolds were tested on the subjects while coupled to the receiver of a body-type hearing aid which was located a fixed distance from a loudspeaker.

"Speech-Bekesy thresholds were obtained under each earmold condition with continuous discourse for detectability, intelligibility, most comfortable loudness and tolerance." Analysis of the findings led Northern and Hattler to state, "significant differences in test scores attributable to earmold modification were difficult to demonstrate, in spite of the fact that substantial variations in the ear inserts were readily apparent in both structural and electroacoustics analysis."

Open Earmold - Wolfe (113) has reported a single case with sharply-falling high-frequency impairment of hearing who obtained superior speech-discrimination scores with a CROS hearing aid as compared with scores obtained using High Frequency Emphasis (HFE) hearing aids, and with unaided sound-field scores. The sound-field conditions are not clearly described, but it appears that a single loudspeaker was used for testing purposes. He stated that the CROS hearing aid was tested "without an earmold." Therefore, it is probable that shaped-tubing was used for conveying the amplified sound to the listener's ear canal. With the hearing aid set to the most comfortable listening level and stimuli presented at 60 dB SPL, a speech-discrimination score of 50% was obtained with the CROS hearing aid, 28% for sound-field unaided, and 32, 34 and 22% respectively for the HFE aids' scores.

Hodgson and Murdock (45) tested subjects with high-frequency hearing impairments and found that speech-discrimination scores obtained with an open earmold were superior to scores obtained with a conventional earmold, both in quiet and in noise. The mean difference between the conventional and open earmolds in quiet was approximately 5%, and the difference between these earmolds in the noise condition was approximately 10%.

Dodds and Harford (26) compared conventional earmolds with open earmolds on subjects having high-frequency impairments of hearing. They found that mean speech-discrimination scores showed significant improvement (10%) when the open earmold was used with a CROS hearing aid.

Jetty and Rintelmann (53) compared the open earmold, shaped-tubing, the conventional earmold, and the unaided sound-field condition using speech stimuli. Testing subjects with conductive impairments or sensorineural impairments either of a precipitous or gradually sloping nature, they found that the open earmold and shaped-tubing offered the best help to persons having precipitous sensorineural impairments. Speech-discrimination scores with the open earmold and the shaped-tubing showed improvements of 17.6% and 18% respectively when compared with the unaided condition, and improvements of 10.2% and 10.6% when compared with the results found with the conventional earmold. No significant difference was noted when comparisons were made between the open earmold and the shaped-tubing. Nor were significant differences found when results with the open earmold, shaped-tubing and a vented earmold were compared. Jetty and Rintelmann concluded that the modified earmolds offered better help for cases having sensorineural hearing impairment than did the conventional earmolds.

Concluding Statement

Vented earmolds and open earmolds have been widely used since they were introduced in 1963 and 1965 respectively. However, a search of the literature has failed to reveal a study of the acoustic changes produced in the human auditory meatus by these drastic earmold modifications. This study is primarily intended to investigate SPL changes which occur in the human auditory meatus when a standard earmold form is modified to a shortened-hollowed form, to a vented-earmold form, and to an open-earmold form.

CHAPTER III

INSTRUMENTATION AND PROCEDURE

Introduction

This study is designed to investigate sound pressure level changes which occur across frequency when a "standard" earmold form is modified so that three different physical and acoustical conditions exist between the diaphragm of a hearing aid receiver and the eardrum of each subject. These changes were investigated with a probe-tube microphone system while the earmolds were in the ears of the subjects. A wide range of fixed-frequency signals were used as input stimuli. While the primary purpose of this study was concerned with the SPL's in real ears, preliminary measurements were made using metal 2-cc couplers. These measurements had the purpose of establishing reference values for the results obtained in the real ear and evaluating the influence of the probe-tube and the input tubing on the measurements.

In addition to instrumentation and procedure, this chapter will discuss subjects, acoustic environment, earmolds and test sequence.

Subjects

Eight adult subjects whose ages ranged between 25 to 40 years, with a mean age of 30 years, were used in this study. Seven subjects were males and one was female. Each subject had air-conduction thresholds of not greater than 15 dB re the 1964 International Standards Organization (ISO) standard, at frequencies 125, 250, 500, 1000, 2000, and 8000 HZ nor greater than 25 dB at 4000 Hz as determined by audiometric evaluations utilizing a regularly-calibrated Beltone 15C audiometer. Bone-conduction thresholds were not better than air-conduction thresholds by more than 10 dB at any of the frequencies tested with the bone conduction vibrator (Radioear Type B-70A); these frequencies were 250, 500, 1000, 2000, and 4000 Hz, and thresholds were re the Hearing Aid Industry Conference (HAIC) interim standard (66). Each subject had physically-normal ears as determined by a physician's otological examination. Only the right ear of each subject was used due to the physical arrangement of the instrumentation. Each subject had an ear canal large enough to produce an earmold impression which could be drilled to accommodate both the sound-input and the probe-tubing channels from the face to the canal-tip portion of the earmold.

Acoustic Environment

All measurements were accomplished in a sound-treated room of a speech and hearing center. Ambient noise level measurements were made in this acoustic environment with the equipment used in making the measurements of SPL's within the ear canal, and also with that used in making the coupler measurements. The root mean-square (RMS) sound pressure levels were measured with the fast meter-switch setting, and the weighting network on Linear 20 - 40,000 (Hz). At no time during the data collection were the readings obtained closer than 8 dB above the noise floor, i.e., the ambient noise level never exceeded an SPL of 55 dB.

Earmolds

All earmolds used in this study were fabricated by the experimenter, who utilized a commercially available quick-setting acrylic material (1). Four earmold impressions were made of the right ear of each of the subjects. These were worked directly into "standard" form. This earmold does not have sound-channel dimensions which correspond to those of the earmold bore simulator on the standard 2-cc coupler. The word "standard" in this instance implies an unvarying earmold form which is to be used as a basis for comparison with earmolds altered from this basic form. From this standard form three of the four earmolds, labeled earmolds B, C and D, were modified as shown in Figure 2. One of the earmolds retained its standard form and is labeled earmold A. The special type of acrylic earmold material used in this study allows the impression itself to be worked into a permanent earmold, and thereby greatly reduces the possibility of subtle unpredictable changes in form which could occur in the processing of plastic earmolds from impressions by commercial laboratories. Mixture proportions were carefully measured for both powder and liquid parts of the earmold material in order to minimize slight differences that might otherwise occur due to shrinkage or flaking. A cotton block was placed in the bony portion of the ear canal while making the impressions so that accurate duplications of the canal walls could be obtained.

As shown in Figure 2, earmold A is a "standard" earmold form, having about the same bulk and canal length as the commercially available conventional type, but without the snap-ring which ordinarily

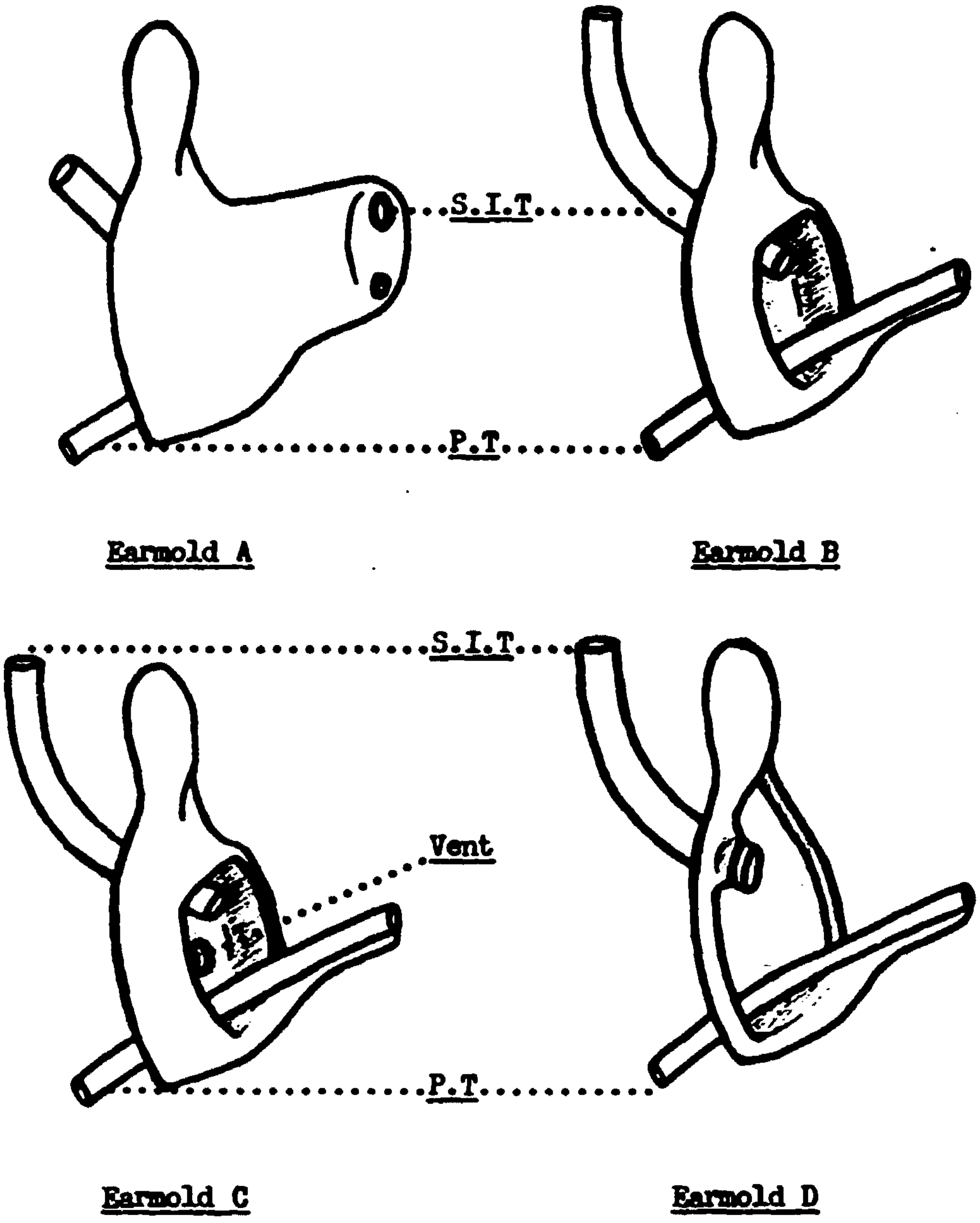


Figure 2 — Earmold Forms Used in This Study.

is used to couple the hearing-aid receiver to the earmold. It is "standard" in the sense that it offers a basis for comparison with other earmold forms used in this study. The snap-ring and recess space were eliminated in favor of polyethylene tubing in an effort to reduce the variability of the sound-input channel. Earmold A, except for bulk is analogous to the widely used "skeleton" and "shell" type earmolds which are most often utilized with ear-level hearing aids. The tubing used in all experimental earmolds has nearly constant dimensions, whereas the dimensions of hand-drilled channels can vary considerably. The tubing will be described in more detail later.

The second style, earmold B, differs from earmold A in that the canal portion of this earmold is shortened into the concha area and then hollowed out.

The third style, earmold C, differs from earmold A in that the canal was shortened as in earmold B, the concha portion was hollowed out as in earmold B, and, in addition, it was vented. Venting in this earmold was accomplished by drilling one channel from the face of the earmold to the air cavity medial to the earmold and within the ear canal. The vent had a length and a diameter of three millimeters.

The fourth style, earmold D, consists of only a ring of earmold material within the rim of the concha of the external ear, which serves a retentive purpose, and a portion of material in the superior-exterior region of the ear canal which serves as a support for the sound-input tubing.

Earmolds C and D are respectively similar to the vented and open earmold types discussed in Chapter II.

Note in Figure 2 that a small ribbon of acrylic was left beneath the lower (probe) tubing of earmolds B, C and D. This served the function of insuring that the probe-tube aperture of each of these earmolds was located in the same position (± 2 mm) as that in the standard-form earmold A, i.e., approximately two millimeters superior to the central-inferior area of the subject's ear canal, and midway between the turns of the ear canal in the cartilaginous portion.

A fairly rigid and yet flexible polyethylene tubing was utilized in each earmold as the probe-tube. It had an outside diameter of two millimeters and was accommodated without apparent leakage, when sealed with vaseline, by the probe-tube nose cone (2 mm probe size) of the Bruel and Kjaer (B & K) assembly used for probe-tube measurements with a one-half inch microphone. The measured inside diameter of the tubing was approximately 1.6 mm, and the probe-tube length was held constant from earmold to earmold at 40 mm.

The sound-input tubing used in the superior portion of each earmold was also a fairly rigid, yet flexible, polyethylene tubing. This particular type and size of tubing frequently is used with ear-level hearing aids. When measured it was found to have an outside diameter of about 3.28 mm and an inside diameter of approximately 2.6 mm. It is usually referred to in the hearing aid industry as "size 11" tubing (15) (38). In each earmold the sound-input channel had a length which was identical from earmold to earmold (55 mm), i.e., the sound-input tubing's aperture which opened into the ear canal varied in position along the canal according to the earmold type of which it was a part. This can be seen in Figure 2; note that in order for the channel to remain a constant length the tubing outside the earmold became longer as the tubing within the modified earmolds became shorter. The 55 mm tubing length included the adapter which was used to couple the tubing to the receiver's nubbin. The adapter's sound channel was about 15 mm long and approximately 1 mm in diameter for a distance of 12 mm, with the remaining 3 mm of the channel being a slit-like channel with unknown dimensions.

Instrumentation

The instruments used along with earmolds in this study were as follows: a Beat Frequency Oscillator (BFO) B & K Type 1014; two Microphone Amplifiers, B & K Type 2603; a standard 2-cc coupler, B & K Type DB 0138, which is used in conjunction with an artificial ear (B & K Type 4152) and is mounted on a B & K Hearing Aid Test Chamber, Type 4212; a special 2-cc coupler which was constructed for earmold-coupler studies by Central Research Laboratories of the University of Oklahoma; two one inch Condenser Microphones, B & K Type 4132, with a flat frequency response in the 20 to 7000 Hz range, a dynamic range of from 15 to 146 dB re .0002 microbar, and a resonant frequency of 8000 Hz; a Cathode Follower, B & K Type 2613; a one-half inch Condenser Microphone, B & K Type 4134, with a flat frequency response in the 30 to 100,000 Hz range, a dynamic range of from 32 to 160 dB, and a resonant frequency of 25,000 Hz; a Cathode Follower, B & K Type 2615; a T-pad (isolation network) with 500 ohms impedance and 10 dB insertion loss; a counter (Universal Counter, Model 361, manufactured by Transistor Specialties, Inc.); an attenuator consisting of two "T network" Daven units, one being a Type 2511 with one decibel steps and a 10 dB total and the other being a Type 2513 with 10 dB steps and a 100 dB total; a transformer (United Transformer Corporation Transformer, Type LS-33); a probe-tube nose cone which accommodates a probe-tube with an outside diameter of two millimeters (for use with the one-half inch microphone); a head-borne microphone and receiver support; and an air conduction hearing-aid receiver (Radioear Type M-7075) which is given a nominal impedance of 800 ohms by the manufacturer, and was found to have an actual impedance of approximately 925 ohms when checked at 1000 Hz. The receiver was chosed from among 25 available hearing-aid receivers (which were tested in a preliminary investigation) on the basis of its across-frequency flatness of response, and because of its relatively high impedance and its production of consistent results on repeated measurements of response.

Receiver-Standard Coupler Measurements

The equipment to be described in this section was used to determine the frequency response of the hearing-aid receiver. In Figure 3 the wide lines of the flow diagram show the arrangement of the equipment used in making measurements with the receiver directly seated upon the standard 2-cc coupler. The BFO drove the receiver at the desired test frequencies. The attenuator controlled the signal delivered to the receiver. The pad isolated the attenuator from frequency-related impedance changes by giving the attenuator a constant resistive load. The transformer offered the desired impedance of 1.2 ohms to the receiver, so that a constant-voltage source was achieved. Ballantine (7) suggests that hearing-aid receivers of the electromagnetic type, such as used in this study, may be tested at eigher constant voltage

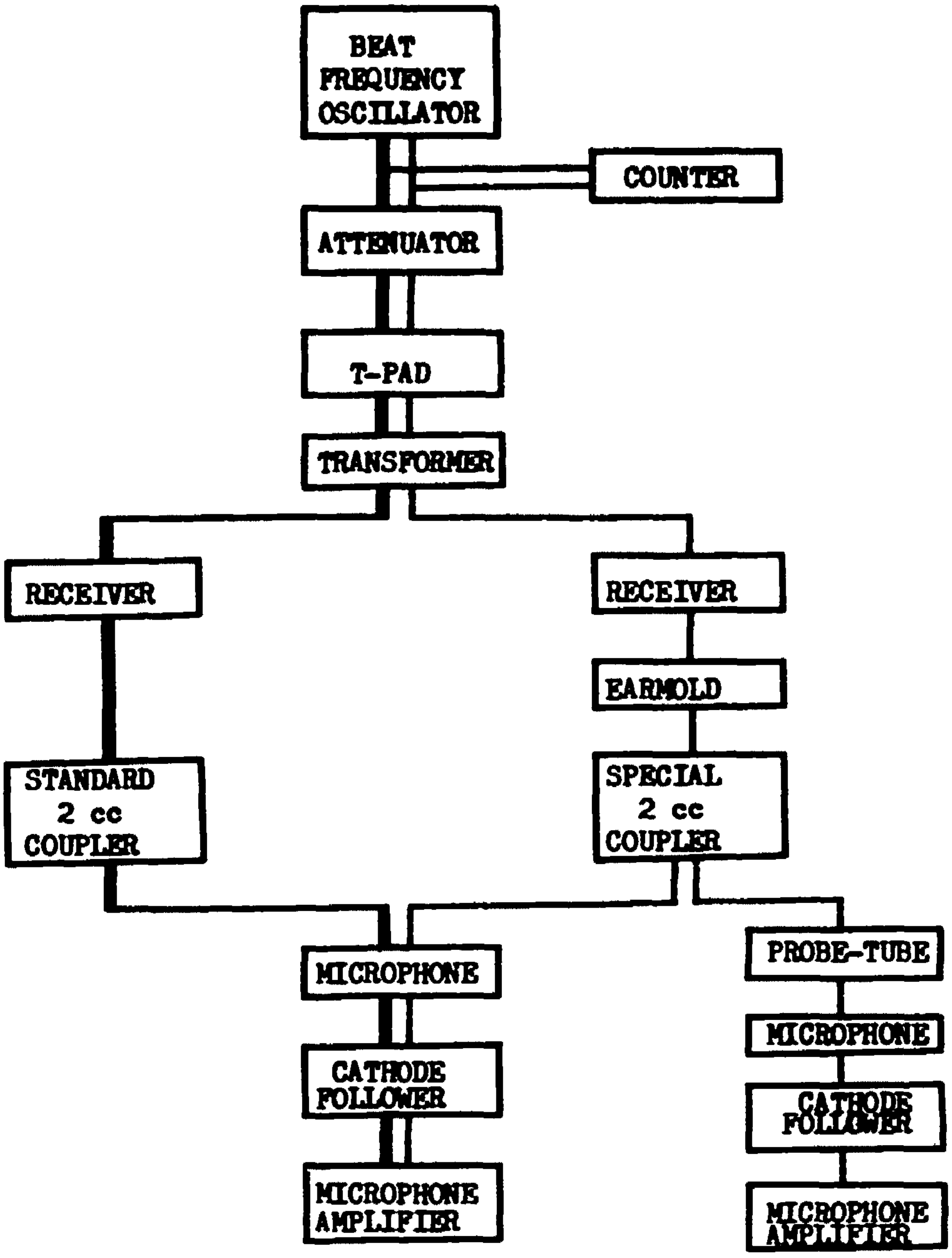


Figure 3 -- Instrumentation Used in Making Coupler Measurements.

or constant current. A preliminary investigation of this arrangement of equipment considered constant-power, constant-current and constant-voltage sources; the latter was chosen as being the most desirable because the source voltage output was least affected by changes in acoustic load on the receiver with this type source. The counter was inserted in to the circuit, in parallel, between the BFO and the attenuator for frequency monitoring purposes. The one inch microphone and cathode follower were used to measure the sound levels generated in the 2-cc cavity. The sound pressure levels were read from the meter of the appropriate microphone amplifier.

Receiver-Earmold A-Special Coupler Measurements

The equipment to be described in this section was used to establish the influence of the sound-input tubing on the hearing-aid receiver's response. Figure 3 also presents the flow diagram of the equipment used for making measurements with the receiver attached to an earmold and the earmold attached to the 2-cc cavity of the special coupler. The instrumentation was identical to that used in the receiver-standard coupler phase. However, the acoustic conditions differed between the receiver and the condenser microphone because of the insertion of the earmold and because of the use of the use of the special 2-cc coupler rather than the standard 2-cc coupler. Figure 4 illustrates the receiver-earmold-special coupler relationship during this measurement procedure. While the measurements were being made the receiver was accommodated by the sound-input tubing of the particular earmold A being used. The tubing conveyed the desired signal through the earmold and into the 2-cc cavity of the special coupler. The earmold was held in place on the coupler by

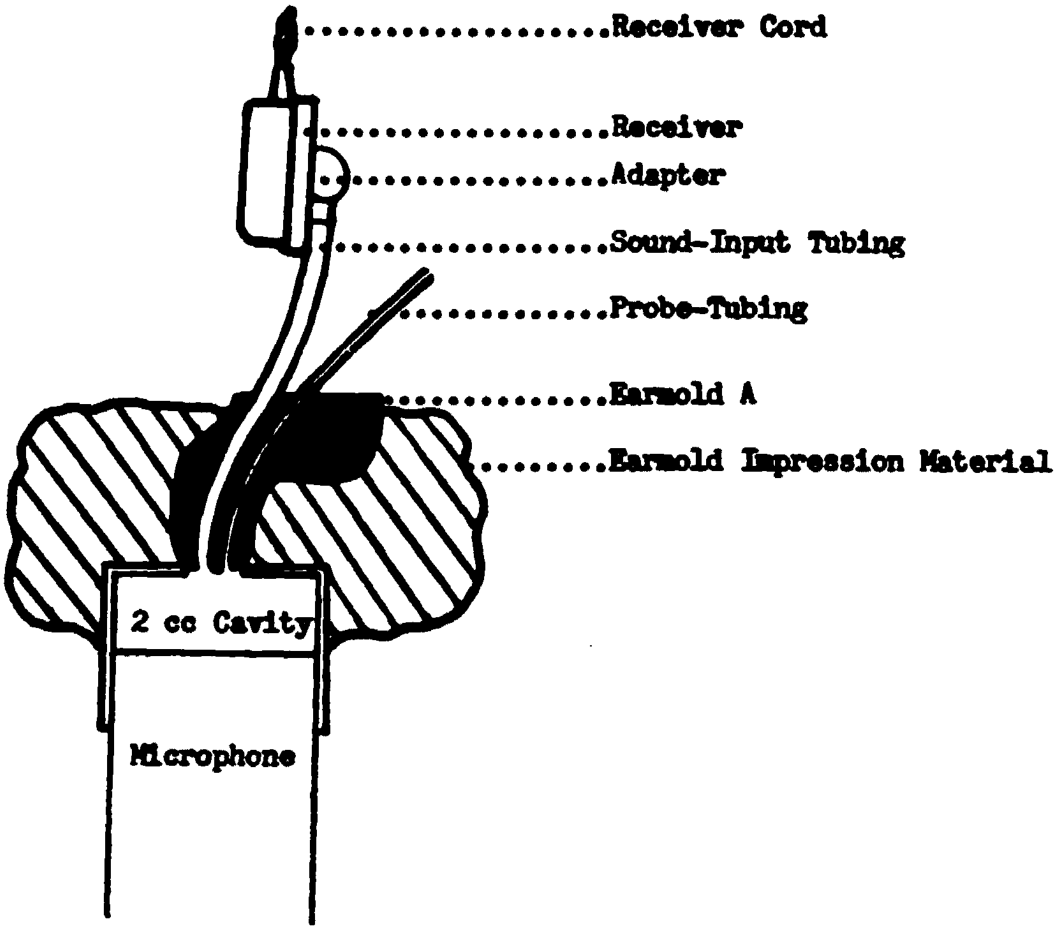


Figure 4 — Receiver-Earmold A-Special Coupler Relationship while Making Measurements with Earmold A on the Special 2-cc Coupler.

earmold impression material. The impression material was placed around the earmold and the upper part of the coupler so that retest conditions were nearly constant relative to earmold positioning on the coupler (see Figure 4).

In-the-Ear Measurements

The equipment to be described in this section was used to measure SPL's with earmolds in real ears. It was selected while taking into consideration Wiener's (110) suggested requirements for equipment which is to be used for measuring sound pressures in the ear canal. These requirements are, in essence, that the apparatus be such that it will measure pressure along the canal without exposing the observer (or subject) to undue hazard and discomfort, that it be small and light, interfering with neither the receiver (in this instance, earmold) seal nor the wearer's comfort, and that it be designed so that its introduction into the canal will not affect the sound-pressure distribution there or the acoustic impedance presented to the receiver.

Sound-Input System. The upper portion of Figure 5 shows the sound-input system used while making in-the-ear measurements. Just as in the two previous measurement conditions the BFO drove the receiver, the counter was used to monitor the frequency of the signal, the T-pad isolated the attenuator from frequency-related impedance changes, the transformer presented the desired source impedance to the receiver, and the receiver emitted the signal. The adapter connected the receiver nubbin to the sound-input tubing of the earmold to be tested, and this tubing conveyed the test signal through the earmold into the subject's ear canal.

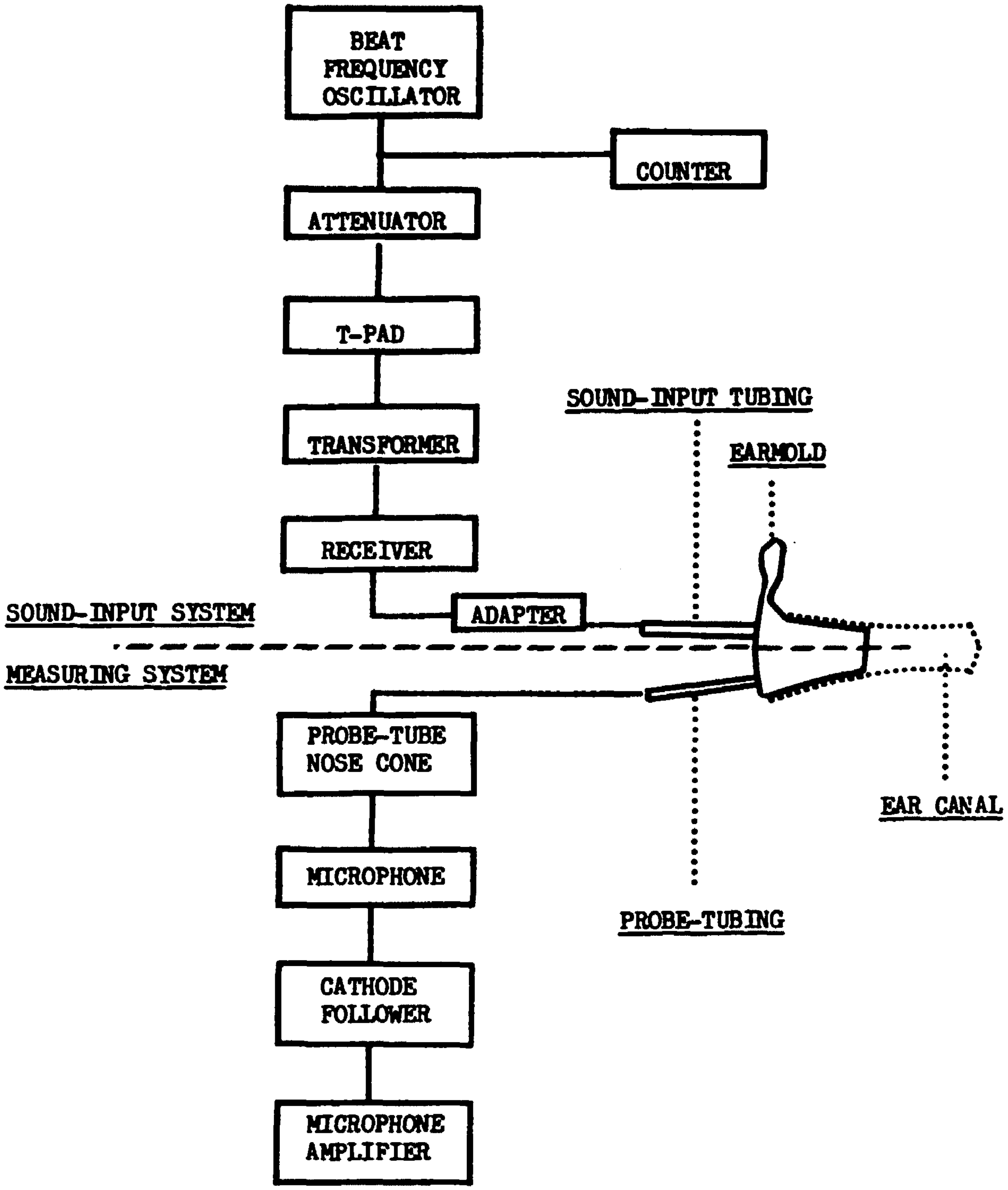


Figure 5 -- Instrumentation Used in Making In-the-Ear Measurements.

Measuring System. In the lower portion of Figure 5 is shown the system used in making in-the-ear measurements. Sound Pressures within the subject's ear canal were channeled outward through the plastic probe-tube which was inserted into the probe-tube nose cone. The probe-tube nose cone was attached to the one-half inch microphone. The microphone and cathode follower delivered a signal to the microphone amplifier's meter scale. This reading was corrected for probe and microphone responses.

The probe-tube microphone assembly and the hearing-aid receiver were held in a fixed position relative to the ear during the measurements through the use of a head-borne device which is illustrated in Figure 6. This device was used in preference to floor-supported devices such as microphone stands for two reasons: First, it allowed the subject to make slight movements with his head without altering the physical arrangement of the sound-input and measuring systems. Second, it allowed the subject to be seated in a comfortable, upright position. Plastic padding was used over the clamps which held the probe-tube microphone assembly. The main supporting element was a nonmetallic U. S. Army helmet liner.

Subjects who desired to read during the test procedure were allowed to do so.

Calibration

The electronic equipment was calibrated immediately prior to and immediately upon completion of all data collection runs as directed by the B & K Instructions and Applications Pamphlets for each of the instruments.

The basic calibrations of the microphones used were supplied

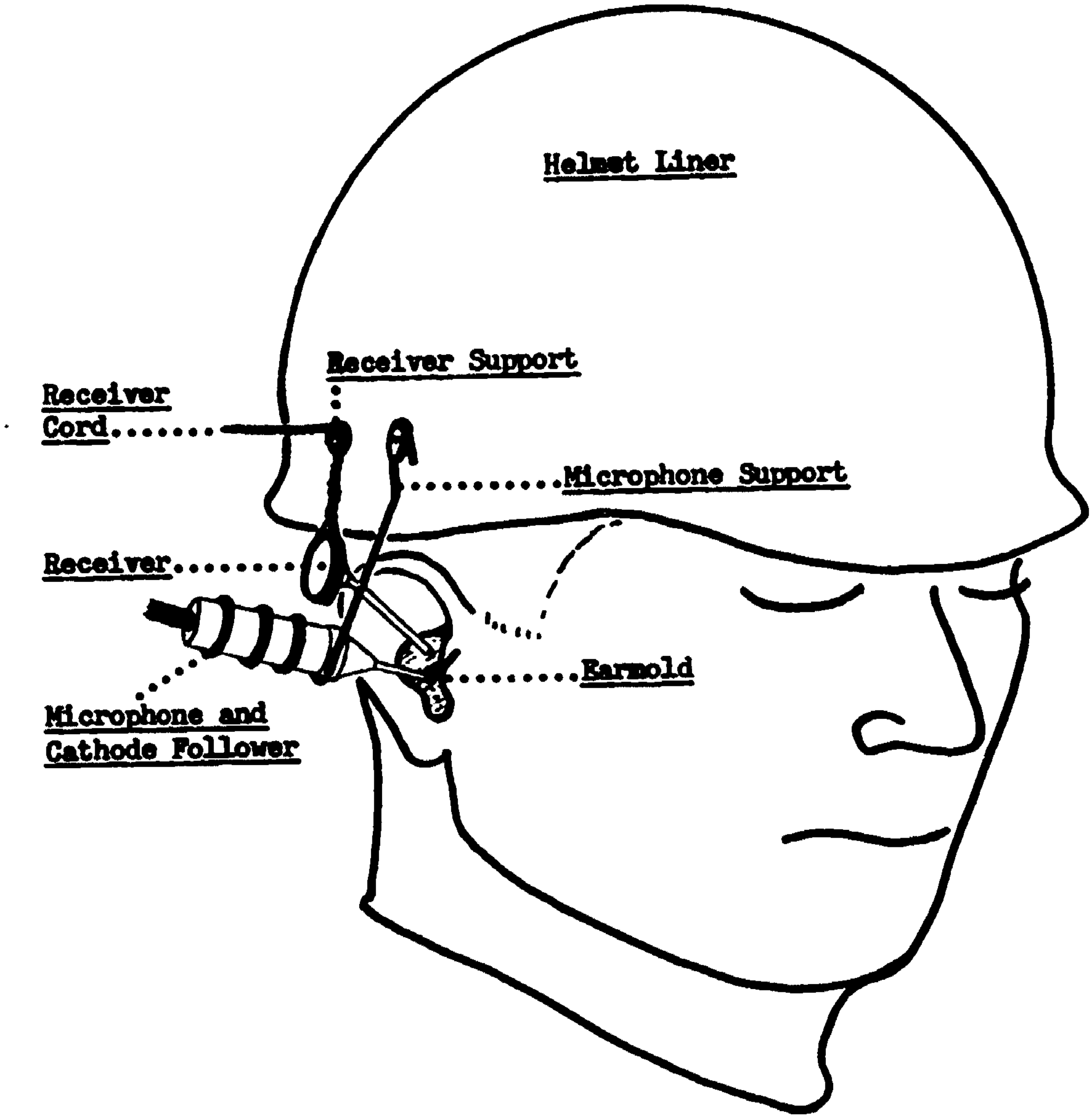


Figure 6 — Head-borne Device Used for Support of the Probe-tube Microphone Assembly and the Hearing-Aid Receiver.

by B & K. The calibration of the microphone system was monitored by an intermicrophone comparison system. The BFO was connected to the hearing aid test box in a manner which allowed it to drive the built-in loudspeaker within the chamber of the box. The BFO was then adjusted to an output voltage which produced a reading of 70 dB on the meter scale of the one inch regulating microphone's microphone amplifier. The one-half inch microphone was placed in the test box near the regulating microphone. They were placed at a 0° azimuth to each other and equidistant from the sides of the test box. Readings were made from both the one inch and the one-half inch microphones.

The calibration of the one-inch microphone which was used in the coupler measurements was monitored in the same manner.

Procedure

Receiver-Standard Coupler Measurements

The hearing-aid receiver was placed on the standard 2-cc coupler and the BFO output voltage knob was set to produce 100 dB SPL at 1000 Hz in the coupler.

Measurements were made at 44 frequencies which are approximately evenly spaced between 100 and 4000 Hz. The frequencies used were: 100, 110, 120, 130, 140, 150, 165, 180, 195, 210, 230, 250, 275, 300, 330, 360, 390, 420, 460, 500, 550, 600, 650, 700, 775, 850, 925, 1000, 1100, 1200, 1300, 1400, 1550, 1700, 1850, 2000, 2200, 2400, 2600, 2800, 3100, 3400, 3700 and 4000 Hz. The counter was used in the setting of the BFO to the desired frequency.

Receiver-Earmold A-Special Coupler Measurements

Only Earmold A of each subject was tested on the special 2-cc coupler. The earmold was coupled to the special 2-cc coupler using earmold impression material. After the hearing-aid receiver's output was set to read 100 dB at 1000 Hz as determined on the standard 2-cc coupler, the receiver nubbin was snapped into a plastic adapter which was inserted into the sound-input tubing of earmold A. The probe-tube nose cone was then coupled to the probe-tubing of Earmold A. Measurements were made at the same 44 frequencies listed in the Receiver-Standard Coupler Measurements section, and the accuracy of the frequency setting was determined in the same manner. The SPL at each of the test frequencies was read directly from the meter scales of two microphone amplifiers, one being in the one inch microphone system and the other in the one-half inch microphone system. Each measurement was made and recorded on two separate successive occasions.

Probe-tube Effects Upon Measurements

The Receiver-Earmold A-Special Coupler Measurements Procedure was followed with the exception that the probe-tube was obstructed at the tip of the earmold to determine what effects the probe-tube might have upon the measurements (as compared with the unobstructed probe-tube condition).

The purposes of these measurements are as follows: (1) to determine the amount of sound energy passing through the earmold material to the probe-tube by comparison of open and closed probe-tube measurements from the one-half inch microphone, (2) to determine the influence of the presence of the probe-tube opening on the levels of sound within the coupler by comparing the open versus closed probe-tube condition measurements from the one inch microphone, and (3) to determine a calibration of the probe-tube microphone by comparing the readings from the one inch microphone with those from the one-half inch microphone under the open probe-tube condition.

In-the-Ear Measurements

All earmolds were sealed in the subjects' ears with vaseline prior to making measurements. The sound pressure levels within the ear canal were measured in the same manner for each of the four different types of earmold, i.e., the probe-tube of each earmold channeled sound to the one-half inch microphone and the SPL for each of the 44 test frequencies (see the Receiver-Standard Coupler Measurements Procedure section) was read from the meter scale of the microphone-amplifier. The signal input was managed as described in the Receiver-Earmold A-Special Coupler Measurements Procedure section. The microphone and receiver assemblies were supported near the right ear of each subject by a head-borne device (Figure 6) and each subject was seated in an upright position during testing.

Each earmold was tested four times in a sequence to be described in the following section.

The Test Sequence

The "receiver-standard coupler" measurements were done first. Two complete sets of measurements were obtained, with the receiver removed and replaced on the coupler between each set.

The test order for the "receiver-earmold-special coupler" measurements are shown in Table 1. The subjects were numbered from one to eight. One-half of the subjects' (1, 3, 5, 7) earmolds were tested first with the probe-tube open for the first run, and then on the second run were tested first with the probe-tube closed. As shown in Table 1, the earmolds of subjects 2, 4, 6, and 8 were tested in all instances in the alternate order.

TABLE 1

TEST ORDER FOR RECEIVER-EARMOLD A-SPECIAL COUPLER MEASUREMENTS

		Earmold Testing Order	
Subjects	Runs	Probe-tube Open	Probe-tube Closed
1, 3, 5, 7	First	1st	2nd
	Second	2nd	1st
2, 4, 6, 8	First	2nd	1st
	Second	1st	2nd

In Table 2 the sequence for making in-the-ear probe tube measurements with the different earmold forms is presented. All earmolds (A, B, C and D for each subject) were tested first, second, third and fourth in order in each of four runs the orders were balanced by runs across four pairs of subjects. For example, Earmold A of subjects one and five was tested first on the first run, fourth on the second run, third on the third run, and second on the fourth run; and for subjects four and eight Earmold A was tested first on the second run, while Earmolds B, C, and D were tested first on the fourth, first and third runs respectively.

TABLE 2

TEST ORDER FOR IN-THE-EAR MEASUREMENTS

		Testing Order				
Subjects	Runs	Earmold:	A	B	C	D
1 & 5	First:		1st	2nd	3rd	4th
	Second:		4th	3rd	2nd	1st
	Third:		3rd	1st	4th	2nd
	Fourth:		2nd	4th	1st	3rd
2 & 6	First:		4th	3rd	2nd	1st
	Second:		3rd	1st	4th	2nd
	Third:		2nd	4th	1st	3rd
	Fourth:		1st	2nd	3rd	4th
3 & 7	First:		3rd	1st	4th	2nd
	Second:		2nd	4th	1st	3rd
	Third:		1st	2nd	3rd	4th
	Fourth:		4th	3rd	2nd	1st
4 & 8	First:		2nd	4th	1st	3rd
	Second:		1st	2nd	3rd	4th
	Third:		4th	3rd	2nd	1st
	Fourth:		3rd	1st	4th	2nd

CHAPTER IV

RESULTS AND CONCLUSIONS

Receiver-Standard Coupler Findings

Figure 7 shows the mean frequency-response curve obtained on the standard 2-cc coupler, with the Radioear M-7075 receiver used in this study feeding directly into the metal tubular entrance. It shows a relatively flat response from about 250 to 1300 Hz. The primary peak is seen to occur at about 1400 Hz, and the secondary peak at about 3100 Hz. The response falls off rapidly for frequencies above the secondary peak region. A slight decrease in amplitude is seen below about 250 Hz, which may be attributable to some leakage in this system. The relatively flat portion of the curve from 250 to 1300 Hz is that expected in a closed acoustic system below the primary resonant frequency (8).

According to Wandsdronk (107), these two peaks, which are normally found in earphone characteristics, "are caused by the membrane /diaphragm/ resonance" (primary peak) "and the resonance of the tube of the coupler with the cavity between the membrane and this tube"(secondary peak). He states that the first resonance is "practically independent of the loading of the membrane" and is determined by the mass, resistance and compliance of the earphone's diaphragm. He reports that the second peak is

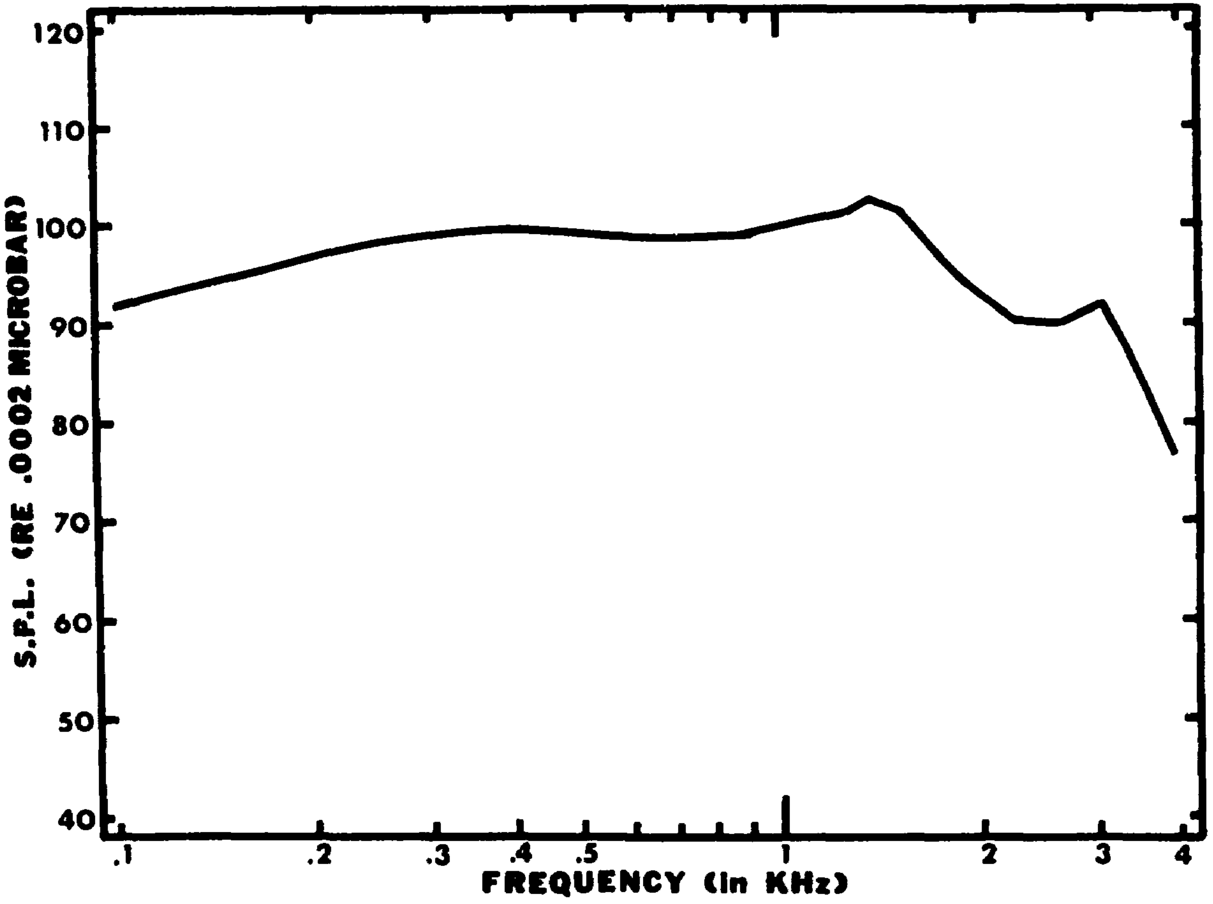


Figure 7 -- The Mean Frequency-Response Curve of the Hearing-Aid Receiver System on the Standard 2-cc Coupler.

> almost independent of the membrane properties, but L_o [inertance of the diaphragm due to its mass] and C' [compliance of the air volume between the front of the diaphragm and the receiver case, which may also be increased by the air volume of the snap-ring recess] have some effect on it.

Lybarger (71) has reported that the factors which most affect the primary-peak region of the hearing-aid frequency-response curve are the receiver diaphragm constants (including the effects of the driving system, which is magnetic in this study), the length and diameter of the sound-input tubing (a finding which is verified in this study) and damping plugs in the sound-input channel. The stiffness and mass of a receiver diaphragm are fixed by design according to the manufacturer's design objective. In a separate experiment the resonant frequency of the unloaded diaphragm of the receiver used in this study was found to be approximately 1500 Hz. Placing the receiver on the standard 2-cc coupler adds the mass of air within the coupler's tubular entrance to the slug of air which is contained in front of the receiver diaphragm and within the receiver nubbin's channel. It can be seen in Figure 7 that the addition of this air mass has resulted in a slight lowering of the resonant frequency of the diaphragm and its driving system to about 1400 Hz. This is due to the increased inertance presented by this additional air mass.

Lybarger (71) has stated that three elements in the receiver-earmold system have "large effects" on the response in the secondary-peak region. He lists these elements as being the size of the cavity immediately in front of the receiver diaphragm, the combined channels of the receiver nubbin's aperture and the earmold sound-input channel, and the snap-ring recess of the earmold.

The resonant frequencies observed in this study will be discussed further in subsequent sections.

Receiver-Earmold A-Special Coupler Findings

Comparison of Earmold A Findings with Those of the Standard Coupler's Tubular Entrance

The frequency response obtained using earmold A with its plastic sound-input tubing (55 mm long with a functional diameter of about 1.8 mm) instead of the metal bore (18 mm long by 3 mm in diameter) of the standard 2-cc coupler is shown in Figure 8. The mass of air contained in the sound-input channel of earmold A consisted of a 40 mm long by 2.6 mm diameter section (tubing) and a 15 mm long by 1.0 mm diameter section (adapter). Calculations using these known values indicate that the functional diameter of the total 55 mm channel is approximately 1.8 mm. In comparing the frequency-response curves of Figures 7 and 8, one finds that the 55 mm sound-input tubing of earmold A produces a very different response from that obtained with the standard coupler's 18 X 3 mm bore.

The longer and narrower sound channel presented by the sound-input tubing of earmold A has caused the primary and secondary peaks of the receiver system to shift toward lower frequencies. It has also caused the appearance of a tertiary peak. The effects on amplitude and frequency response can be seen more clearly in Figure 9, which shows the frequency-response curve obtained with earmold A on the special 2-cc coupler plotted relative to the response of the hearing-aid-receiver system on the standard 2-cc coupler. Note that the low-

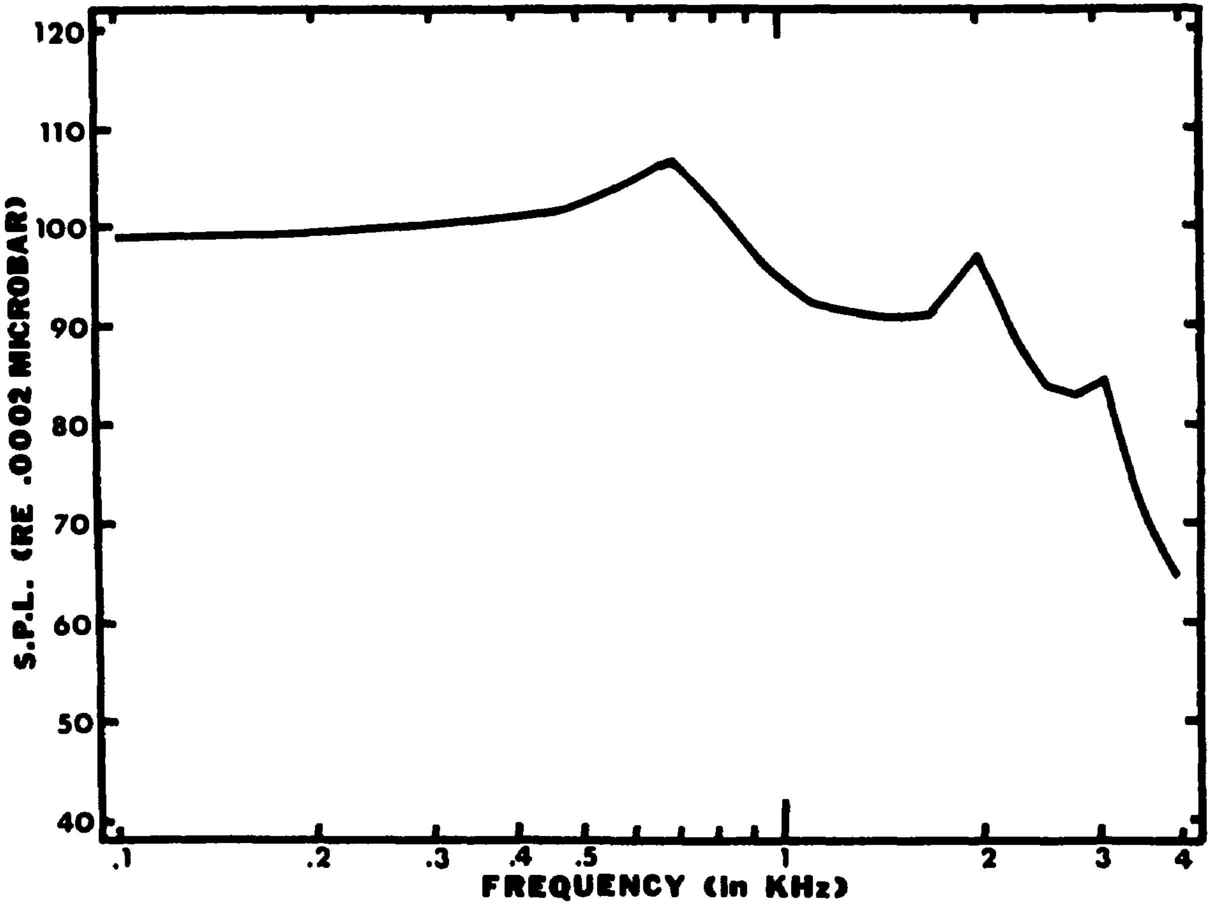


Figure 8 -- The Mean Frequency-Response Curve Obtained with Earmold A on the Special 2-cc Coupler.

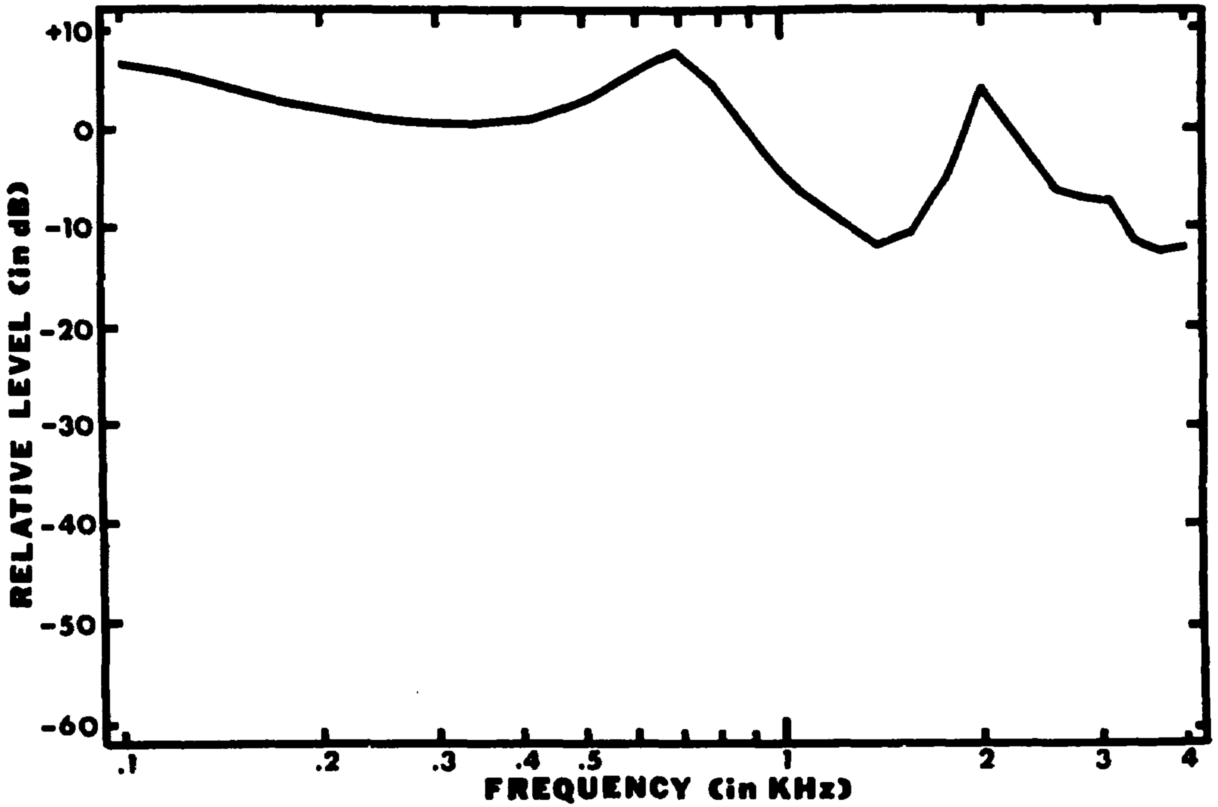


Figure 9 -- The Mean Frequency-Response Curve Obtained with Earmold A on the Special 2-cc Coupler Plotted Relative to the Response of the Hearing-Aid Receiver System on the Standard 2-cc Coupler.

frequency response is higher in amplitude from 100 to approximately 880 Hz for the response obtained with earmold A, with a resonant peak occurring at about 700 Hz. Another increase in amplitude is seen in the 1900 to 2400 Hz region for earmold A, with a resonant peak occurring at approximately 2000 Hz. Earmold A gave responses of relatively less amplitude for the remainder of the frequency range, with an anti-resonance occurring at about 1400 Hz.

The principal features of Figures 7, 8 and 9 may be explained as follows. In the standard coupler arrangement the 1400 Hz resonance is produced by a combination of the compliance of the receiver diaphragm acting together with the inertance of the diaphragm and the inertance of the air in the 18 X 3 mm tube. The results of this study and the discussions of others (71) (107) suggests that these two inertances act in series and, therefore, may be added directly.

When the 55 mm sound-input tubing is inserted in place of the 18 X 3 mm bore the inertance of the system is increased substantially, thereby lowering the frequency of the primary earphone-diaphragm resonance. Although exact values for the mass and equivalent volume of the diaphragm used are not available, calculations based on what appears to be a reasonable value for inertance (107) and the observed resonant frequency (1400 Hz) were used to calculate the diaphragm's equivalent volume (.19 cc). The increased inertance supplied by the 55 mm tube was then added and the resonant frequency (Helmholtz) of this system was calculated. The result was found to be 701 Hz, which was practically the same value as the observed finding of 700 Hz.

The apparent anti-resonance seen at 1400 Hz in Figure 9 is, in large part, a result of the resonance at 1400 Hz seen in Figure 7, which appears as a trough when plotted relative to the response of the receiver on the standard 2-cc coupler.

The secondary peak is thought to be produced by the inertance of the air in the tube acting with the compliance of the air over the diaphragm (71) (107). The necessary compliance can be inferred, but at this time it is felt that further investigation is needed. In any event, it seems certain that this resonant frequency is decreased by the addition of mass and that the wave length of the resonant frequency is not four times or twice that of the length of the input tubing. This suggests a Helmholtz resonance rather than a tube-length resonance. The calculation of the resonant frequency of a Helmholtz resonator will be discussed later.

The tertiary peak which occurs in the region of 3100 Hz is probably produced by a half-wave length resonance of the sound-input tubing. The calculated half-wave length resonant frequency of a 55 mm tube falls at 3218 Hz. A series of curves run with tubes of this general size revealed that quarter-wave length resonances do not appear.

The relative increase in amplitude below 300 Hz in Figure 9 may be attributed to the receiver's not being as tightly sealed on the standard 2-cc coupler as on the special coupler, allowing leakage to occur between the receiver and the coupler and thereby producing some reduction in the low frequencies in the standard coupler condition.

Probe-tube Effects upon Measurements as Determined on the Special Coupler Using Earmold A

Effects of Open Versus Closed Probe-tube Conditions upon Results Obtained with the One-half Inch Microphone. When the probe-tube aperture which opened into the coupler's 2-cc cavity was obstructed with modeling clay, only random fluctuations of the microphone amplifier's meter were observed and these were at about 35 dB SPL. All data readings were well above this level and, therefore, it can be said that transmission of the signal through the walls of the tubing or through the material of the earmold itself was not sufficient to influence the data.

Effects of Open Versus Closed Probe-tube Conditions upon Results Obtained with the One Inch Microphone. Figure 10 shows the SPL's obtained with the one inch microphone (solid line, A) when the probe-tube aperture was closed relative to the SPL's obtained on the same one inch microphone with the probe-tube aperture open. The comparison shows that differences no greater than 1.1 dB were observed across the entire frequency range tested, with the largest difference (1.1 dB) occurring at 700 Hz. This finding indicates that the volume of air contained within the probe-tube microphone system when introduceded into the receiver-earmold-special coupler acoustical system affects the levels obtained only to an insignificant degree.

Probe-tube Effects upon SPL Readings from the One-half Inch Microphone. Also shown in Figure 10 are the effects of the probe-tube upon measurements of SPL made with the one-half inch microphone. Using earmold A of all subjects on the special 2-cc coupler, the frequency-

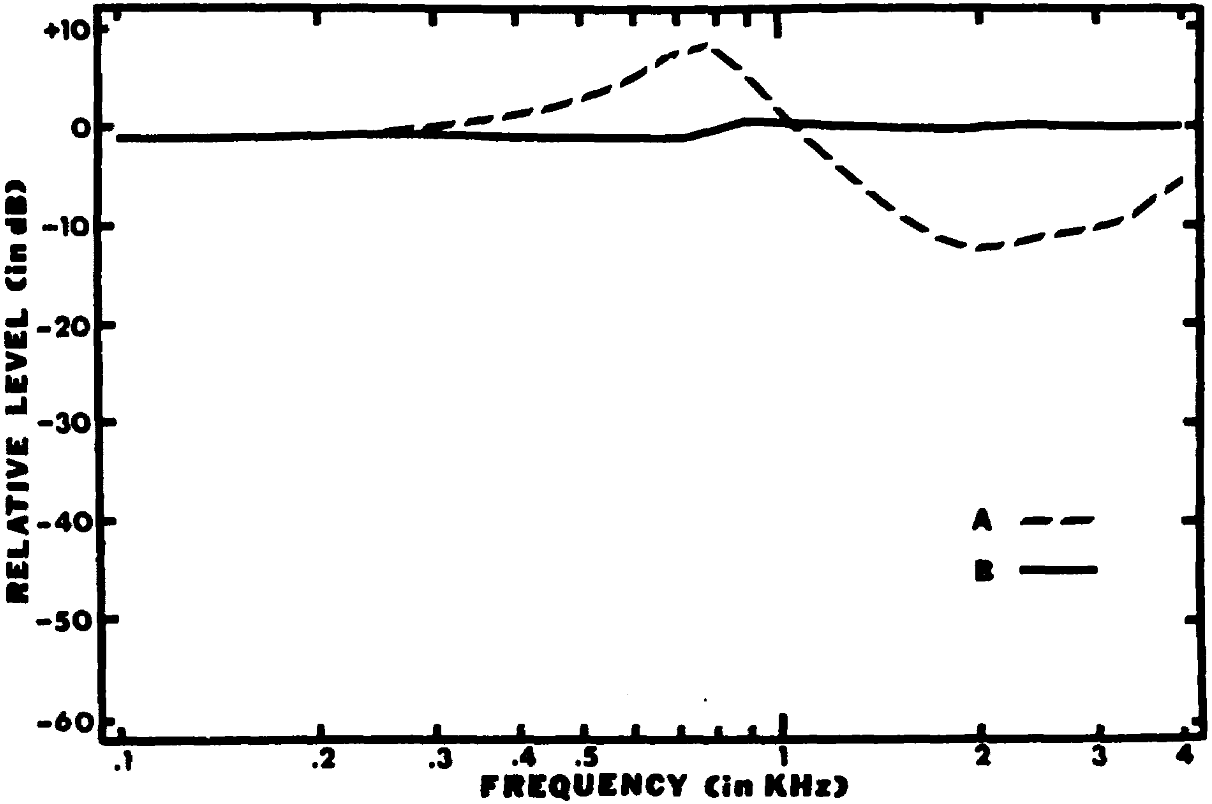


Figure 10 -- The Mean Frequency-Response Curves of Earmold A (Open Probe Condition) on the Special 2-cc Coupler as Measured by the One-half Inch Probe-Tube Microphone (Line A) and as Measured by the One Inch Artificial-Ear Microphone (Line B) Plotted Relative to the Response Curve Obtained Using the One Inch Microphone Under the Closed Probe-Tube Condition.

response curve obtained with the one-half inch microphone is plotted relative to the frequency-response curve obtained simultaneously from the one inch microphone. Essentially no difference exists between the SPL's at the diaphragms of the two microphones below about 400 Hz. Above 400 Hz, however a resonance is seen to build to a peak (+8.1 dB) at about 775 Hz and fall off slightly above 1000 Hz. This fall-off in the probe-tube microphone's relative response continues downward to 2000 Hz, where the anti-resonance occurs (-12.2 dB). The curve then gains amplitude toward the higher frequencies to a relative difference of about minus 5.5 dB at 4000 Hz. The quarter-wave length resonance of the 40 mm probe-tube is 2156 Hz, while the half-wave length resonance is 4312 Hz. Although an anti-resonance rather than a resonance is seen in the 2200 Hz region, where a quarter-wave length resonance would be expected to appear, a resonance is seen to build toward higher frequencies, i.e., the curve is rising toward a resonance at the highest frequency tested (4000 Hz). It is suspected that the peak would fall around the calculated half-wave length resonance were the frequency range extended upward (beyond the calculated peak of 4312 Hz).

The resonance which is seen to occur at about 775 Hz is somewhat more difficult to explain, principally because of the very low equivalent volume of the one-half inch microphone (less than 0.01 cc). Also, the air volume over the diaphragm is very small (about 0.12 cc). Because of these small volumes, slight errors make rather large differences in the calculated results of formulae used to determine resonance. In spite of these difficulties, calculations based on certain apparently reasonable assumptions result in a resonant frequency within one octave of that actually observed. However, these assumptions are not now firmly based and it is felt that further investigation is needed before more definitive statements can be made.

The curve discussed in this section shows the corrections which were made for the probe-tube effects when it was used with the one-half inch microphone to measure SPL.

Coupler Measurement Variability

The "intrasubject" variability (test-retest on same earmold A) obtained on the special 2-cc coupler while testing earmold A was very small. Test results obtained in the two runs with both the one inch (2-cc coupler) and the one-half inch (probe-tube) microphones were found to differ by no more than one-half of a decibel at any frequency tested. The "intersubject" variability (test-retest between earmolds A of all subjects) for these same conditions was also small. The mean values obtained from the one inch microphone differed across earmolds by no more than 1.2 dB at any frequency tested. The mean values obtained from the one-half inch microphone differed between "subjects" (earmolds) by no more than 2 dB from 100 to 3100 Hz, no more than 2.7 dB at 3400 Hz, and no more than 3.2 dB at 3700 and 4000 Hz.

Receiver-Earmold A-Special Coupler Findings Compared with the Receiver-Earmold A-Real Ear Findings

In Figure 11 are shown the frequency-response curves obtained with earmold A in the real ear and with earmold A on the special 2-cc coupler. In the test procedure each earmold was sealed in the real ear with vaseline, thereby eliminating any apparent leakage effects that

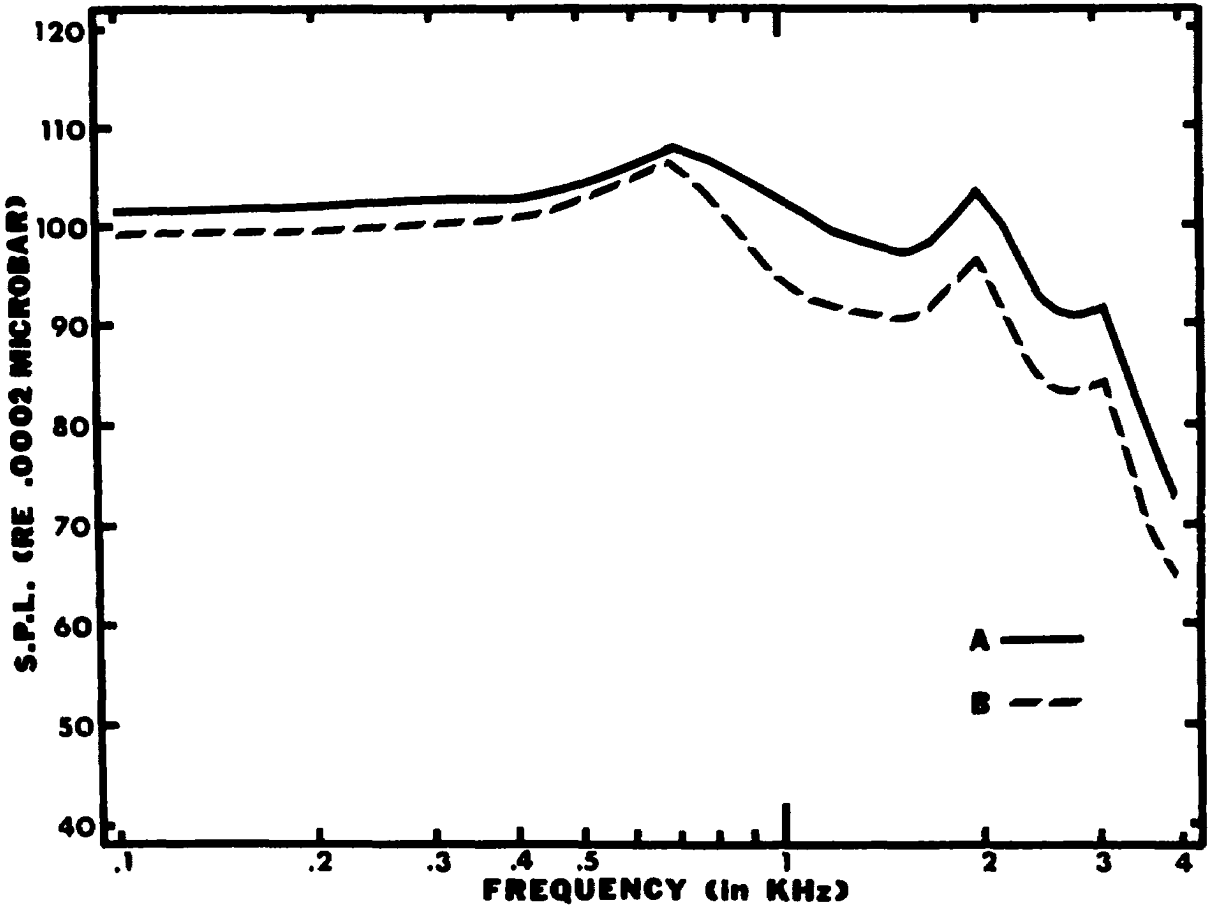


Figure 11 -- The Mean Frequency-Response Curves Obtained with Earmold A in the Real Ear (Line A) and with Earmold A on the Special 2-cc Coupler (Line B).

may be present in an unsealed condition. Under normal conditions of use, where leakage is present between the skin of the ear canal and the earmold, a comparison between a vented coupler curve and that of the real ear might be a more realistic comparison. Note in Figure 11 that the response curve found in the real ear is of greater amplitude across the entire range of frequencies tested, with the greatest differences occurring in the frequencies above about 800 Hz. In the low frequencies below approximately 700 Hz the two curves are essentially parallel; however, above about 700 Hz the coupler response falls off relative to the response found in the real ear.

Other writers (28) (114) have also reported sound levels to be higher in the real ear than in the 2-cc coupler. It appears that the probe-tube microphone, while measuring the response of earmold A in the real ear, reacts as if it is measuring sound in a cavity which is smaller in size than the coupler's 2-cc cavity. Wandsdronk (107) found that increasing the size of the cavity between the earmold tip and the eardrum causes a decrease in the over-all response. Conversely, a decrease in the size of this cavity should cause an increase in the over-all response. It is not clear what causes the greater separation between the two curves in the high frequencies, although Nichols, et al. (86) (10) and Zachman (114) observed that sound levels in the coupler decreased relative to those in the real ear as frequency was increased.

Briskey, Greenbaum and Sinclair (15) reported that ". . . probe-tube measurements show the resonant frequency to be lower [in frequency] in the [ear] canal cavity than in the 2-cc coupler." This study does not support their finding. The resonant peaks which were present in the response curve found with earmold A on the special 2-cc coupler were in the same relative locations in the frequency-response curve found with earmold A on the real ear. The differences in amplitude across frequency were found to be the significant variable. The real-ear response was greater than the special 2-cc coupler response at all frequencies tested, with the greatest differences occurring in the high-frequency range.

Receiver-Earmold Findings Obtained in the Human Auditory Meatus

Earmold A

Presented in Figure 12 is the mean frequency-response curve for Earmold A as tested in the human ear canals of all subjects. This is the same curve as the upper curve in Figure 11. On the same figure is the range of individual levels obtained with Earmold A. The small range between the highest and lowest levels obtained in the individual tests is indicative of the high consistency of acoustic conditions between tests of Earmold A on different subjects. Standard deviations for intrasubject and intersubject comparisons were computed for the findings of Earmold A in the real ear, and are presented in Table 3 for all frequencies tested. The intrasubject standard deviations were all less than 1.20 dB, and the intersubject standard deviations were all less than 2.66 dB.

The mean frequency-response curve for Earmold A in the real ear is presented in Figure 12 and seen to be essentially flat from 100 to about 400 Hz, where a resonant peak starts to build and reaches its maximum at approximately 700 Hz. Above 700 Hz the curve falls off in

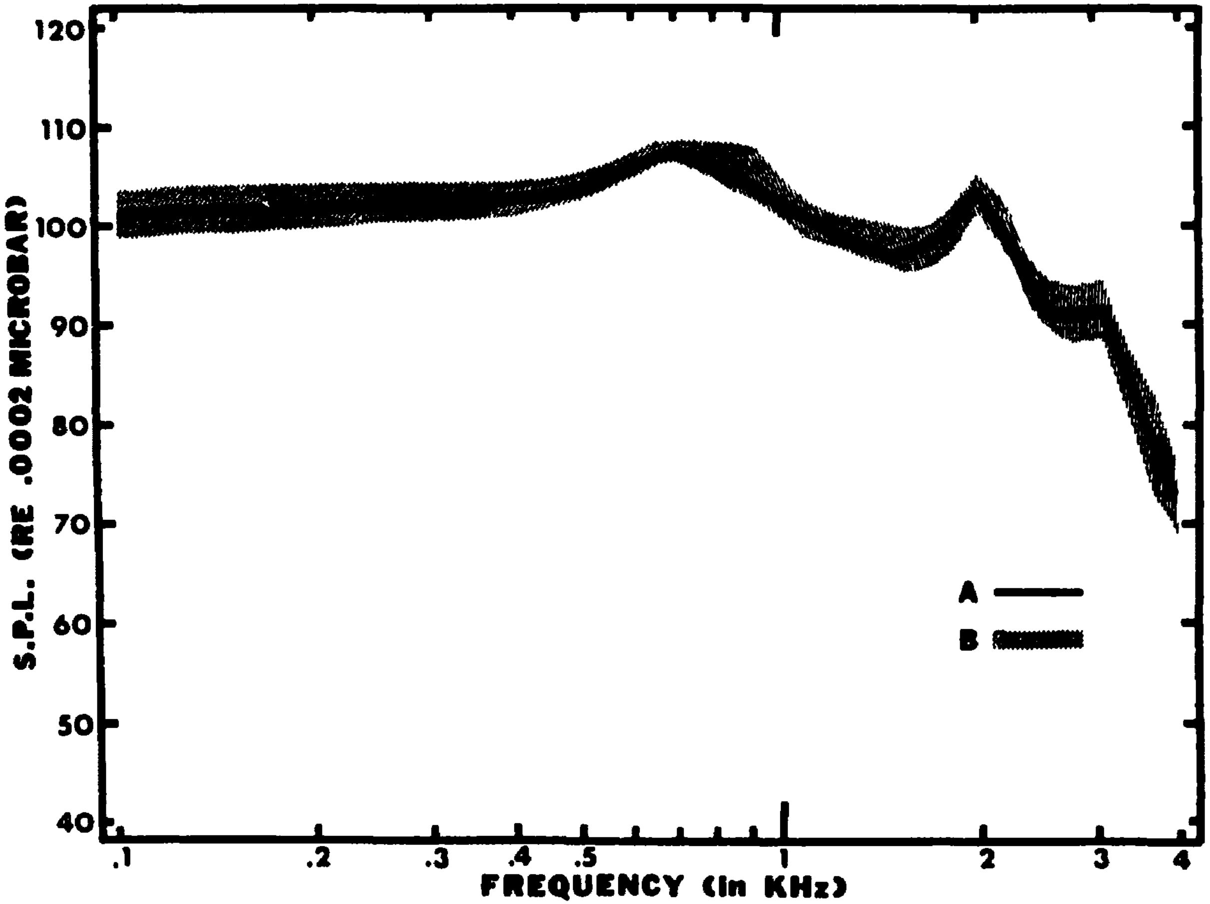


Figure 12 -- The Mean Frequency-Response Curve (Line A) and Range of Individual Levels (Area B) Obtained when Testing Earmold A in the Real Ear.

TABLE 3

INTRASUBJECT AND INTERSUBJECT STANDARD DEVIATIONS FROM EARMOLD A RESULTS (REAL EAR) IN dB

	Intrasubject								
	Subject								
Hz	1	2	3	4	5	6	7	8	Intersubject
100	0.13	0.17	0.55	0.05	0.27	0.17	0.46	0.49	1.60
110	0.08	0.18	0.57	0.08	0.14	0.18	0.46	0.46	1.55
120	0.22	0.15	0.47	0.13	0.08	0.17	0.45	0.48	1.50
130	0.31	0.10	0.51	0.14	0.14	0.13	0.49	0.48	1.45
140	0.27	0.10	0.44	0.13	0.25	0.15	0.50	0.50	1.43
150	0.26	0.08	0.42	0.13	0.29	0.18	0.54	0.48	1.41
165	0.24	0.08	0.47	0.13	0.35	0.18	0.54	0.47	1.33
180	0.31	0.05	0.58	0.17	0.31	0.18	0.49	0.50	1.31
195	0.36	0.06	0.59	0.13	0.34	0.18	0.49	0.51	1.30
210	0.35	0.05	0.61	0.13	0.39	0.22	0.49	0.51	1.28
230	0.36	0.05	0.63	0.15	0.46	0.18	0.49	0.51	1.24
250	0.44	0.05	0.59	0.15	0.55	0.19	0.46	0.46	1.21
275	0.32	0.10	0.43	0.10	0.50	0.22	0.45	0.38	1.16
300	0.29	0.08	0.43	0.15	0.46	0.17	0.45	0.39	1.14
330	0.35	0.10	0.51	0.15	0.53	0.22	0.50	0.39	1.12
360	0.26	0.10	0.70	0.15	0.53	0.25	0.50	0.29	1.04
390	0.26	0.10	0.50	0.15	0.60	0.17	0.34	0.31	1.00
420	0.31	0.08	0.56	0.10	0.55	0.22	0.33	0.31	0.97
460	0.29	0.16	0.71	0.12	0.41	0.21	0.37	0.19	0.95
500	0.33	0.13	0.67	0.08	0.44	0.18	0.41	0.26	0.92
550	0.35	0.13	0.83	0.13	0.35	0.22	0.41	0.22	0.87
600	0.29	0.10	0.68	0.14	0.37	0.22	0.37	0.29	0.79
650	0.37	0.05	0.55	0.13	0.31	0.22	0.34	0.29	0.79
700	0.37	0.10	0.39	0.13	0.33	0.17	0.25	0.34	0.71
775	0.45	0.10	0.43	0.14	0.34	0.30	0.17	0.48	0.97
850	0.63	0.00	0.67	0.20	0.44	0.40	0.18	0.50	1.42
925	0.69	0.15	0.58	0.19	0.42	0.37	0.14	0.48	1.71
1000	0.81	0.25	0.62	0.26	0.31	0.33	0.25	0.53	1.58
1100	0.90	0.19	0.82	0.33	0.44	0.26	0.29	0.45	1.59
1200	0.79	0.15	0.72	0.24	0.47	0.28	0.25	0.54	1.47
1300	0.54	0.08	0.82	0.21	0.58	0.39	0.31	0.37	1.31
1400	0.40	0.08	0.79	0.21	0.58	0.41	0.48	0.37	1.36
1550	0.44	0.10	0.52	0.13	0.53	0.39	0.13	0.50	1.31
1700	0.33	0.10	0.40	0.15	0.58	0.40	0.57	0.41	1.36
1850	0.17	0.13	0.46	0.08	0.56	0.36	0.73	0.43	1.49
2000	0.19	0.10	0.53	0.17	0.37	0.44	0.74	0.50	1.42
2200	0.35	0.41	0.71	0.49	0.39	0.57	0.70	0.52	1.73
2400	0.29	0.84	0.61	0.32	0.52	0.28	0.70	0.24	1.67
2600	0.26	0.87	0.98	0.24	0.43	0.62	0.77	0.26	1.85
2800	0.59	0.57	1.01	0.17	0.33	0.61	0.69	0.51	2.09
3100	0.65	0.54	0.90	0.13	0.41	0.44	0.71	0.58	2.10
3400	1.09	1.17	0.97	0.05	0.62	0.65	0.69	0.30	2.48
3700	0.56	0.24	1.00	0.37	0.67	0.56	0.57	0.29	3.30
4000	0.54	0.30	1.10	0.54	1.05	0.84	0.68	1.19	2.65

amplitude at a rate of about 10 dB per octave to 1550 Hz, where a second resonance begins to build steadily until it reaches its maximum at 2000 Hz. Beyond the resonant peak at 2000 Hz the response falls off sharply to about 2600 Hz, where a third resonance starts to build and reaches its peak at 3100 Hz. Beyond the 3100 Hz peak the response curve falls off precipitously and continuously to 4000 Hz. This mean response curve will be the basis for real-ear comparisons, i.e., the results for earmolds B, C, and D will be compared with the response curve of this unmodified earmold.

Earmold B

The mean frequency-response curve found with earmold B is shown in Figure 13, along with the range of individual levels obtained with earmold B on each subject. Intertest consistency was good, as is indicated by the narrow range seen in Figure 13 and the calculated standard deviations shown in Table 4. Both intrasubject and intersubject standard deviations were calculated for earmold B and are presented in Table 4. Intrasubject standard deviations for this earmold were less than one decibel below 3400 Hz, with no standard deviation being greater than 1.25 dB for all frequencies except 2800 and 4000 Hz, where standard deviations were 2.20 and 3.10 dB respectively.

The amount of change in frequency response due to the alteration of shortening and hollowing an earmold's canal, but without venting it, as shown in Figure 14, where the mean frequency response curve obtained with Earmold B in the real ear is plotted relative to the mean frequency-response curve obtained with Earmold A in the real ear. Note that the response of Earmold B falls approximately 3 to 6 dB below that

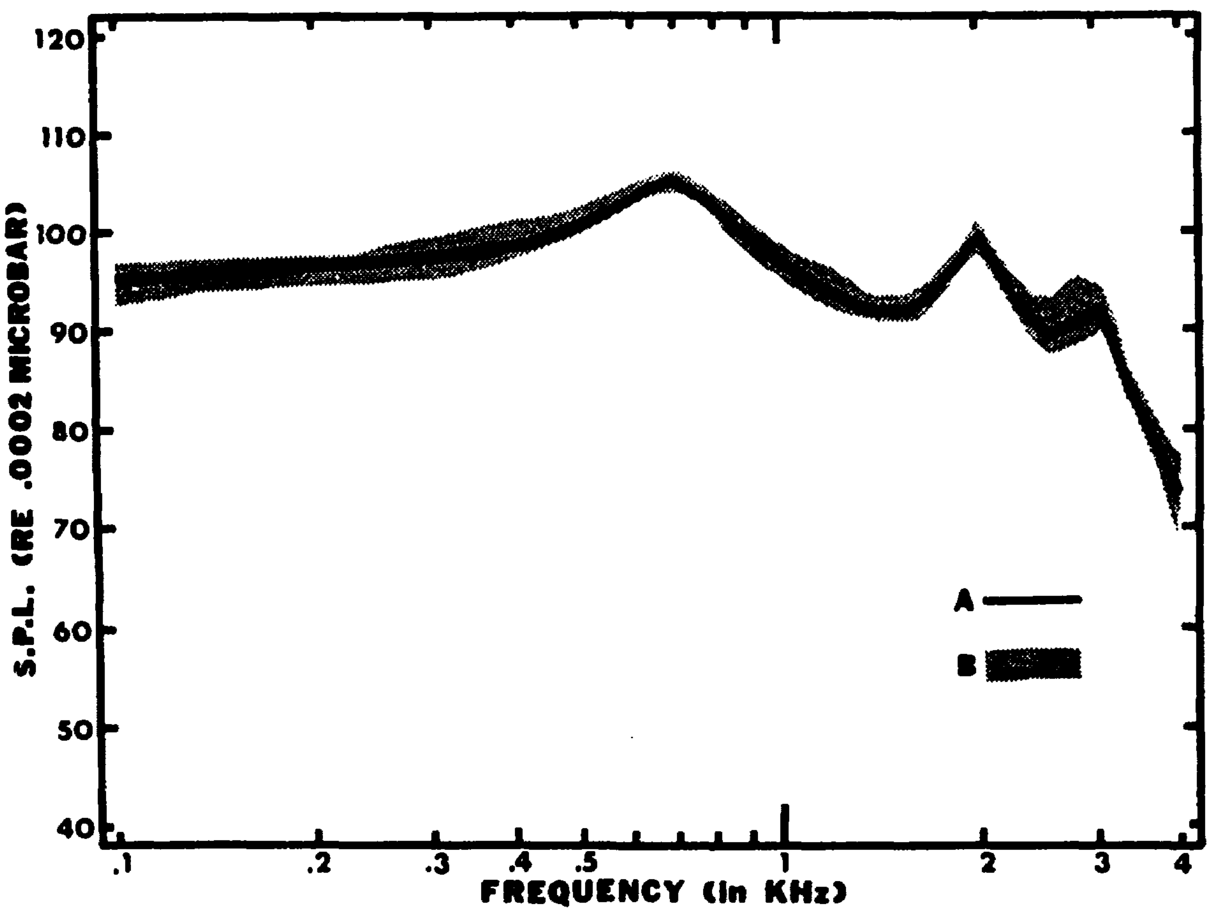


Figure 13 -- The Mean Frequency-Response Curve (Line A) and Range of Individual Levels (Area B) Obtained when Testing Earmold B in the Real Ear.

TABLE 4

INTRASUBJECT AND INTERSUBJECT STANDARD DEVIATIONS FROM EARMOLD B RESULTS (REAL EAR) IN dB

	Intrasubject								
	Subject								
Hz	1	2	3	4	5	6	7	8	Intersubject
100	0.29	0.31	0.44	0.57	0.57	0.27	0.39	0.47	1.85
110	0.30	0.32	0.62	0.49	0.38	0.25	0.34	0.51	1.72
120	0.28	0.36	0.67	0.49	0.31	0.21	0.37	0.50	1.62
130	0.31	0.34	0.54	0.33	0.24	0.21	0.34	0.47	1.49
140	0.31	0.38	0.49	0.26	0.17	0.21	0.29	0.47	1.35
150	0.31	0.34	0.30	0.31	0.13	0.32	0.28	0.54	1.20
165	0.36	0.29	0.30	0.31	0.10	0.32	0.28	0.53	1.13
180	0.36	0.29	0.33	0.38	0.15	0.29	0.31	0.58	1.12
195	0.38	0.21	0.26	0.39	0.21	0.25	0.27	0.63	1.09
210	0.33	0.19	0.24	0.44	0.22	0.24	0.25	0.65	1.06
230	0.38	0.19	0.36	0.54	0.29	0.28	0.34	0.66	1.02
250	0.33	0.13	0.29	0.42	0.29	0.21	0.27	0.70	1.04
275	0.13	0.17	0.39	0.47	0.32	0.17	0.22	0.68	1.09
300	0.15	0.13	0.33	0.27	0.31	0.22	0.24	0.62	1.12
330	0.06	0.13	0.15	0.41	0.28	0.22	0.22	0.56	1.13
360	0.13	0.17	0.45	0.49	0.29	0.29	0.19	0.28	1.38
390	0.27	0.21	0.59	0.57	0.24	0.29	0.18	0.27	1.09
420	0.41	0.17	0.80	0.61	0.17	0.29	0.15	0.22	1.05
460	0.48	0.24	0.90	0.45	0.15	0.29	0.10	0.27	0.95
500	0.41	0.24	0.95	0.50	0.22	0.27	0.17	0.30	0.92
550	0.33	0.25	0.93	0.44	0.26	0.25	0.19	0.29	0.89
600	0.28	0.21	0.63	0.44	0.22	0.19	0.21	0.24	0.81
650	0.24	0.21	0.70	0.22	0.22	0.19	0.21	0.19	0.77
700	0.10	0.25	0.83	0.22	0.38	0.10	0.19	0.26	0.78
775	0.15	0.40	0.75	0.32	0.54	0.26	0.37	0.26	0.88
850	0.22	0.48	0.41	0.41	0.56	0.50	0.54	0.35	1.06
925	0.27	0.47	0.81	0.51	0.60	0.50	0.61	0.34	1.25
1000	0.24	0.39	0.62	0.37	0.53	0.37	0.49	0.43	1.18
1100	0.29	0.42	0.34	0.34	0.50	0.31	0.46	0.26	1.28
1200	0.22	0.40	0.93	0.41	0.39	0.29	0.48	0.37	1.38
1300	0.25	0.50	0.55	0.38	0.59	0.26	0.46	0.38	1.12
1400	0.34	0.41	0.59	0.26	0.55	0.31	0.27	0.42	0.97
1550	0.30	0.31	0.93	0.28	0.59	0.22	0.36	0.48	1.07
1700	0.34	0.26	0.85	0.32	0.69	0.17	0.42	0.31	1.15
1850	0.40	0.27	0.57	0.17	0.57	0.13	0.49	0.46	1.15
2000	0.31	0.31	0.85	0.15	0.71	0.17	0.41	0.66	1.22
2200	0.44	0.76	0.94	0.26	0.90	0.25	0.22	0.79	1.33
2400	0.29	0.75	0.56	0.08	0.89	0.25	0.10	0.53	1.48
2600	0.35	0.66	0.76	0.08	0.76	0.26	0.14	0.65	1.79
2800	0.35	0.57	0.90	0.13	0.86	0.33	0.05	0.67	2.20
3100	0.30	0.59	0.78	0.14	0.75	0.44	0.59	0.70	1.35
3400	0.27	0.76	0.46	0.46	1.13	0.73	0.96	0.82	1.22
3700	0.79	0.44	0.31	0.72	0.96	1.13	1.04	1.01	1.54
4000	0.48	1.19	0.42	0.96	0.92	1.25	0.71	0.75	3.10

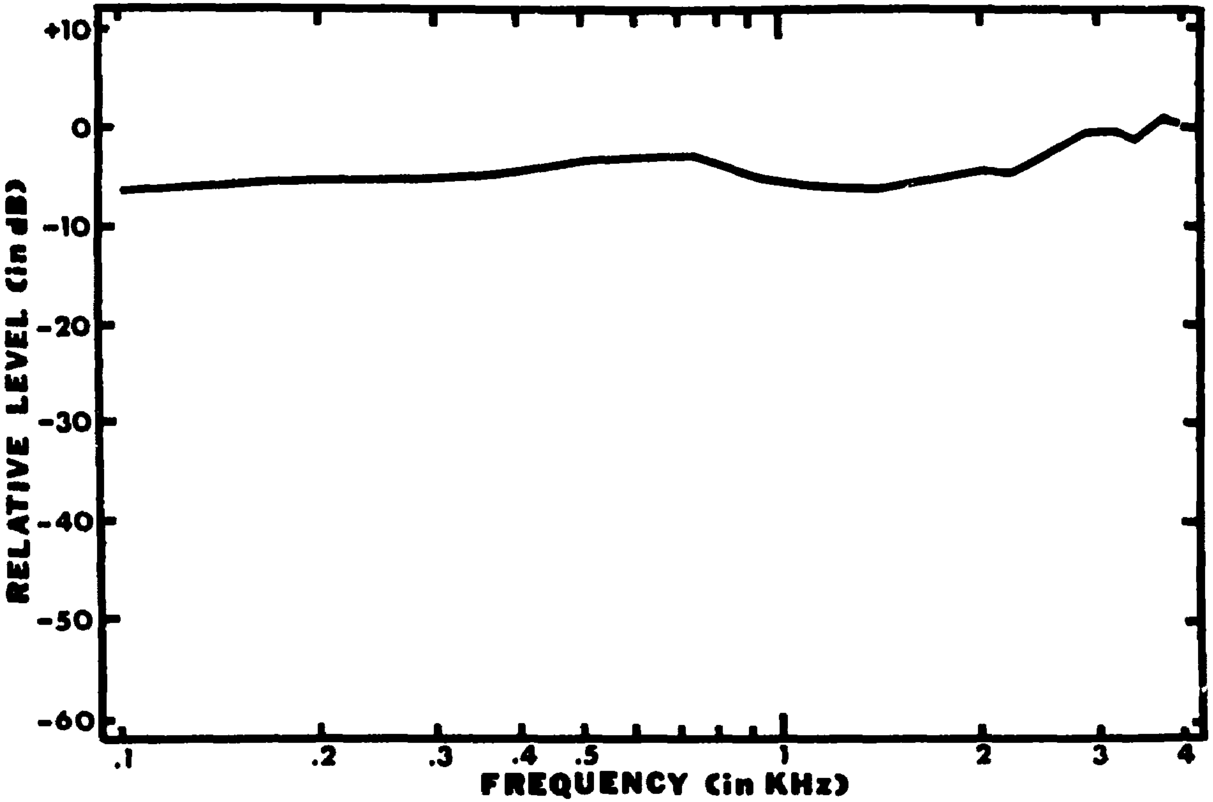


Figure 14 — The Mean Frequency-Response Curve Obtained with Earmold B in the Real Ear Plotted Relative to the Mean Frequency-Response Curve Obtained With Earmold A in the Real Ear.

of earmold A from 100 to 2400 Hz, and shows less than ± 2 dB difference for the frequencies 2600 to 4000 Hz. Attention is also called to a very slight resonance effect at about 700 Hz.

Wandsdronk (107) worked with earmolds in real ears and found that increasing the size of the cavity between the earmold and the eardrum tends to decrease the over-all level response of an input system. Lybarger (71), on the other hand, worked with earmolds on couplers and indicates that changes in the volume between the eardrum and the earmold will primarily affect the low-frequency range of the response curve. The findings of this study indicate that the earmold having a shortened-hollowed canal, when sealed in the ear, produces a reduction in response for the low and middle frequencies, with the frequencies in the high range being affected only slightly.

Earmold C

The mean frequency-response curve obtained with earmold C is shown in Figure 15, along with the range of individual levels obtained for each subject. The narrow range shown in Figure 15 and the calculated intrasubject and intersubject standard deviations shown in Table 5 are indicative of very good test consistency. Intrasubject standard deviations were no greater than 1.3 dB at any test frequency. Intersubject standard deviations were no greater than 2.1 dB at any test frequency.

The sound pressure changes brought about by shortening, hollowing and venting an earmold in the manner described for earmold C are shown in Figure 16, where the mean frequency-response curve obtained with earmold C in the real ear is plotted relative to the mean

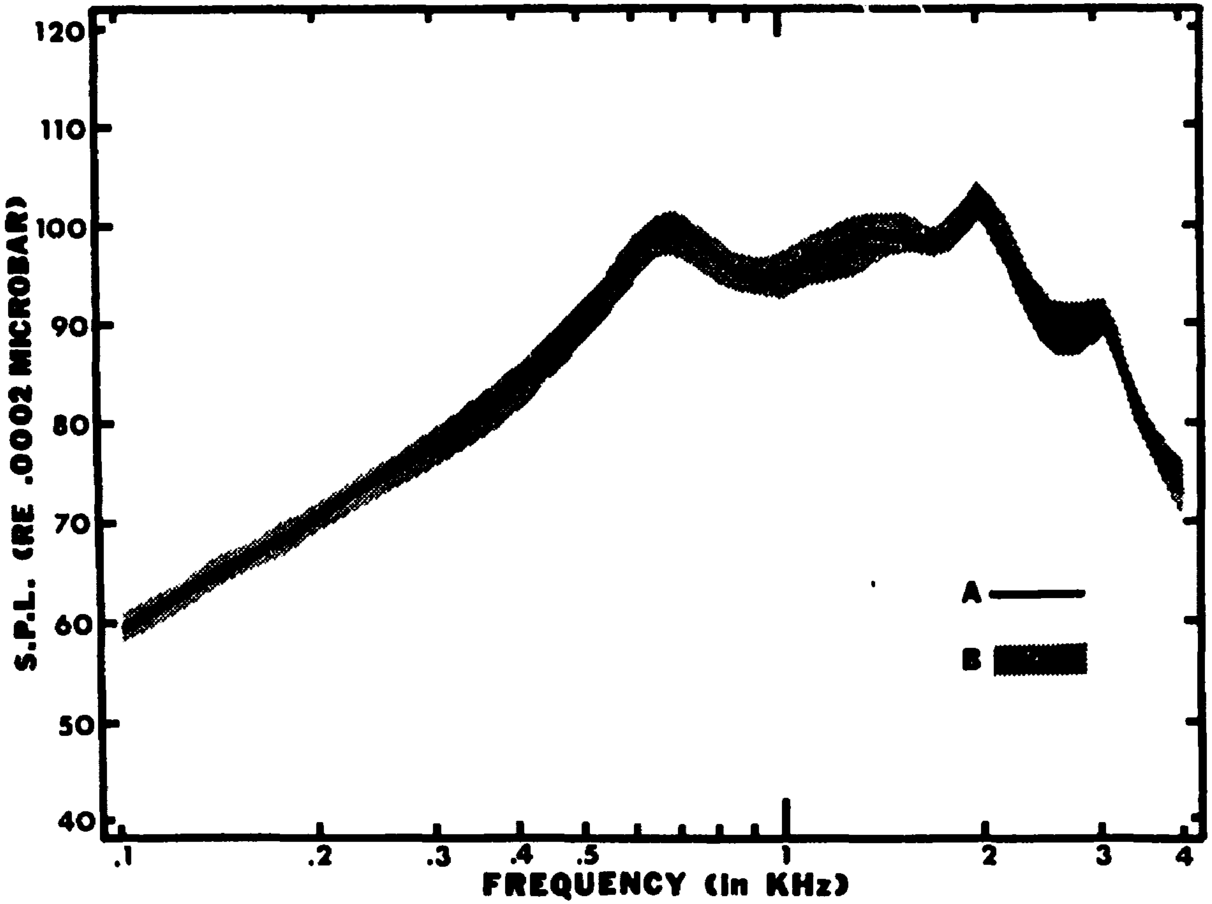


Figure 15 -- The Mean Frequency-Response Curve (Line A) and Range of Individual Levels (Area B) Obtained when Testing Earmold C in the Real Ear.

TABLE 5

INTRASUBJECT AND INTERSUBJECT STANDARD DEVIATIONS FROM EARMOLD C RESULTS (REAL EAR) IN dB

	Intrasubject								
	Subject								
Hz	1	2	3	4	5	6	7	8	Intersubject
100	0.34	0.21	0.53	0.41	0.53	0.10	0.36	0.41	0.87
110	0.27	0.13	0.29	0.28	0.40	0.13	0.42	0.45	0.93
120	0.36	0.21	0.48	0.42	0.40	0.15	0.41	0.41	0.99
130	0.43	0.18	0.26	0.52	0.45	0.18	0.48	0.45	1.02
140	0.44	0.27	0.29	0.37	0.51	0.06	0.51	0.41	1.01
150	0.55	0.14	0.47	0.14	0.25	0.10	0.46	0.39	1.00
165	0.59	0.33	0.51	0.32	0.08	0.33	0.64	0.47	1.04
180	0.73	0.40	0.43	0.38	0.13	0.43	0.64	0.43	1.07
195	0.75	0.50	0.48	0.39	0.24	0.44	0.70	0.53	1.06
210	0.73	0.49	0.50	0.45	0.31	0.39	0.50	0.53	1.10
230	0.85	0.48	0.54	0.45	0.25	0.48	0.40	0.58	1.15
250	0.79	0.29	0.67	0.39	0.22	0.44	0.48	0.48	1.12
275	0.47	0.26	0.29	0.27	0.19	0.30	0.52	0.46	1.23
300	0.59	0.22	0.61	0.26	0.22	0.35	0.54	0.41	1.27
330	0.63	0.15	0.68	0.26	0.22	0.28	0.96	0.50	1.41
360	0.67	0.25	0.67	0.29	0.22	0.29	0.64	0.43	1.46
390	0.56	0.18	0.65	0.28	0.21	0.39	0.52	0.36	1.44
420	0.44	0.25	0.49	0.26	0.21	0.36	0.66	0.49	1.39
460	0.50	0.17	0.48	0.24	0.18	0.26	0.71	0.43	1.47
500	0.72	0.17	0.42	0.10	0.22	0.25	0.71	0.32	1.46
550	0.67	0.17	0.13	0.13	0.21	0.22	0.44	0.34	1.57
600	0.78	0.22	0.44	0.08	0.22	0.24	0.71	0.37	1.59
650	0.46	0.17	0.50	0.13	0.17	0.14	0.68	0.47	1.53
700	0.64	0.20	0.47	0.32	0.25	0.21	0.70	0.49	1.47
775	0.99	0.31	0.68	0.71	0.25	0.29	0.68	0.86	1.49
850	0.90	0.35	0.48	0.77	0.39	0.37	0.84	0.55	1.32
925	0.93	0.38	0.54	0.87	0.36	0.45	0.99	0.59	1.38
1000	1.04	0.48	0.40	0.76	0.34	0.46	0.66	0.41	1.66
1100	1.15	0.71	0.48	0.73	0.33	0.50	0.69	0.44	1.74
1200	0.76	0.86	0.66	0.55	0.29	0.49	0.65	0.44	1.99
1300	0.98	0.75	0.49	0.44	0.24	0.55	0.44	0.43	2.07
1400	1.01	0.48	0.27	0.43	0.22	0.45	0.69	0.70	1.61
1550	0.31	0.47	0.65	0.53	0.32	0.42	0.42	0.82	1.37
1700	0.44	0.44	0.38	0.37	0.30	0.40	0.40	0.84	1.28
1850	0.65	0.53	0.34	0.25	0.33	0.45	0.44	0.76	1.39
2000	0.59	0.42	0.39	0.29	0.32	0.35	0.45	0.76	1.39
2200	0.18	0.33	0.48	0.39	0.22	0.44	0.33	0.64	1.57
2400	0.42	0.77	0.47	0.20	0.22	0.39	0.57	0.70	1.64
2600	0.57	0.62	0.47	0.42	0.35	0.41	0.71	0.74	1.61
2800	0.73	0.34	0.80	0.47	0.47	0.47	0.64	0.83	1.53
3100	0.37	0.40	0.54	0.47	0.99	0.48	0.62	0.67	1.28
3400	0.89	0.24	0.92	0.83	0.94	0.53	0.54	0.62	1.48
3700	1.13	0.37	0.64	1.08	0.90	0.69	0.68	0.73	1.81
4000	0.90	0.66	1.30	1.01	1.04	1.03	0.95	1.26	2.10

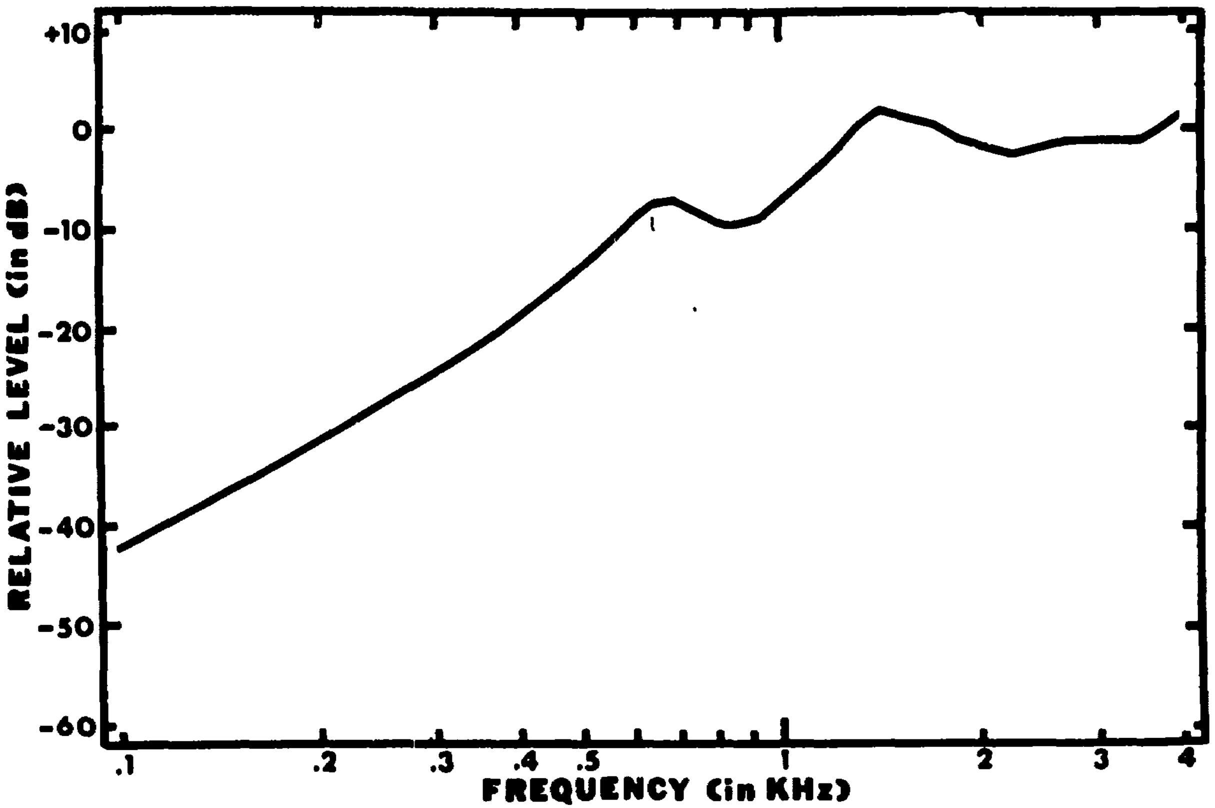


Figure 16 -- The Mean Frequency-Response Curve Obtained with Earmold C in the Real Ear Plotted Relative to the Mean Frequency-Response Curve Obtained with Earmold A in the Real Ear.

frequency-response curve obtained with earmold A in the real ear. Note that there is a drastic drop in low-frequency response with the vented earmold, and that the drop is approximately 12.5 dB per octave below 400 Hz. Above 400 Hz a resonance starts to build on the relative response curve and reaches a peak at about 700 Hz. The curve above 700 Hz falls off at about 6 dB per octave to 850 Hz where a second resonance starts to build and reaches a peak around 1400 Hz. The relative amplitudes of the first and second resonant peaks are about minus seven and plus two decibels respectively. Above 2200 Hz, up to 4000 Hz, the response curve of earmold C differs from that of earmold A by less than two decibels.

The low-frequency filtering effect of vents in earmolds has been reported by earlier writers (71) (21) (114), and is known to vary according to the diameter and length of the vent. The vent used with earmold C was three millimeters in diameter and three millimeters in length. Power-transmission ratios expressed in decibel losses for the sound-input channel and the vent of earmold C were calculated according to side-branch theory.

Kinsler and Frey (55) discuss side-branch theory and state that when the length of the side branch is much smaller than the wave length the side branch may be treated as an orifice, and the sound-power-transmission ratio down the bore, past the vent, is defined by the formula:

$$P_t = \frac{1}{1 + (\pi a^2 / 2Sl' k)^2}$$

where P_t = the ratio between the sound power in the main pipe prior to the side branch and the sound power in the main pipe beyond the side branch,

π = 3.1416

a = the radius of the side branch

S = the cross-sectional area of the main pipe,

l'= the length of the branch (l) plus 1.7a (end correction for the inertance of air at the orifice),

k = a wave length constant or $\frac{2\pi}{\lambda}$, where λ = wave length.

Using the formula suggested by Kinsler and Frey, the power-transmission ratios expressed in decibel losses were calculated for earmold C at 100, 210, 500, 700, 1000, 1400, 2000 and 4000 Hz. These losses were found to be 41.9, 35.5, 27.9, 25, 21.9, 19, 16 and 10.3 dB respectively. These eight calculated frequency points allow one to estimate the total power-transmission ratio curve with a good degree of accuracy by drawing a slightly curving line through these calculated points plotted graphically. The actual reduction in level as represented graphically in Figure 16 was 41.8 dB at 100 Hz, which is only .1 dB less than the calculated loss. At 210, 500, 700, 1000 and 2000 Hz the actual losses were 30.3, 13.2, 7.5, 7.3 and 1.4 dB, while at 1400 and 4000 Hz relative gains of 1.9 and 1.5 dB were obtained instead of the calculated losses of 19 and 10.3 dB respectively. On the basis of comparing the power-transmission ratio curve with the actual findings on earmold C, it becomes apparent that the calculated losses are accurate only for the low-frequency signals which fall below the lowest resonance of the frequency-response curve. The differences noted between the calculated and actual experimental finding for earmold C may be explained on the basis of resonance.

In resonant circuit theory a greater resistance in a circuit will result in reduced resonant peak height. This also holds true in acoustic circuits. The resistance of a tube is decreased at the rate of $\frac{1}{\pi r^4}$ according to Benson (8). It is clear on the basis of this formula that resistance decreases rapidly as a function of increasing radius. Therefore, larger vents in earmolds should produce noticeably larger resonances. Zachman (114) found this to be the case in his study of vented conventional earmolds.

As explained earlier in this chapter, a 700 Hz resonance is produced by the receiver when it is loaded with the air in the plastic adapter and sound-input tubing of earmold A. Because all experimental earmolds utilized the same type adapter and the same size sound-input tubing, the signal emitted at the medial aperture of the sound-input channel of earmold C was essentially the same as that emitted from earmold A. The prominence of the 700 Hz peak, which is seen clearly in the relative plot of Figure 16, can be attributed to a reduction of the resistance within the ear canals of the subjects due to the presence of the three millimeter vent of earmold C. The decreased resistance increased the size of the resonance, thereby causing it to appear when plotted relative to the findings with earmold A.

The peak seen at about 1400 Hz in Figure 16 can be explained on the basis of the ear canal's forming the volume portion of a Helmholtz resonator with the vent of earmold C forming the neck portion. The resonant frequency of the ear canal in combination with the earmold C vent was calculated using the formula presented by Beranek (11, p. 69):

$$\omega = \frac{1}{\sqrt{M\,C}}\,.$$

where ω is found in radians/second, M= acoustic mass (inertance) of the air within the neck of the resonator in kilograms/meter^4, and C= acoustic compliance of the volume of air undergoing compression, expressed in meters^5/Newton. The vent of earmold C was calculated as a neck portion of a Helmholtz resonator, having a length and a diameter of three millimeters. The ear canal was calculated as the volume portion of the resonator, having a total volume of three cubic centimeters. This volume was used on the basis of the approximate physical volume of the ear canal medial to the shortened and hollowed earmold C plus the equivalent volume of the eardrum (.8 cc) as reported by Zwislocki (116). The calculated resonance, given these dimensions, was approximately 1543 Hz. This value is very close to the observed resonance which peaked at approximately 1400 Hz.

Earmold D

The mean frequency-response curve obtained with earmold D in the real ear is shown in Figure 17, along with the range of individual levels obtained for each subject. The range of scores was somewhat wider for earmold D than for the other earmolds. Standard deviations are shown in Table 6 for both the intrasubject and the intersubject comparisons. Intrasubject standard deviations at frequencies 2400 Hz and below were no greater than 1.17 dB, nor greater than 1.37 dB for those frequencies above 2400 Hz. Intersubject standard deviations were no greater than 3.19 dB at any of the test frequencies other than 3400, 3700 and 4000 Hz, which showed standard deviations of 3.64, 3.68 and

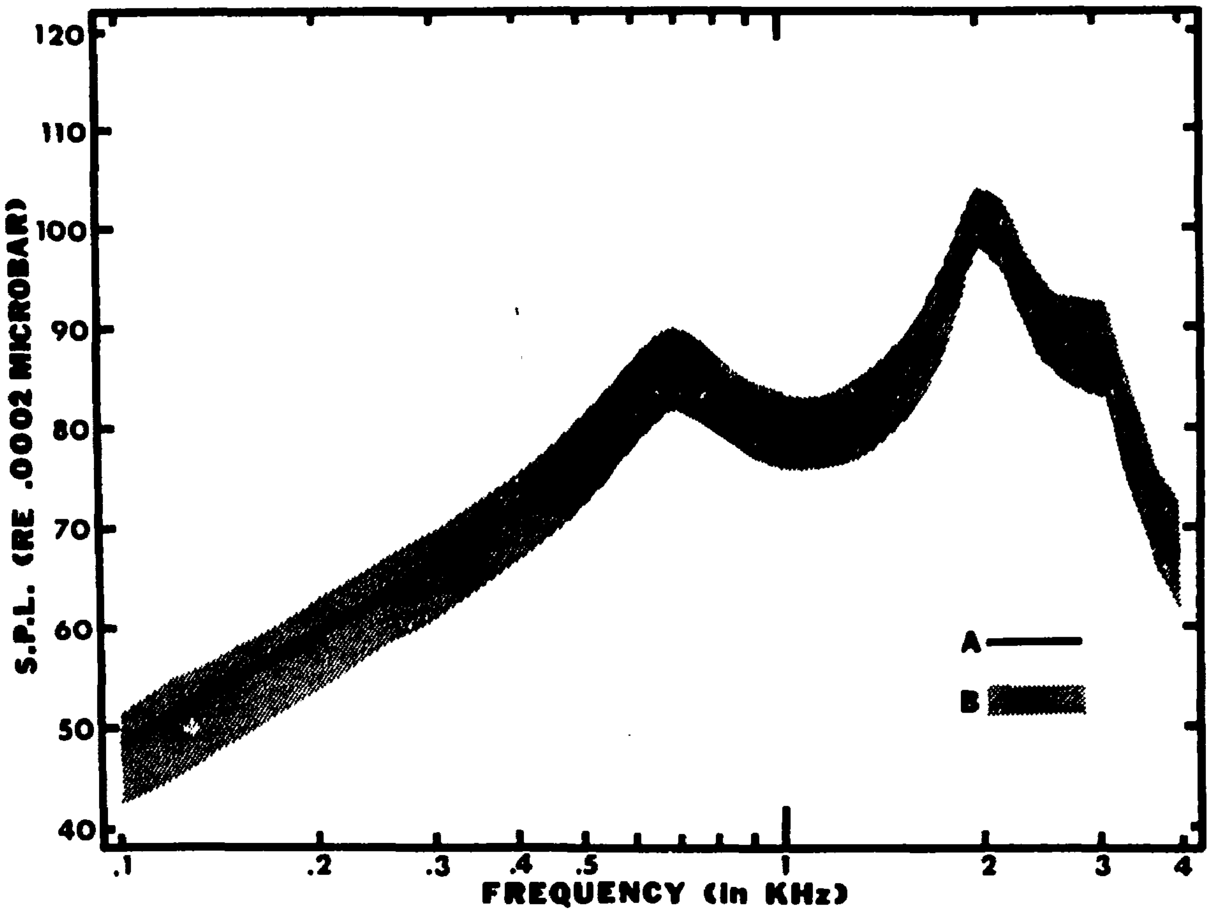


Figure 17 -- The Mean Frequency-Response Curve (Line A) and Range of Individual Levels (Area B) Obtained when Testing Earmold D in the Real Ear.

TABLE 6

INTRASUBJECT AND INTERSUBJECT STANDARD DEVIATIONS FROM EARMOLD D RESULTS (REAL EAR) IN dB

	Intrasubject								
	Subject								
Hz	1	2	3	4	5	6	7	8	Intersubject
100	0.34	0.46	0.63	0.28	0.29	0.84	0.58	0.29	2.98
110	0.25	0.42	0.44	0.38	0.25	0.85	0.55	0.47	3.09
120	0.46	0.42	0.36	0.45	0.24	0.92	0.61	0.44	3.07
130	0.51	0.33	0.62	0.44	0.22	0.86	0.59	0.50	3.04
140	0.46	0.38	0.70	0.37	0.31	0.79	0.54	0.44	3.02
150	0.40	0.39	0.48	0.44	0.39	0.83	0.62	0.38	3.02
165	0.39	0.47	0.56	0.50	0.26	0.85	0.65	0.32	3.02
180	0.44	0.63	0.60	0.44	0.39	0.87	0.56	0.30	3.02
195	0.40	0.65	0.54	0.40	0.40	0.79	0.65	0.39	3.02
210	0.44	0.67	0.49	0.36	0.38	0.86	0.59	0.42	3.01
230	0.36	0.70	0.41	0.43	0.44	0.84	0.44	0.35	2.99
250	0.39	0.59	0.42	0.43	0.39	0.71	0.52	0.35	2.99
275	0.38	0.59	0.55	0.45	0.42	0.76	0.44	0.35	2.98
300	0.30	0.53	0.61	0.40	0.39	0.76	0.43	0.15	3.02
330	0.34	0.62	0.37	0.39	0.41	0.83	0.38	0.13	3.04
360	0.33	0.59	0.39	0.53	0.38	0.79	0.44	0.19	3.04
390	0.41	0.57	0.51	0.48	0.47	0.59	0.33	0.17	2.99
420	0.37	0.65	0.56	0.53	0.34	0.78	0.36	0.17	2.97
460	0.25	0.67	0.60	0.48	0.46	0.80	0.29	0.15	3.02
500	0.39	0.67	0.65	0.51	0.29	0.81	0.21	0.31	3.09
550	0.39	0.69	0.72	0.43	0.34	0.84	0.39	0.25	3.04
600	0.31	0.74	0.73	0.34	0.42	0.83	0.44	0.33	3.10
650	0.40	0.58	0.62	0.33	0.41	0.76	0.32	0.60	3.04
700	0.34	0.50	0.63	0.22	0.46	0.69	0.36	0.55	2.92
775	0.53	0.29	0.70	0.37	0.42	0.44	0.67	0.66	2.80
850	0.69	0.33	0.61	0.29	0.34	0.45	0.73	0.66	2.70
925	0.72	0.43	0.84	0.29	0.34	0.47	0.73	0.54	2.67
1000	0.64	0.38	0.61	0.30	0.35	0.59	0.63	0.54	2.67
1100	0.52	0.33	0.54	0.68	0.39	1.17	0.57	0.61	2.73
1200	0.53	0.33	1.00	0.82	0.45	0.61	0.49	0.50	2.79
1300	0.47	0.33	0.76	0.49	0.45	0.59	0.39	0.48	2.87
1400	0.44	0.27	0.75	0.49	0.50	0.60	0.40	0.47	2.93
1550	0.37	0.27	0.79	0.48	0.74	0.73	0.47	0.59	3.09
1700	0.34	0.25	0.81	0.55	0.50	0.62	0.56	0.62	3.19
1850	0.44	0.52	0.79	0.50	0.53	0.56	0.74	0.99	3.07
2000	0.61	0.90	0.93	0.34	0.49	0.51	0.65	0.59	2.33
2200	0.86	0.50	0.71	0.13	0.64	0.76	0.51	0.30	2.41
2400	0.34	1.14	0.67	0.43	0.70	0.66	0.58	0.25	2.65
2600	0.58	1.37	0.61	0.26	0.47	0.61	0.43	0.54	2.48
2800	0.59	0.66	0.68	0.30	0.47	0.54	0.33	0.85	2.74
3100	0.56	1.12	0.62	0.39	0.68	0.59	0.57	0.98	3.02
3400	0.90	1.26	0.77	0.30	1.12	0.79	0.63	1.06	3.64
3700	0.53	1.02	0.86	0.52	1.36	1.03	0.65	1.21	3.68
4000	1.36	0.86	0.98	0.25	0.95	1.13	0.60	0.47	3.52

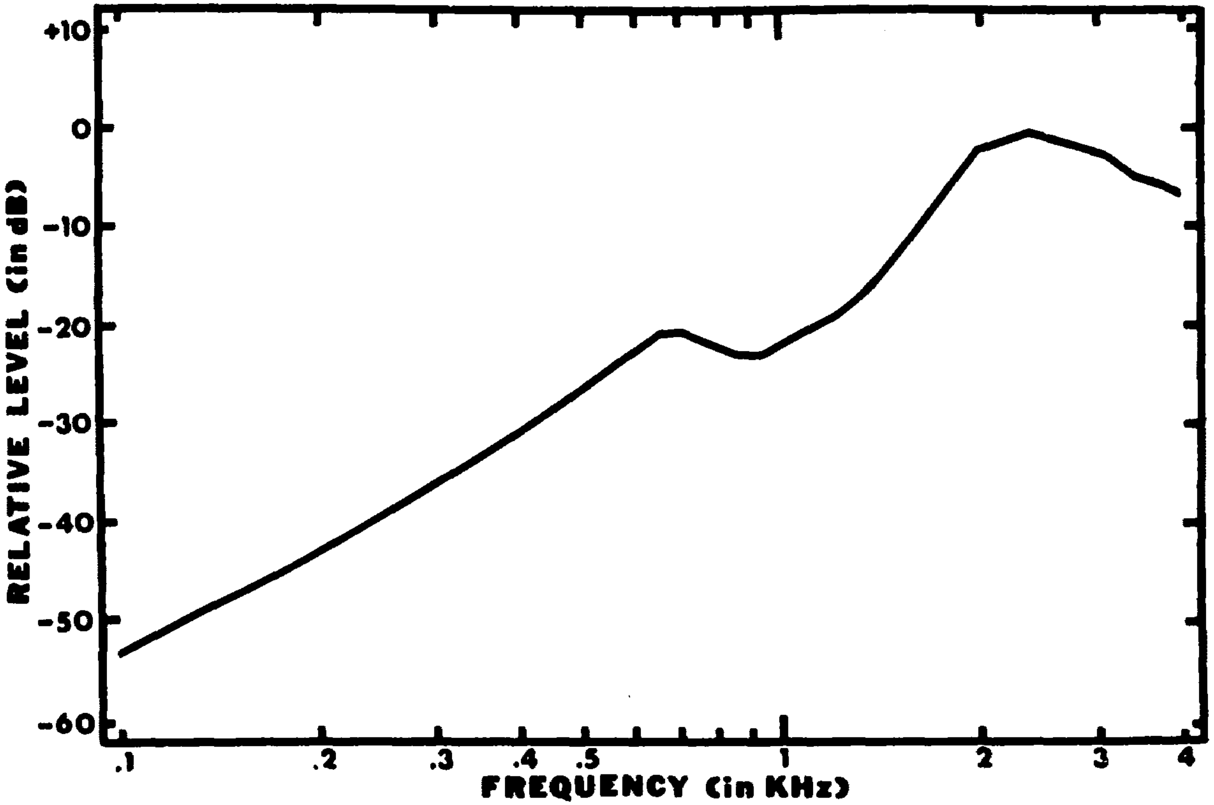


Figure 18 — The Mean Frequency-Response Curve Obtained with Earmold D in the Real Ear Plotted Relative to the Mean Frequency-Response Curve Obtained with Earmold A in the Real Ear.

3.52 dB respectively. These figures indicate that intrasubject variability for Earmold D was essentially the same as for the other earmolds. Intersubject variability, however, was greater.

Figure 18 shows the mean frequency-response curve obtained with earmold D in the real ear plotted relative to the mean frequency-response curve obtained with earmold A in the real ear. Note that this open earmold causes a marked reduction in the low-frequency response, and affects the middle frequencies to a lesser degree. It is apparent that all frequencies below about 2000 Hz are reduced by a progressively greater amount until at 100 Hz a relative reduction of 53.1 is seen. From 100 to about 500 Hz the relative-response curve of Figure 18 increases from the minus 53.1 relative level at a rate of about 12.5 dB per octave. From about 500 to 900 Hz a resonance curve is seen to peak at about 700 Hz. Above 900 Hz a resonance is seen to build to a peak at approximately 2400 Hz with a slow fall-off in the relative response evident above 2400 Hz.

Power-transmission ratios expressed in decibel losses for the sound-input channel as the main pipe and the vent of earmold D as the side branch were calculated according to side-branch theory. Due to the asymmetry of the venting condition formed by earmold D with each subject's ear, measurements of the "vent" portion of the earmolds required some degree of estimation. Due to the open nature of the earmold, it is assumed that the length of the vent should be taken as the distance from the medial aperture of the sound-input tube to the face of the earmold (a distance of five millimeters). Based upon measurements of each subject's ear canal and concha area, the diameter of the vent was given an average value of six millimeters. The dimensions for the vent were then used to represent the side-branch and the sound-input channel dimensions were used to represent the main branch in calculation of power-transmission ratio losses. Due to the irregular form of earmold D, because of anatomical differences between subjects, these arbitrary dimensions assumed may be somewhat in error. Calculations were performed from 100, 210, 500, 700, 1000, 2200 and 4000 Hz. The respective loss ratios were found by these calculations to be 48.7, 42.3, 34.7, 31.8, 28.7, 22.0 and 16.8 dB. The experimentally observed values, as plotted in Figure 20, for these same frequencies were 53.1, 41.6, 26.0, 20.4, 21.7, .8 and 6.3 respectively. The power-transmission ratios obviously fall short of explaining the relative response curve of earmold D above the lowest frequencies, and resonance effects must be taken into consideration.

The first resonance on the relative-response curve in Figure 18 peaks in the region of 700 Hz, and can be identified as the primary peak of the hearing-aid receiver system when coupled to the sound-input tubing and adapter. The prominence of this peak can be explained on the basis of the open earmold's producing a condition of decreased resistance which has allowed an increase in the resonance associated with the earphone diaphragm and the sound-input channel.

The second resonance on the relative response curve of Figure 18 peaks at about 2400 Hz, and may be due to the forming of a Helmholtz resonator by the ear canal and earmold D of each subject. As in the case of earmold C, for the purpose of calculation a three cubic centimeter volume was taken as being representative of the volume of air undergoing compression. The neck of the resonator was taken as being five millimeters long and six millimeters in diameter. These dimensions of the neck were taken to be approximately equal to the actual dimensions based upon measurements made in the region concerned. The calculated resonant frequency for a Helmholtz resonator having the dimensions just described is 2394.5 Hz, which falls very near the frequency region occupied by the second peak of the relative response curve. On the basis of this calculation it seems reasonable to conclude that the second reresonant peak in the relative curve is produced because earmold D's placement in the ear creates the acoustic conditions necessary to form a Helmholtz resonator.

However, an alternative explanation may exist as revealed by the results ploted in Figure 19. The figure suggests that the 2400 Hz resonance may be the secondary resonant peak of the sound-input system made more prominent by changes in levels at the surrounding frequencies. Or perhaps both the original and alternative explanations apply. Resolution of this point will require further study.

Concluding Statement

The measurements which were porformed with earmold A on the special 2-cc coupler have shown that a lengthening and narrowing of a sound-conveying channel will result in a downward shift in frequency for the primary and secondary resonances which are generally present in hearing-aid receiver response curves. This observation is in agreement with findings reported by other writers (15) (19) (71) (107).

A comparison of earmold A findings on the special 2-cc coupler with those found with earmold A in the real ear reveals that under these

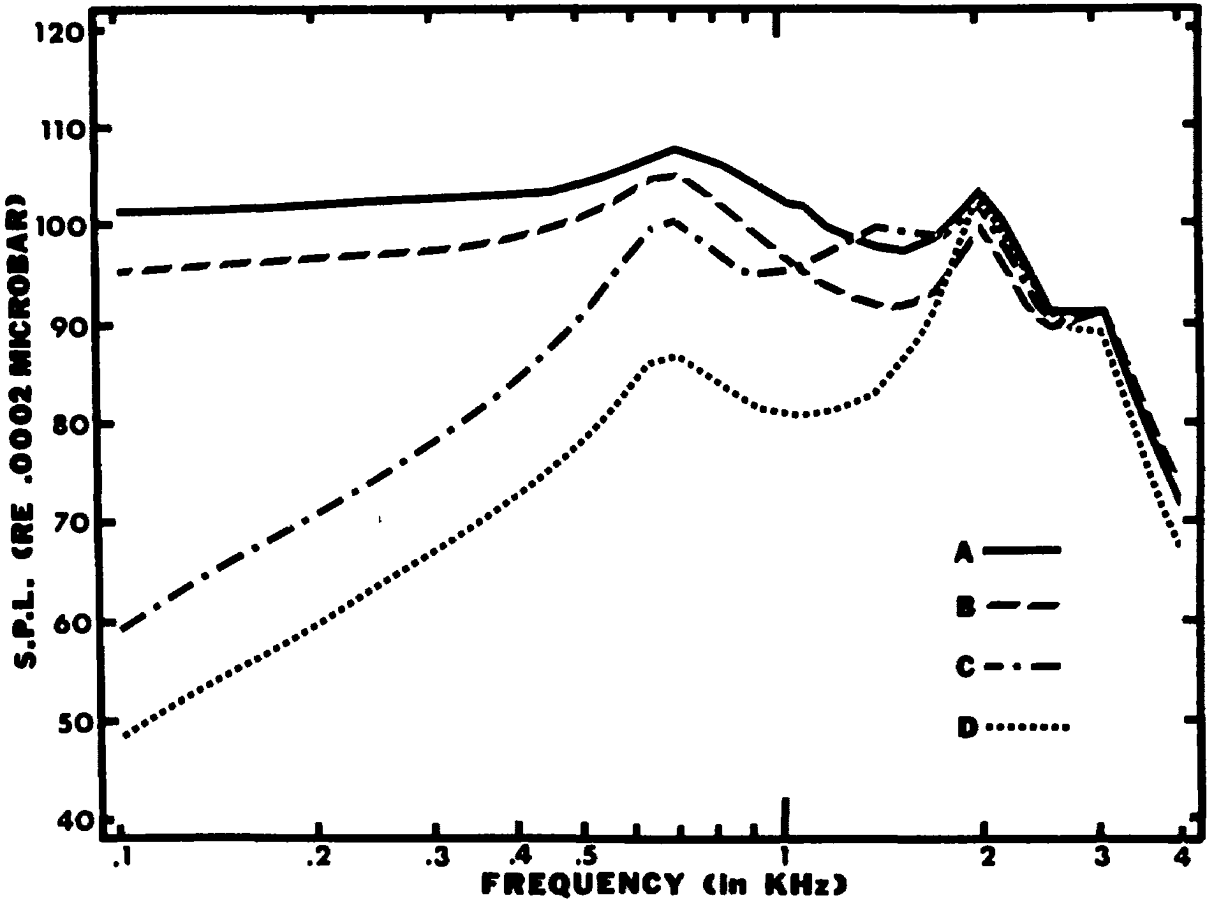


Figure 19 — The Mean Frequency-Response Curves Obtained in the Real Ears of the Subjects Using all Earmolds (A, B, C, D).

conditions the coupler response falls below the real-ear response. The difference was greater in the high frequencies (above about 800 Hz) than in the lower frequencies. Although these differences exist, it is felt that the agreement between the coupler response and that of the real ear is close enough for the coupler to be considered useful in obtaining a general idea of the receiver-response characteristic for standard unfented earmolds, providing one is aware of the differences which have been pointed out above and provided that the earmold is well sealed in the ear.

Figures 19 and 20 show the progressive effects of the earmold alterations used in this study. It can be seen that the more drastic alterations produced the most drastic change in the frequency-response curve of the total acoustic system. Note that when the shortened-canal alteration is compared with the response of earmold A there is a reduction in the level of all frequencies except 3700 and 4000 Hz, and a very slight resonance effect is present at aroung 700 Hz.

The next most drastic alteration, consisting of putting a vent (3 mm in length by 3 mm in diameter) in the shortened-canal form, is seen to cause a marked decrease in the low-frequency response, with resonances becoming more prominent due to decreased resistance (700 Hz) and due to formation of a Helmholtz resonator (1400 Hz).

The most drastic alteration, consisting of changing the earmold to an "open" type, is seen to cause the most significant reduction in low-frequency response with prominent resonances in evidence due to decreased resistance (700 Hz and possibly 2400 Hz) and/or due to formation of a Helmholtz resonator (possibly 2400 Hz).

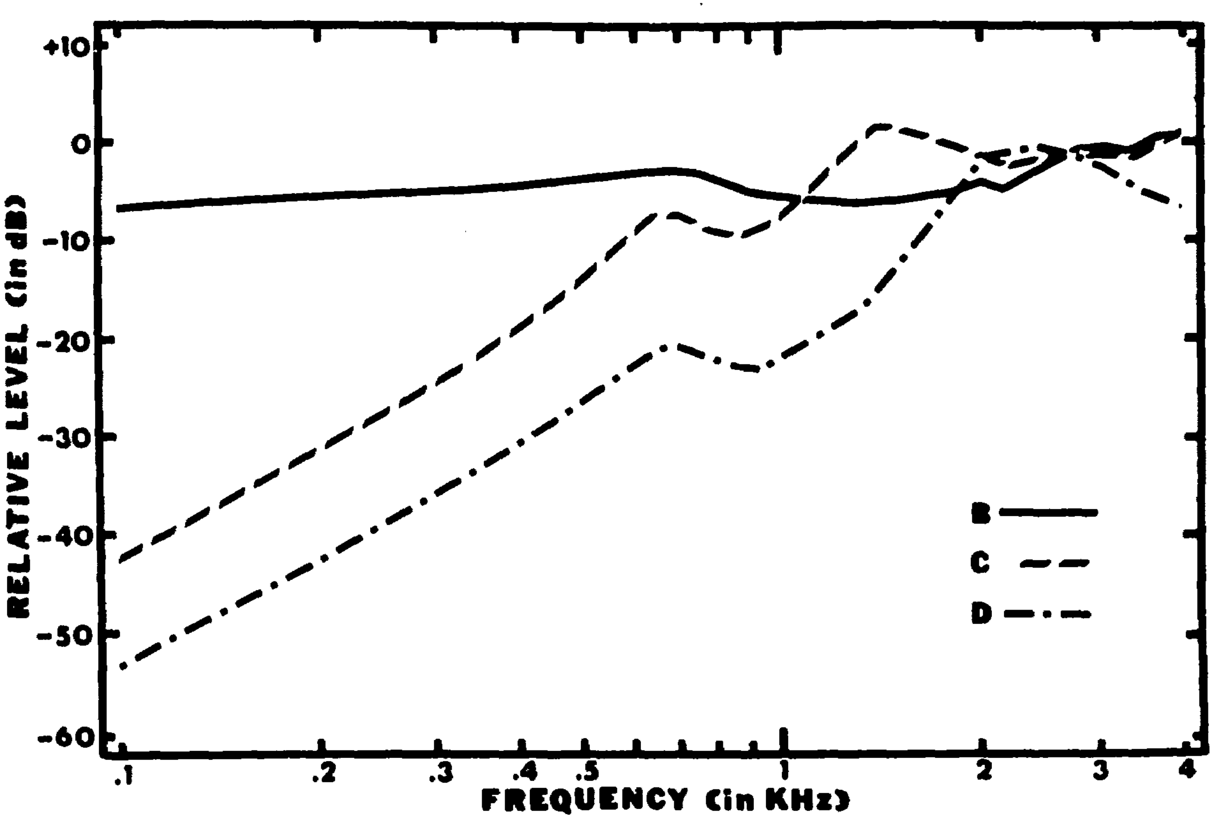


Figure 20 — The Mean Frequency-Response Curves Obtained with Earmolds B, C and D in the Real Ear Plotted Relative to the Mean Frequency-Response Curve of Earmold A in the Real Ear.

CHAPTER V

SUMMARY

The conventional earmold form has undergone several drastic modifications since it came into common use with hearing aids in the 1920's. These modifications have resulted in the appearance of a number of different earmold styles which may be worn with either body-type or ear-level hearing aids. These alterations in form have generally consisted of changes in the length of the earmold's canal portion, venting from the face of the earmold to its sound-input channel or to the ear-canal space between the earmold tip and the eardrum, or giving the earmold a form which is nonoccluding relative to the ear canal of the wearer. Although some of these modified forms are now being used as extensively as the conventional form, little has been done relative to defining what effects their altered forms produce on SPL's within the ear canals of the users.

This study investigated sound pressure level (SPL) changes occurring in the human auditory meatus, as determined with a probe-tube microphone system, when an earmold having a standard form (earmold A) was modified to a form having a shortened, hollowed canal (earmold B), a form having a shortened, hollowed, vented canal (earmold C), and a form which was nonoccluding relative to the ear canal of the wearer (earmold D). Although the principal purpose of this study concerns SPL's occurring in real ears as a result of earmold alteration, preliminary procedures were accomplished which measured SPL's on couplers. These concerned measurement of SPL's with a hearing-aid receiver placed directly upon a standard 2-cc coupler, and measurement of SPL's in a special 2-cc coupler with earmold A interposed between the receiver and the 2-cc cavity of the special coupler.

Coupler Findings

Comparison of the frequency-response curve found using earmold A (55 mm long X 1.8 mm functional diameter sound-input channel) on the special 2-cc coupler with the response curve obtained with the receiver directly coupled to the bore (18 mm long X 3 mm diameter sound-input channel) of a standard 2-cc coupler reveals that the longer and narrower sound-input channel of earmold A caused a shift of the primary peak from 1400 Hz to 700 Hz, a shift of the secondary peak from 3100 Hz to about 2000 Hz, and the appearance of a half-wave length tube resonance at 3100 Hz which was not present in the receiver-standard 2-cc coupler-response curve.

Contrasting the frequency-response curve obtained using earmold A in the real ear with the frequency-response curve obtained using earmold A on the special 2-cc coupler, it is found that the coupler response fell below that of the real ear at all frequencies tested. The difference between the two curves is slight in the low frequencies, with the coupler response essentially parallel to that of the real-ear response; however, in the higher frequencies (above approximately 800 Hz) the coupler tends to fall below the response of the real ear to a progressively greater degree as frequency is increased.

Real Ear Findings

Each measurement made in the real ear was obtained while the earmold was sealed in the ear with vaseline.

With the frequency-response curve of earmold A in the real ear as a basis for comparison, earmold B's response curve reveals that an increase in the volume between the earmold tip and the eardrum resulted in a reduction of the low and middle frequencies, with relatively little effect in the higher frequencies.

Comparison of the findings using earmold C with those using earmold A shows that a vent (3mm long X 3 mm diameter) drilled in the form represented by earmold B caused a marked reduction in low-frequency response, with the lowest frequencies being affected to the greatest degree. In this earmold form it is also seen that resonances are made more prominent due to the decreased resistance in the acoustical system produced by the vent. Also, the vent provides the inertance to form a Helmholtz resonator with the ear canal.

Contrasting earmold D findings with those of earmold A reveals that its nonoccluding feature reacts acoustically as a large vent, causing a relatively greater reduction of the low frequencies than did earmold C. The larger vent of earmold D, like earmold C, also causes a reduction in the resistance of the acoustical system, thereby enhancing resonances within the system, and possibly creating a Helmholtz resonator similar to that seen with earmold C.

Acoustical explanations of the findings are presented relative to the frequency-response curves of each measurement condition. Results of calculations of sound-power-transmission ratios expressed in decibel losses, Helmholtz resonators, and tube-length resonators are presented in order to explain the principal features of the response curves obtained under the various test conditions.

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