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REAL EAR VERSUS COUPLER FREQUENCY RESPONSE MEASURES OF HEARING-AID-RECEIVER-EARMOLD SYSTEMS

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REAL EAR VERSUS COUPLER FREQUENCY RESPONSE MEASURES OF HEARING-AID-RECEIVER-EARMOLD SYSTEMS

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CHAPTER I

INTRODUCTION

With the development of electronic hearing aids it became desirable to devise methods for the measurement of their electroacoustic characteristics. Since it was not practical to measure hearing-aid performance routinely with the hearing-aid-receiver system fixed in a human ear, electro-mechanical devices (artificial ears) were devised which were intended to simulate the acoustic properties of the human ear. The most commonly used over the years has been the 2-cc coupler specified by the then American Standards Association and called the Type 2 coupler (ASA-224.9-1949) (2).

Early investigations of the properties of this 2-cc coupler remain obscure. In 1942, Romanow (23) presented the earliest available reference on the 2-cc coupler in which he described the same basic physical characteristics that are specified for this device today (ASA-224.9-1949).

Nichols *et al.* (5) studied the equivalent volume remaining in the ear canal after placing an earmold in the canal. This volume, on the basis of a few tested ears, was found to be approximately 2 cc, confirming the specifications given three years earlier by Romanow.

According to the literature (2, 7, 8, 9. 12, 13, 19) a bore of standard length and diameter is considered to be an integral part of the 2-cc coupler. Romanow (23) gives unreferenced specifications for the earmold bore simulator (metal slug) section of the 2-cc artificial ear. The bore length is .710 inch (18 mm) and the diameter is .120 inch (3 mm). No reference for the source of these dimensions could be found.

The dimensions of the bore in the metal slug of the 2-cc coupler have received some investigation. In 1956, Ewertsen, Ipsen and Nielsen (8) studied the relationship between the frequency response obtained with the metal slug of the 2-cc coupler and with an acrylic earmold with the same bore dimensions (length, 18 mm and diameter, 3 mm) mounted on a 2-cc cavity. The authors reported close agreement between the frequency response measures. They reported, however, that an acrylic earmold bore of 22 mm length and 2.4 mm diameter best approximated the frequency response of the bore in the metal slug of the 2-cc coupler. The Ewertsen, Ipsen and Nielsen (8) results show the acrylic earmold also produced increases in the frequency of peak output in the 1200 Hz region by about 20 to 50 Hz when compared with the frequency response from the standard coupler.

There are relatively few investigations comparing real-ear measures of frequency response with those obtained from a 2-cc coupler. Nichols *et al*. (5) evaluated six different receivers each attached to a 2-cc coupler and to a molded earpiece placed in a human ear. The frequency response measures taken from the real ear were within approximately ± 5 dB from 200 to 1000 Hz of those measures taken from the 2-cc coupler. From 1000 to 5000 Hz, the real-ear measures differed by as much as ± 10 dB with the largest discrepancy above 2000 Hz. No specifications were given for the earmolds used in the study and test-retest variability was not evaluated.

Wiener and Filler (28) measured the frequency response of a hearing-aid receiver using a 2-cc coupler and the real ear. Frequency response with the two systems was essentially similar from 500 to 1000 Hz and from 2000 to 4000 Hz. Between 200 and 500 Hz the real-ear measures were approximately 10 dB lower than those taken from the coupler. According to the authors, this was caused by leakage around the earmold. No explanation was given for the real-ear measures being approximately 10 dB lower between 1000 and 2000 Hz.

In recent years, Lybarger (15, 16, 17) has called attention to the importance of earmold modifications and their effects on the frequency response of hearing-aid-receiver systems. He points out that a small vent in the earmold filters the frequencies below 1000 Hz. Increasing the diameter of the vent serves to reduce the low frequencies even more; however, the relationship between vent size and the magnitude of the reduction of low frequencies, particularly on the real ear, has not been thoroughly studied.

It was the purpose of this study to investigate the effect of certain earmold vents on the frequency response of a hearing-aid-receiver system as measured in the real ear and in a 2-cc coupler. Also studied was the relationship between real ear and artificial ear measures of frequency response and the effect of replacing the metal slug with an earmold having the same bore dimensions.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

The development of the techniques for the measurement of electroacoustic characteristics of hearing-aid-receiver systems has taken place gradually over the last thirty years. As the use of hearing aids increased, so did the need for a standard of measuring the acoustic output of these amplifying instruments. Artificial ears were designed to simulate the acoustic properties of the real ear in a stable and reproducible form. The most commonly used is the ASA Type Two 2-cc coupler (2). Incorporated into it is a device contrived to simulate the bore of an earmold.

The accuracy with which the bore of the metal slug in the Type Two 2-cc coupler simulates the acoustic properties of an acrylic earmold with the same dimensions has not been thoroughly investigated. Also, the accuracy with which the 2-cc coupler simulates the acoustic properties of the human ear has not been firmly established. Recent innovations in earmold design raise a question as to the effects these earmold modifications have on measures taken from the 2-cc coupler and the real ear. One type of earmold modification is the vent. It has been noted (16, 24) that vented earmolds produce the effect of reducing the output below 1000 Hz. However, the extent to which vents of different sizes produce a low frequency reduction has not been adequately studied.

This investigation is concerned with the relationship between 2-cc coupler and the real-ear measures of frequency response and also with the effects of certain earmold vents on these measures.

American Standards

Prior to a discussion of studies of couplers used for the measurement of the electroacoustic characteristics of hearing aids, a brief review of the origin of this aspect of our present day Standards seems desirable. Kranz (12) reports on a tentative code for measuring hearing-aid performance which was drawn up by a technical committee of the American Hearing Aid Association and published in 1945. In this report, the following basic specifications were set forth for the measurement of frequency response.

> Adjust the sound field to 60 dB at the point where the hearing aid and body simulating baffle (if used) is to be placed. Input sound pressure should not exceed ± 3 dB at 60 dB. The hearing aid volume control is adjusted to a pressure of approximately 100 dB of the artificial ear at the frequency of greatest response of the hearing aid. Receiver output will be measured between 200 and 5000 cycles.

The present method does not differ greatly from the one quoted above. The United States of America Standards Institute (U.S.A.S.I., S3.3-1960) (3) recommends the following format for the measurement of frequency response.

> Adjust the free field sound pressure level to 60 dB ± 1 dB at 1000 Hz. Adjust the gain control to give a sound pressure level in the coupler of 100 dB ± 2 dB at 1000 Hz. Vary the sound source frequency range from 200 to 5000 Hz maintaining the S.P.L. constant at 60 dB. Recordings of the frequency

response can be continuous or discrete.

These procedures were designed to allow a standardized approach for the measurement of frequency response in hearing aids. The format specifies that the hearing-aid receiver be attached to a 2-cc coupler which is designed to simulate the compliance of the space medial to the earmold tip when placed in the real ear.

Studies of 2-cc Couplers

The origin of the standard 2-cc coupler remains obscure. Lybarger (15) believes that the 2-cc coupler had its origin at the Bell Telephone Laboratories. The earliest available reference to such a coupling device is that of Romanow in 1942 (23).

Romanow (23) described the 2-cc coupling device as being representative of the average volume left in the ear after the insertion of the earpiece. Romanow (23) also described the bore of the small metal cylinder situated on top of the 2-cc volume as being representative of an earpiece with the dimensions of .710 inch length and .120 inch diameter.

Nichols (5) shows how the frequency response of a transducer mounted on a 2-cc coupler differs from that obtained with the unit attached to an earmold in the human ear. (N = three subjects.) At 250 Hz, the sound pressure level (S.P.L.) in the human ear canal was approximately 2 dB greater than in the coupler. At 500 Hz it was approximately 4 dB greater and it was 1 to 2 dB greater at 1000 Hz. At 2000 Hz the real-ear measures were approximately 5 to 10 dB greater than the coupler S.P.L. and the two measures attenuated rapidly beyond 4000 Hz, making comparisons difficult.

One of the early studies dealing with an attempt to standardize hearing-aid measures was that of Sabine (24). It was his contention that the 2-cc coupler would yield reliable measures for comparison of different hearing-aid units. With an earmold embedded in soft wax and fixed to a 2-cc cavity, Sabine measured the frequency response of various hearing-aid-receiver systems. The results indicated that the coupler was adequate for measuring the frequency response of the different hearing-aid units. Sabine did not report the dimensions of the earmold used.

In 1945 Kranz (12) reported on a tentative code for the performance measurement of hearing aids. A committee of the American Hearing Aid Association suggested that the tube simulating the receiver attachment to an earpiece should be .710 inch or 18 mm in length and have a diameter of .120 inch or 3 mm. Kranz (12) also reported that the space between the end of the receiver and the initiation of the .710 inch tube should not exceed .010 inch. No reference is made as to the basis for selecting these dimensions.

After 1945 some literature concerning the acoustic characteristics of the artificial ear began to appear. Nichols (21) questioned the "reliability" of the 2-cc coupling device by stating that differences between the real ear and the coupler would appear because of the soft walls found in the real ear. These soft walls are more yielding than the hard walls of the artificial ear and, therefore, provide more damping of peaks than the coupler.

Morton and Jones (20) investigated real ear versus artificial ear impedance and reported that a better simulation of the human ear impedance by a coupler is possible. On the basis of 141 earmold samples, Morton and Jones constructed a coupler with the following earmold simulator dimensions: bore length, 1.85 cm and diameter, .249 cm with a recess volume below the snap ring of .092 cc and a cavity of .86 cc. Morton (19) compared the British 1.5-cc coupler and the American 2-cc coupler with the one previously mentioned and found that the acoustic impedance of the three differed by as much as 300 acoustical ohms at the frequencies below 400 Hz. The coupler designed by the authors most closely approximated the frequency responses obtained within the human ear canal.

Lybarger (15) reports that the traditional 2-cc coupler does not differ from the real ear by more than 5 dB below 1000 Hz or more than 8 dB above 1000 Hz. He does not mention how these values were obtained.

Van Eysbergen and Groen (26) compared the frequency response of a transducer on a 2-ml coupler and on human ears. The results showed a 20-dB drop in the coupler curve beyond 3000 Hz as compared with the response obtained on the human ear. They did not report that the two ear inserts used in the study (Mold 1, length 22.5 mm and diameter 3 mm. Mold 2, length 17.4 mm and diameter.5.2 mm) had the same bore dimensions as those used in the 2-ml coupler earmold simulator and no mention was made of the recess space beneath the insert snap ring.

Investigations of real-ear and 2-cc coupler measures of frequency response have demonstrated a certain degree of similarity between the two systems. Questions remain, however, as to the adequacy with which the coupler represents the acoustic properties of the real ear when using an earmold with a bore of the same dimensions as the bore of the metal slug in the coupler; i.e., small recess volume under the earmold snap ring and the same bore length and diameter in the earmold as that in the metal slug of the 2-cc coupler.

Studies of Earmolds

Individually molded earpieces have been used for approximately forty years (27). They were initially fabricated from semi-hard rubber, but with the advent of plastic materials they have been made of acrylics and other materials. The effect that acrylic earmolds have on the acoustic characteristics of hearing-aid-receiver systems has not been fully demonstrated. From a survey of the available literature, it is apparent that the earmolds, in effect, are not often considered to be an integral part of the hearing-aid-receiver system.

Various investigators have mentioned the importance of earmolds in relation to hearing-aid systems. Grossman and Molloy (10) report that earmolds with large diameter bores affect the frequency response of hearing-aid receivers. Schier (1945) (25) suggests that an evaluation of hearing-aid-receiver systems must include the individual earpiece and that the total system must be evaluated when connected to the human ear. His studies of various earmold filters (vents) showed that such vents act as a high-pass filter. On the basis of his investigations, Schier (25) advocated using a bore length as long as the patient could tolerate. Menzel (18) states that the least understood criterion of good earmold fitting is the acoustic coupling it provides between the receiver and the eardrum. He feels that a deliberate impedence mismatch between the receiver and the earmold could be a valuable tool for modifying hearing-aid response.

Not all of the literature reviewed suggests that earmold modifications significantly change the hearing-aid-receiver frequency response characteristics. Revoile _et al_. (_22_) tested discrimination with three different ear-insert types, including a vented mold and found no apparent differences in discrimination scores obtained with the different earmolds when tested on conductive and sensorineural loss subjects.

The most extensive treatment of earmold acoustics is presented by Lybarger (_16_, _17_). Lybarger (_16_, _17_) states that a receiver diaphragm with a high stiffness factor can attenuate frequencies below 500 Hz as well as increase the primary peak region, usually found between 800 and 2000 Hz. He states that leaks around the periphery of the mold or small acoustic vents have a large "resistance component" and these leaks or vents will reduce the energy in the low frequencies. Another factor affecting frequency response according to Lybarger is the size of the cavity between the earmold tip and the drum membrane (_16_). An increased cavity size increases the attenuation of low frequency sounds. In a more recent article, Lybarger (_16_) presents data on the earmold's effect on high frequencies. Keeping bore length constant while increasing the bore diameter can result in an increase in intensity between 800 and 2000 Hz. He further reports that an increase in bore length while holding bore diameter constant can result in an attenuation of the frequencies between 800 and 2000 Hz.

Lybarger (_16_) goes on to state that large vents produce a "free vibrating slug or mass of air" in the vent bore, thereby reducing the output at extreme low frequencies and increasing the output at the frequencies around 400 Hz. Langford (14) reports that larger (in diameter) vent holes decrease the amount of energy reaching the drum membrane, *e.g.*, a vent diameter increase of .067 inch will decrease the energy at 1000 Hz approximately 16 dB. Langford also states that two vent holes equal in size are acoustically equal to one hole with a diameter twice that of the smaller holes.

From a physical point of view, an earmold vent may be considered as a "side branch." The presence of a side branch in a rigid pipe causes the acoustic impedance at the junction of the branch and the main pipe to differ from the characteristic value found with the pipe alone (11). In the case of side branch, a portion of the incident energy is transmitted into and dissipated in the branch and a portion is reflected back toward the source (11). The energy in the pipe beyond the side branch is reduced. A single side branch converts the pipe into a high pass filter. As the radius of the side branch is increased relative to the radius of the main pipe, attenuation of low frequencies is increased. Several side branches very near to one another may be considered as the sum of the diameters of the branches. The low frequency attenuation produced by a number of side branches (separated by not more than a small fraction of a wavelength) can be much greater than that of a single side branch (11).

Ewertsen, Ipsen and Nielsen (8) investigated real-ear measures versus coupler measures as a function of varying earmold bore lengths and diameters. For their real-ear measures of frequency response, Ewertsen *et al*. used a 120 mm probe tube with an inside diameter of .65 mm. The sound source was a hearing-aid receiver driven by a beat frequency oscillator (B.F.O.). Their results indicate that a mold with a bore diameter of 2.4 mm and a length of 22 mm agreed well with the tranditional 2-cc coupler measures. The coupler measures were approximately 5 dB lower than the real-ear measures below 1000 Hz and approximately 10 dB lower above 2000 Hz. There seemed to be an upward frequency shift of approximately 20 to 50 Hz of the peaks in the area of 1200 Hz when using the acrylic earmold in the real ear. The authors conclude that the traditional 2-cc coupler with its metal earmold simulator is an adequate representation of what takes place in the human ear. The authors did not consider the recess space between the snap ring and bore initiation. This factor is of importance according to other investigators.

Perhaps the most detailed of the few studies of earmolds and their effects on hearing-aid-receiver systems (7, 8, 16, 17) is that of Dalsgaard, Johansen and Chisnall (7). They report that the frequency response of a hearing-aid receiver may be subject to great variations when coupled with earmolds of differing specifications. Dalsgaard *et al*. found that changes in coupler volume result only in an amplitude change which is equal across frequency; *e.g.*, increasing the volume from 2 to 4 cc decreases the amplitude across frequency by approximately 15 dB. Dalsgaard *et al*. (7) report that as the diameter of the earmold bore is increased the frequency response of the receiver's primary peak shifts upward by as much as 500 Hz (increase in diameter from 1.6 to 6 mm). They also found that by assembling and disassembling the earmold from the special coupler ten times the repeated measures could be maintained within a range of ± 1 dB from 200 to 2500 Hz and ± 2 dB from 3150 to 5000 Hz.

Dalsgaard, et al. (7) also studied the effects of the recess volume below the snap ring and the effects of earmold fit. They found that a recess volume of more than approximately 1 mm had some effect on the frequency response. The larger the recess volume the greater will be the attenuation of the frequencies above 3000 Hz. A poor seal of the earmold, when situated in the ear, resulted in a 2- to 4-dB variability in frequency response between 300 and 7000 Hz. Leaks were apparently eliminated and this difference was not found when the earmold was coated with Vaseline.

In summary, the authors of studies on the effects of earmolds on the frequency response of hearing-aid-receiver systems conclude that physical variations in the mold affect the frequency response of the system. Some conclude that the 2-cc coupler simulates the real ear reasonably well while others conclude that significant differences exist between real-ear and artificial-ear measures.

The effect of bore dimensions has been relatively thoroughly investigated. However, beyond the generalization that vents attenuate low frequencies these common earmold modifications have been little studied, particularly on real ears. It is the purpose of this study to provide further evidence concerning the relationship between the frequency response obtained with vented and unvented earmolds both on real ears and on couplers.

CHAPTER III

INSTRUMENTATION AND PROCEDURES

Introduction

This investigation was designed to study the effects of certain earmold modifications upon the frequency response of a hearing-aid-receiver-earmold system, as well as compare real-ear and artificial-ear (coupler) measures. Hearing-aid-receiver systems are normally evaluated using a metal coupler having a 2 cc volume. The standard coupler includes a metal slug between the hearing-aid receiver and the 2-cc cavity. The metal slug has a hole bored through it which is designed to approximate an earmold bore with a length of 18 mm and a diameter of 3 mm (U.S.A.S.I. S3.3-1960) (3). A drawing of this coupler is shown in Figure 1.

A search of the literature revealed only limited information relative to the accuracy with which the bore of the metal slug simulates the influence of the bore of a standard acrylic earmold on a hearing-aid-receiver system. Also limited are data on the extent to which measures on the standard coupler differ from those obtained with the receiver-earmold system fixed in the human ear and data relative to the effects of vented earmolds on the frequency response of a hearing-aid receiver as measured in a 2-cc coupler and in the real ear.

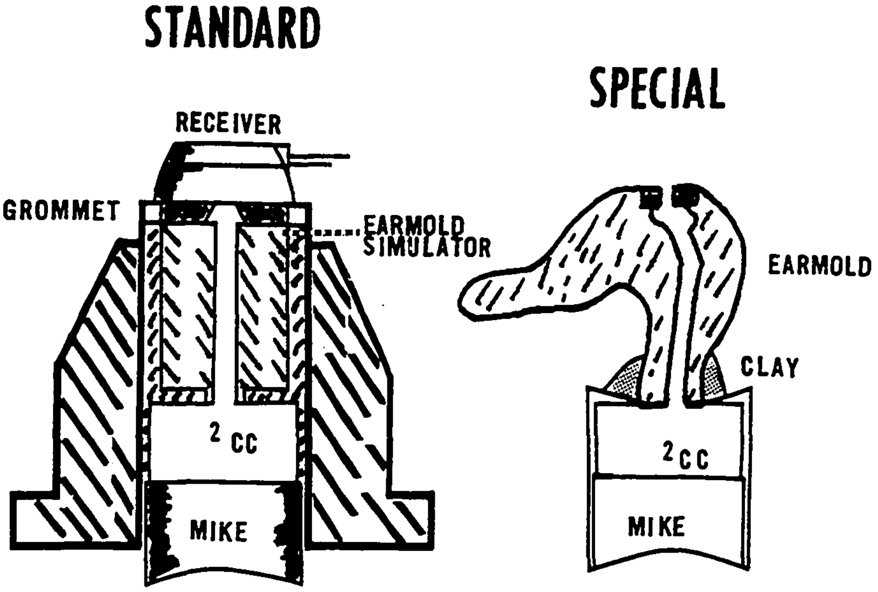

Figure 1.—Cross-sectional diagram of a standard 2-cc coupler. (Bruel and Kjaer type 4132) and of the "special" 2-cc coupler. (Not drawn to scale.)

This investigation was divided into four major phases. The measure obtained in each phase of the study was the acoustic output observed at discrete frequencies under the conditions assigned to the phase in question.

Phase I: This phase consisted of four repeated sets of measures of output at discrete frequencies (frequency response) taken with the hearing-aid receiver mounted on a standard coupler and on a special coupler system. (The special coupler is designed to accommodate an earmold and will be discussed in a later section.) The hearing-aid-receiver-special-coupler system consisted of the receiver connected to the metal screw cap, rubber grommet and metal slug which had been removed from the standard coupler and fixed with clay to the special coupler.

Phase II: This phase consisted of four repeated sets of measures of output at discrete frequencies taken with sixteen different earmolds (four molds for each of four subjects) inserted between the receiver and special coupler as shown in Figure 1. One mold of each subject was unmodified while three molds per subject were "vented" with holes of three different sizes. Each mold was fixed to the special coupler with clay.

Phase III: This phase consisted of four repeated sets of measures of output at discrete frequencies taken with the same sixteen molds of Phase II. In this phase, each of the four earmolds of each of the four subjects was drilled to accommodate a small probe tube approximately paralleling the standard bore in the mold. After placing the probe tube in the mold, each mold was, in turn, connected to the hearing-aid receiver and attached to the special coupler with clay. The purpose of this phase was twofold: first, to determine the effects of the presence of the probe tube on the sound pressure levels in the coupler and second, to calibrate the probe-tube device for Phase IV.

Phase IV: This phase consisted of four repeated sets of measures of gain at discrete frequencies taken from the hearing-aid-receiver and earmold fixed in one ear of the subject. Each of the four earmolds of each of the four subjects was attached to the hearing-aid receiver and placed in the ear of the subject to whom the mold belonged. Measures of gain were taken from a probe-tube assembly inserted in the mold.

A detailed description of the experimental apparatus, subjects and procedures will be presented in the following sections.

Apparatus

The following discussion will deal with the earmolds, hearing-aid-receiver system, couplers and test equipment used in this investigation.

Earmolds

The material for taking the earmold impressions is distributed in individual kits by the All American Mold Laboratories Incorporated, Oklahoma City, Oklahoma (1). The procedure for making the impression is fundamentally that outlined by Watson and Tolan (27). It consists of inspecting the ear canal for debris and then preparing the material for insertion into the subject's external auditory canal. The impressions taken by the experimenter were used by the earmold laboratory to make four identical "Lucite" earmolds for each subject. The four molds were made to the following specifications. They were constructed to coincide with the specifications of the United States of America Standards Institute standard bore size for 2-cc couplers (3). Each earmold had a bore length of 18 mm and a diameter of 3 mm as measured from the medial surface of the earmold snap ring, through the bore, to the tip of the earmold canal (Figure 2). Each mold was drilled and the snap ring inserted so that there was about a 2 mm^3 space between it and the initiation of the bore. Dalsgaard et al. (7) report that the recess between the snap ring and the bore initiation has an effect on the frequencies above 3000 Hz, e.g., a volume increase of 2.5 mm^3 will reduce 3000 Hz by as much as 10 dB.

One earmold remained unvented. The second earmold was constructed with the same bore diameter and length as the first, but in this mold, a small vent, 0.75 mm in diameter (16), was drilled from the point on the earmold approximating the anti-tragus to the area immediately medial to the snap ring (Figure 2). The length of all vents was arbitrarily kept constant at approximately 11 mm (± 1 mm). This length was chosen because it best approximates the average distance from the snap ring edge to the anti-tragus. The third earmold was fabricated with the same specifications as the first except that in this piece the vent was drilled with a diameter of 1.5 mm (16), or one-half the diameter of the first vent. The fourth earmold was constructed to conform to the specifications of the first except that the vent was drilled with a diameter of 3 mm (16), or the same diameter as the bore of all of the molds.

There is a dearth of information relative to the effect of

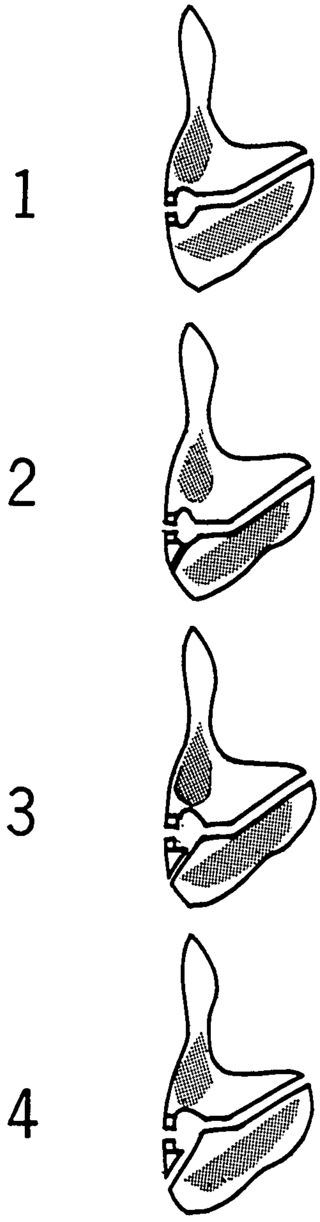

Figure 2.--Earmold specifications. (Not drawn to scale.)

earmold vents of specific dimensions on frequency response. Of the literature reviewed, only Lybarger (16) reports on selected vent diameters and their effect on the low frequencies. Due to the lack of such information, the selection of vent diameters for this investigation was arbitrary. The third vent diameter (3 mm) was selected because it was as large as it could be made without exceeding the standard bore diameter of 3 mm. The second (1.5 mm) and first (0.75 mm) vent diameters were arbitrarily selected to demonstrate the effects of progressively increased vent diameters on the characteristics of the hearing-aid-receiver-earmold system.

Hearing Aid

One hearing aid was used which appeared representative of moderate gain instruments. The instrument was equipped with one receiver which in conjunction with the hearing aid gave a relatively flat frequency response.

The Zenith Super Extended Range was used for the purpose of this experiment. Its H.A.I.C. performance characteristics, according to the manufacturer (30), are: Gain, 61 dB; Maximum Power Output, 133 dB; frequency range, from 252 to 2933 Hz. This instrument was employed at external switch position "C" which causes the instrument to yield its flattest frequency response.

The receiver employed with the Zenith Super Extended Range was the "Y-5R." The frequency response characteristics of the hearing-aid-receiver system will be reported in the next chapter.

Special Coupler

Figure 1 shows a cross-sectional diagram of the standard and the special couplers. The special coupler was designed to eliminate the screw cap, rubber grommet and metal slug, but to maintain the 2-cc volume. Its upper surface was tapered in a slightly concave fashion to accommodate the canal tip of an earmold. The special coupler was manufactured by the Central Research Laboratory, Norman, Oklahoma (6).

Hearing-Aid Test Equipment

The measurement of output of the aforementioned hearing-aid-receiver system was accomplished with a hearing-aid test box (Bruel and Kjaer type 4212). This instrument is equipped with a standard 2-cc coupler, an associated condenser microphone (Bruel and Kjaer type 4132) and a cathode follower (Bruel and Kjaer type 2613). The microphone assembly is powered by a microphone amplifier (Bruel and Kjaer type 2604). Sound pressure levels (S.P.L.) were taken directly from the microphone amplifier.

Within the hearing-aid test box is another condenser microphone (Bruel and Kjaer 4132) and cathode follower (Bruel and Kjaer 2613). This microphone was placed at a right angle to the sound source and adjacent to the hearing aid. When this microphone is coupled to a microphone amplifier (Bruel and Kjaer type 1604) the S.P.L. in the test box can be read.

The measuring arrangement for the recording of the frequency response of the hearing-aid-receiver system is shown in Figure 3. The loudspeaker in the hearing-aid test box was driven by a beat-frequency oscillator (B.F.O.) (Bruel and Kjaer type 1013). The frequency of the

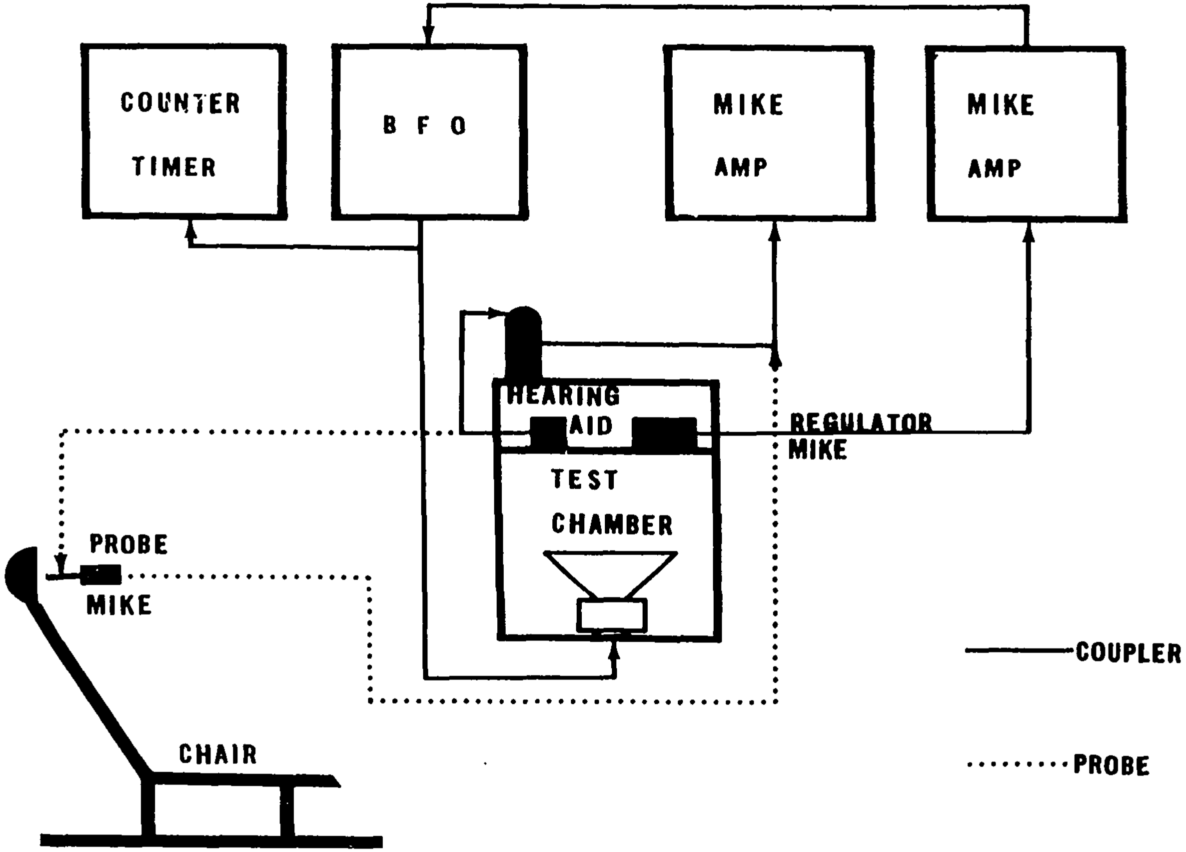

Figure 3.--Block diagram of the experimental apparatus.

B.F.O. was checked with a counter-timer (Transistor Specialties Inc. type 861). The output of the B.F.O. was regulated by means of the amplified output voltage from the regulating microphone located on the cloth mesh in the test chamber. By varying the gain of the regulator microphone amplifier and adjusting the input potentiometer for the compressor circuit in the B.F.O. the test box sound level could be adjusted and held constant at any value between 50- and 90-dB S.P.L. with a tolerance of approximately ± 1.0 dB over the frequency range of interest. This tolerance was arrived at in a preliminary study of the variability of repeated measures of frequency response taken from within the test box itself. The receiver of the hearing aid was connected to the coupler. The output of the microphone within the coupler was connected to a microphone amplifier from which output S.P.L. readings were taken at each frequency.

The measurement of the output of the hearing-aid-receiver-earmold(s) system(s) employed all of the previously discussed equipment with the exception of the standard coupler. This coupler was replaced by the previously discussed special coupler (Figure 1) which was designed to accommodate the earmolds used in the investigation.

Probe-Tube Test Equipment

For Phases III and IV of the investigation, each of the four earmolds per subject was drilled at the earmold laboratory (1) to accommodate a 2-mm (outside diameter, 1.45 mm inside diameter) polyethylene tube. The hole was drilled in the earmold so that it ran in a line approximately parallel to the standard bore with its orifice immediately adjacent to and on a plane with that of the bore opening at the tip of the earmold canal. The tubing was then inserted into the earmold. At the lateral surface of the earmold, the tubing was inserted into a 2-mm probe-tube nose cone (Bruel and Kjaer Probe Microphone Kit, UA 0052) using Vaseline to insure an air-tight seal (4). For each earmold the tubing was kept at a constant length of 25 mm. This length was sufficient to pass the probe tube through the mold approximately parallel to the bore of the earmold with enough remaining outside the mold to fit into the nose cone of the probe microphone. The probe-tube nose cone was attached to a one-half inch condenser microphone (Bruel and Kjaer type 4132). For the probe-tube measurements the cathode follower was connected to a microphone amplifier from which the sound pressure levels at the frequencies of interest were read.

Calibration of the Bruel and Kjaer probe microphone ensemble (described in The Bruel and Kjaer Manual) is ordinarily performed with the probe inserted in a 2-cc metal chamber designed for probe tubes. The angle of incidence of the probe-tube opening in the chamber is 90° to the microphone diaphragm. In this experiment, the probe tube in the earmolds, when situated in the ear of a human subject, was at an angle of approximately 0° to the main axis of the ear canal. Therefore, after the earmolds were fitted with a polyethylene probe-tube they were attached to the special coupler with clay and the probe ensemble was calibrated through a comparison with the output of the microphone in the coupler. The probe was at an angle of incidence to the sound source equal to that of the ensemble in the human ear.

Subjects

Data were collected from four normal-hearing subjects ranging in age from twenty-five to thirty-eight years. One requirement for subject inclusion was that they had ear canals sufficiently large to accommodate earmolds containing the bore and the probe tube.

In order to determine the approximate size of the subject's earmolds in relation to average normal adult ears, anterior-posterior (A-P) and superior-inferior (S-I) measurements were taken approximately two millimeters from the tip of the earmold. The mean A-P dimension was 7.0 mm with a standard deviation of 0.707 mm. The mean S-I dimension was 11.3 mm with a standard deviation of 0.902 mm. Similar measurements were taken from 100 earmolds which were randomly selected from the stock of an earmold manufacturer. The mean A-P dimension of the 100 earmolds was 7.8 mm with a standard deviation of 0.811 mm. The mean S-I dimension was 12.1 mm with a standard deviation of 1.3 mm. The A-P and S-I standard deviations of the subjects' earmolds were slightly smaller than the standard deviation of the 100 randomly selected earmolds. The scores for the experimental earmolds in the A-P dimension are: -1.414, 0, +1.414 and 0. The z scores for the experimental earmolds in the S-I dimension are: -0.277, +0.277, -1.388 and +1.388. It is evident that the experimental earmold dimensions are not larger than what might be considered to be the average earmold dimension.

Procedures

This section deals with the procedures employed in the four phases of the study as well as the United States of America Standards Institute (U.S.A.S.I.) method for the measurement of gain (3).

The U.S.A.S.I. method for measuring the gain of hearing aids is as follows. The sound field S.P.L. is adjusted to 60 dB, ± 2 dB at 1000 Hz. The frequency of the sound source is then varied over a range from 200 to 5000 Hz keeping the sound field S.P.L. constant at 60 dB, ± 2 dB. The response curve obtained from a sound field input of 60-dB, ± 2 dB, S.P.L. is considered the basic frequency response of the instrumentation under test. For this investigation, the sound field was adjusted to 60 dB at 1000 Hz and monitored to maintain this indicated value ± 0.5 dB over the frequency range of interest.

Measures of Gain

The measures of frequency response in the four phases of the experiment consisted of measures of output at ten discrete frequencies per octave. The following frequencies were arbitrarily selected: First octave; 200, 220, 240, 260, 280, 300, 320, 340, 360 and 380 Hz. Second octave; 400, 440, 480, 520, 560, 600, 640, 680, 720 and 760 Hz. Third octave; 800, 880, 960, 1040, 1120, 1200, 1280, 1360, 1440 and 1520 Hz. Fourth octave; 1600, 1760, 1920, 2080, 2240, 2400, 2560, 2720, 2880 and 3040. Fifth octave; 3200, 3520, 3840, 4160, 4480 and 5000 Hz. The B.F.O. was adjusted to within ± 3 Hz of the aforementioned frequencies using the counter-timer.

Phase I

The hearing aid was situated in the test chamber and its associated receiver fixed to the standard coupler. The hearing-aid external switch was turned to "C" (flat response). With the speaker output in the test chamber fixed at 60 dB, ± 0.5 dB, at 1000 Hz, the gain of the hearing aid was adjusted to produce 100 dB, ± 0.5 dB, in the coupler. Readings at ten frequencies per octave from 200 to 5000 Hz were taken four separate times to determine the repeatability of the measures. The input to the hearing-aid was maintained at 60 dB, ± 0.5 dB, at all frequencies. The receiver was removed from the coupler and then replaced between each series of measures.

The same procedures used with the standard coupler were employed with the previously discussed special coupler with the following exceptions. The hearing-aid receiver was attached to the screw cap, rubber grommet and metal slug of the standard coupler (Figure 1). This assembly was then fixed to the special coupler with clay. Four separate sets of readings were taken at ten frequencies per octave from 200 to 5000 Hz. The experimenter disassembled and reassembled the coupling system between each series of measurements.

Phase II

In this condition the previously mentioned sixteen earmolds were used in place of the metal slug and were connected, in turn, to the hearing-aid receiver and fixed with clay to the special coupler. The specifications of these molds are as follows: Mold 1, bore length 18 mm, bore diameter 3 mm; mold 2, same bore length and diameter as mold 1 but with a vent diameter of 0.75 mm and a vent length of approximately 11 mm; mold 3, same bore length and diameter as mold 1, but with a vent diameter of 1.5 mm and approximately 11 mm in length; mold 4, same bore length and diameter as mold 1, but with a vent diameter of 3 mm and approximately 11 mm in length. Four separate sets of measurements were taken from each of the sixteen earmolds. The experimenter disassembled and reassembled the coupling system between each measurement series.

The sound levels in the test chamber and the gain setting of the hearing aid were the same as that used in Phase I of the investigation.

Phase III

In this condition the four earmolds of each of the four subjects were drilled and fitted with a 2-mm (outside diameter, 1.45 mm inside diameter) probe tube.

Because of the necessity of ordering the test conditions (this will be discussed in a later section) the four earmolds of two of the four subjects were drilled for probe tubes prior to the initiation of the investigation. After these subjects and their earmolds were evaluated in Phases III and IV of the study (those phases involving the probe tubes), the probe holes in the molds were plugged and the molds were evaluated in Phases I and II. The other two sets of four molds each were studied on Phases I and II, then drilled for the probes and studied in Phases III and IV. A preliminary investigation indicated that the measurements made on earmolds with plugged probe-tube holes were not different from the measurements made on the earmolds before the probe holes were drilled. The method of measuring gain with the earmolds fixed to the special coupler was the same as that in Phase II of the investigation. The probe microphone and nose cone, however, were attached, in turn, to the probe tube of each of the earmolds. Output readings were obtained from the probe microphone and compared to the readings from the coupler microphone measurements made in Phase II, thereby giving a calibration for the probe microphone. The measurements were repeated four times. The experimenter disassembled and reassembled the earmold-coupler combination and the probe tube between each series of measurements. The mean values at each frequency of the four separate measures served as the calibration figures for Phase IV of the investigation. Measurements were subsequently taken from the one inch microphone with the probe tube in place and these were compared with the one inch microphone measurements from Phase II to determine the effect of the presence of the probe tube on the S.P.L.'s in the coupler.

The sound levels in the test chamber and the gain setting of the hearing aid were the same as those used in Phases I and II of the investigation.

Phase IV

This section of the investigation dealt with measures of the gain of the hearing-aid-receiver-earmold(s) system(s) with the earmold situated in the ear of the subject. Dalsgaard _et al_. (7) found that moderate leakage due to poor fit resulted in a 2- to 3-dB attenuation at frequencies between 700 and 3000 Hz and that sealing the earmolds with Vaseline tended to eliminate this intensity reduction. For the purposes of this investigation, each subject's earmolds were coated with a thin layer of Vaseline prior to inserting them into the subject's ear. The measures were the same as those discussed in the three previous phases. In this phase, the four earmolds per subject were connected, in turn, to the hearing-aid-receiver system and were fitted into the ear of the subject for whom the earmolds were fabricated. The subject was seated in a dental chair with his head cushioned and supported in position by the adjustable head-rest pads (Figure 3). The probe tube was inserted in a 2-mm nose cone which was attached to a one-half inch microphone. The cathode follower was connected to a microphone amplifier from which direct readings in S.P.L. were taken at the ten frequencies per octave. The sound level in the test chamber and the gain of the hearing aid were the same as those in the previous phases of the investigation. In order to guard against variation in the test box sound field over time, a periodic check of the frequency response was made. This consisted of removing the condenser microphone from the coupler and placing it in the chamber on the cloth mesh directly opposite the regulator microphone. Measures of gain at ten frequencies per octave from 200 to 5000 Hz were simultaneously taken from the regulator and coupler microphone amplifiers. This procedure was carried out prior to the initiation of the investigation and after each sequence of four phases.

Ordering of Test Conditions

Table 1 shows the order in which the four phases of the study were carried out with the earmolds of the four experimental subjects. Phase I involved only the standard and special couplers. Phases II and III involved the sixteen earmolds and the special coupler. Phase IV involved the sixteen earmolds and the probe-tube apparatus. The sequence moves from left to right with Phase I appearing first under subject one, Phase IV under subject two, Phase III under subject three, Phase II under subject four, Phase II under subject one, _etc_. This ordering had the effect of causing each phase to appear first, second, third, _etc_. an equal number of times (once) both across sequences and across subjects.

Table 2 shows the ordering of the appearance of the earmolds in the four phases of the investigation. This table does not show the ordering scheme of subjects and phases across time as does Table 1. For purposes of clarity, it was designed principally to present the order

TABLE 1

THE ORDERING OF THE PHASES ACROSS SUBJECTS AND TIME. THE SEQUENCE MOVES FROM LEFT TO RIGHT. PHASE I INCLUDES THE STANDARD AND SPECIAL COUPLERS ONLY. PHASES II, III, AND IV INCLUDE THE EARMOLDS AND SPECIAL COUPLER.

Subject 1	 2	 3	 4
	Phase Sequence ⟶		
I	IV	III	II
II	III	IV	I
III	II	I	IV
IV	I	II	III

of appearance of the earmolds within the various phase-by-subject combinations. Tables 1 and 2 must be used in conjunction for the entire ordering scheme.

In Table 2, moving from left to right across subjects and phases, the earmolds are ordered so that each of the four earmolds of each subject appeared first, second, third and fourth an equal number of times in a given phase, and so that four different orders were used in a given phase for the four different subjects, *e.g.*, Subject 1, Phase II, the order 1, 2, 3, and 4 appears first. For Subject 2, Phase II, this same order appears fourth. For Subject 3, Phase II, this order appears third. For Subject 4, Phase II, this order appears second. For Phase III, a reverse order of the molds for Subject 1, Phase II, was employed. In Phase III, Subject 1, the order 3, 4, 1, 2 appears first. For Subject 2, it appears fourth, for Subject 3 it appears third and for Subject 4

TABLE 2

THE ORDERING OF THE FOUR MOLDS UNDER EACH COMBINATION OF "SUBJECT" AND PHASE. ALSO INCLUDED IS THE ORDERING OF THE SPECIAL AND THE STANDARD COUPLERS IN PHASE I.

	Subject 1				Subject 2			
Sets of Repeated Gain Measures	Phases				Phases			
	I couplers	II molds	III molds	IV molds	IV molds	III molds	II molds	I couplers
A.	X Y	1 2 3 4	3 4 1 2	2 1 4 3	1 2 3 4	2 1 4 3	4 3 2 1	Y X
B.	Y X	4 3 2 1	2 1 4 3	1 2 3 4	4 3 2 1	4 3 2 1	2 1 4 3	X Y
C.	X Y	2 1 4 3	4 3 2 1	4 3 2 1	3 4 1 2	1 2 3 4	3 4 1 2	Y X
D.	Y X	3 4 1 2	1 2 3 4	3 4 1 2	2 1 4 3	3 4 1 2	1 2 3 4	X Y

	Subject 3				Subject 4			
Sets of Repeated Gain Measures	Phases				Phases			
	III molds	IV molds	I couplers	II molds	II molds	I couplers	IV molds	III molds
A.	4 3 2 1	4 3 2 1	X Y	2 1 4 3	3 4 1 2	Y X	3 4 1 2	1 2 3 4
B.	1 2 3 4	3 4 1 2	Y X	3 4 1 2	1 2 3 4	X Y	2 1 4 3	3 4 1 2
C.	3 4 1 2	2 1 4 3	X Y	1 2 3 4	4 3 2 1	Y X	1 2 3 4	2 1 4 3
D.	2 1 4 3	1 2 3 4	Y X	4 3 2 1	2 1 4 3	X Y	4 3 2 1	4 3 2 1

X = special coupler
Y = standard coupler

it appears second and so on for the remaining sets of repeated measures of gain. For Phase IV, the order of the molds for Phase II, Subject 1, was modified as in the other phases.

As previously mentioned, Phase I of the investigation involved the standard and special couplers and not the earmolds. Table 2 also shows the ordering of the two couplers for this phase of the study.

The lowest frequency tone was always used as the first test signal. Data were then collected at the progressively higher frequencies with the 5000 Hz tone serving as the last test tone of each series.

Evaluation of the Data

After the data were gathered the measures for each phase were tabulated under that phase, *i.e.*, each phase was treated as a separate experiment. The four separate measures of frequency response for each earmold under each phase were treated to obtain means and standard deviations. The means are plotted graphically for each phase of the experiment and comparisons are made between the same earmolds between phases and different earmolds within phases. Comparisons are made between couplers within phases and between couplers between phases. A comparison is made between couplers and the real ear measures. Only parametric descriptive statistics were used in the investigation.

CHAPTER IV

RESULTS AND CONCLUSIONS

Phase I

Figure 4 describes the basic frequency response of the hearing-aid-receiver system recorded from the one inch microphone in the standard 2-cc coupler (B & K Model 4132). The response is relatively flat from approximately 300 Hz to 1200 Hz. There is approximately an 8-dB drop from 1200 to 1800 Hz followed by an increase to the prior level in the 2300 to 3000 Hz region which, in turn, is followed by a very sharp drop commencing at approximately 3000 Hz.

Phase I of the investigation is designed to show the differences between the standard and special couplers with the same standard metal slug attached to each. Figure 5 records the differences in dB between the frequency response of the hearing-aid-receiver system on a standard 2-cc coupler and on the special 2-cc coupler. The differences are not greater than 1 dB above 250 Hz. At 200 Hz the difference is less than 2 dB. The standard deviations of the results of the four repeated measures do not exceed 0.7 dB at any frequency for either coupler.

Phase II

In Phase II the earmolds (molds) were mounted on the special

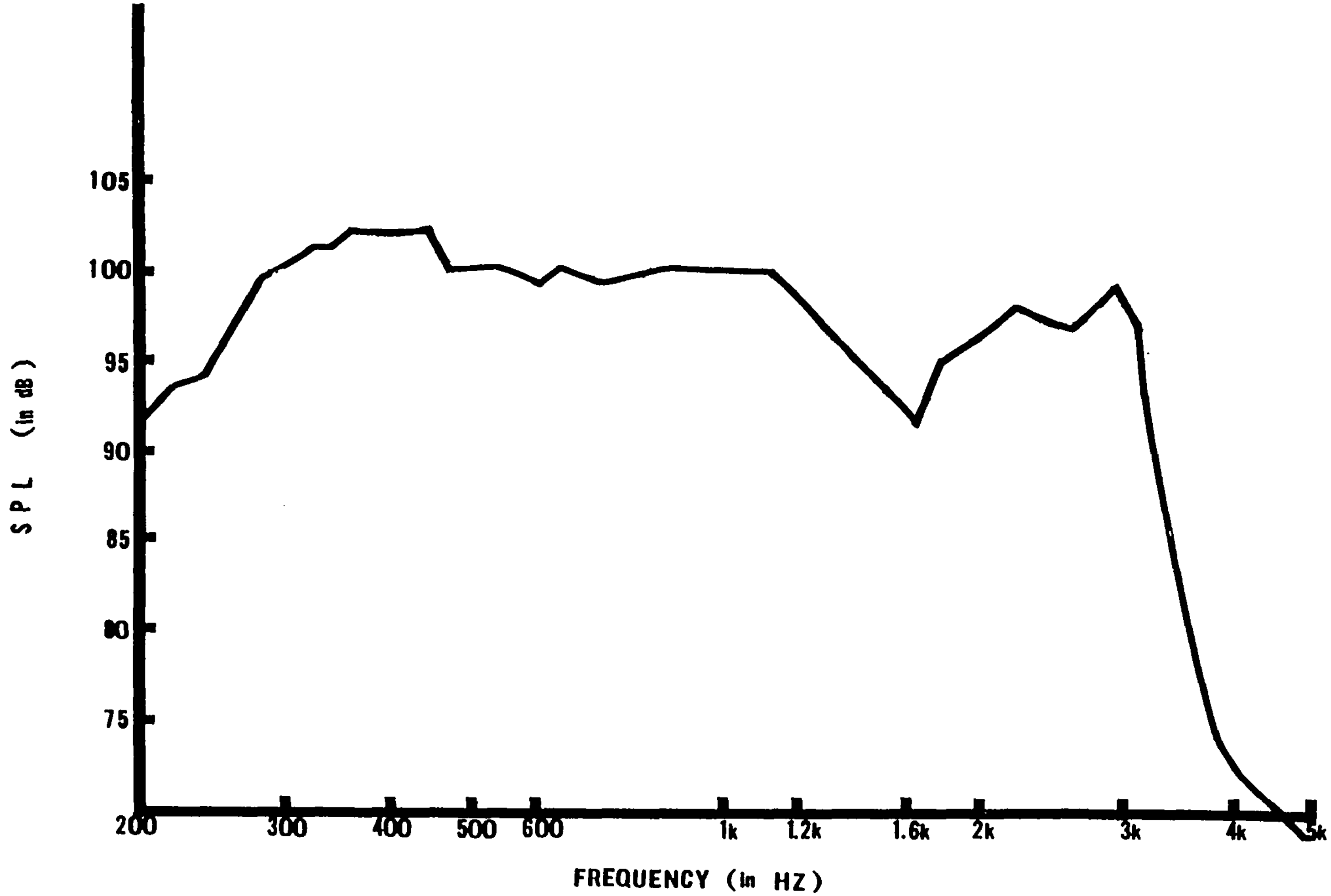

Figure 4.--The frequency response of the hearing-aid-receiver system on the standard 2-cc coupler.

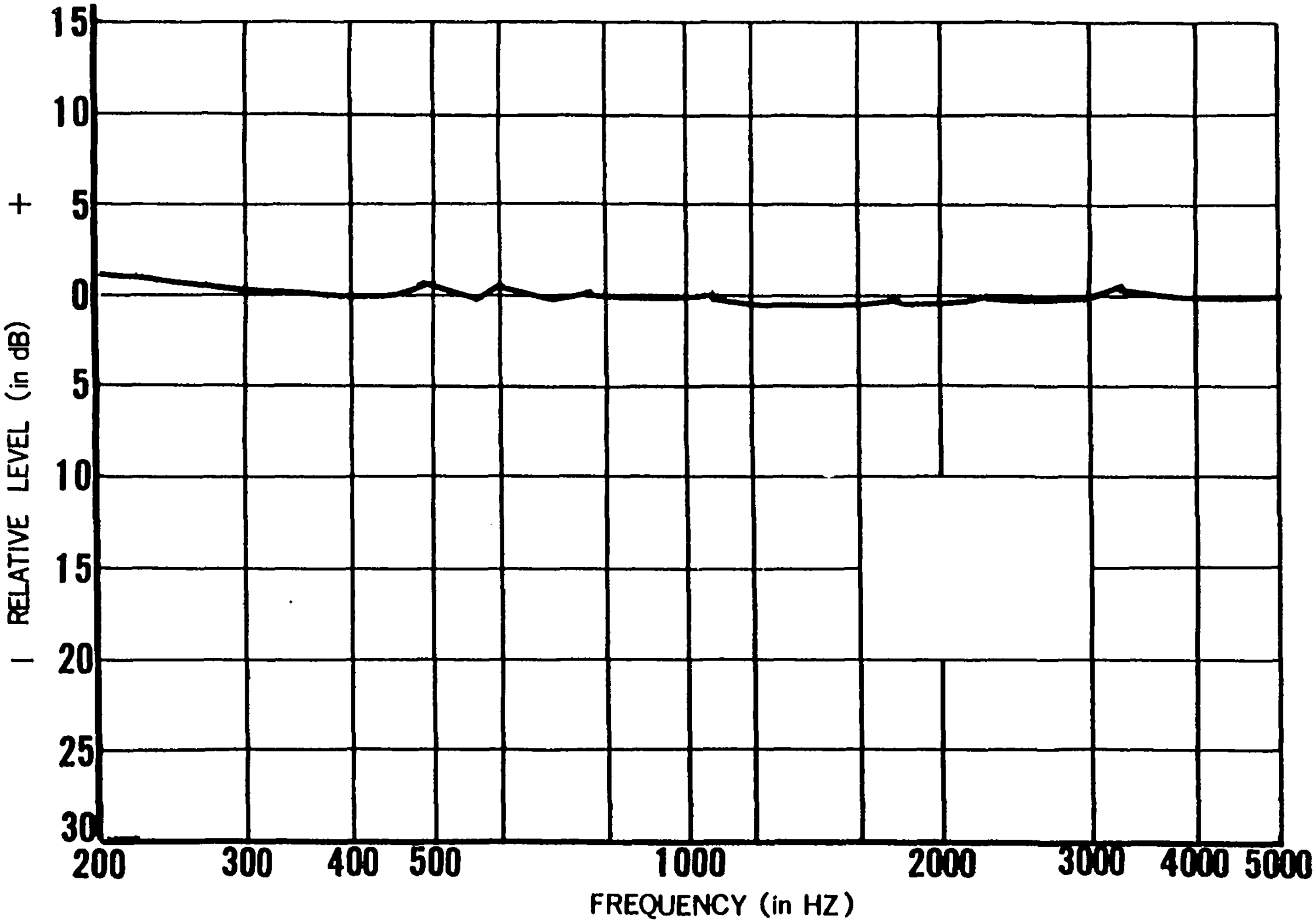

Figure 5.--The special 2-cc coupler results plotted relative to the standard 2-cc coupler results.

2-cc coupler in place of the standard metal slug. Both the molds and the metal slug have bores with the same dimensions, i.e., a length of 18 mm and a diameter of 3 mm. Mold 1 has no vent while mold 2 has a vent diameter of 0.75 mm and a length of 11 mm. Mold 3 has a vent diameter of 1.50 mm and a length of 11 mm, and mold 4 has a vent diameter of 3 mm and a length of 11 mm.

Figure 6 shows the hearing-aid-receiver-earmold frequency response recordings of molds 1 through 4 mounted, in turn, on the special 2-cc coupler. These curves are plotted relative to the results obtained with the hearing-aid receiver mounted on the standard 2-cc coupler (zero dB line). The results for mold 1 (no vent) are less than 2 dB different from those of the standard coupling system between 200 and about 2880 Hz. There is an anti-resonance in the 3200 Hz region with this type earmold as compared to the standard coupler.

The results for the earmold with the smallest vent (mold 2) vary no more than about 2.5 dB from the zero line between 200 and 2880 Hz. Mold 2 shows an anti-resonance at 3040 Hz of approximately equal size to that produced by mold 1.

The results for the earmold with the middle-sized vent (mold 3) show a definite low frequency filtering effect of about 8 dB below about 320 Hz. The curve above 320 Hz continues to rise to a flat resonant area at about 5 to 6 dB between 400 and 520 Hz. From 520 Hz to approximately 1760 Hz, the mold 3 curve drops gradually, reaching a minimum of approximately -4 dB at 1760 Hz (Figure 6). The mold 3 curve then shows a gradual rise to the zero line beyond 1760 Hz.

The mold with the largest vent (mold 4) shows a definite low

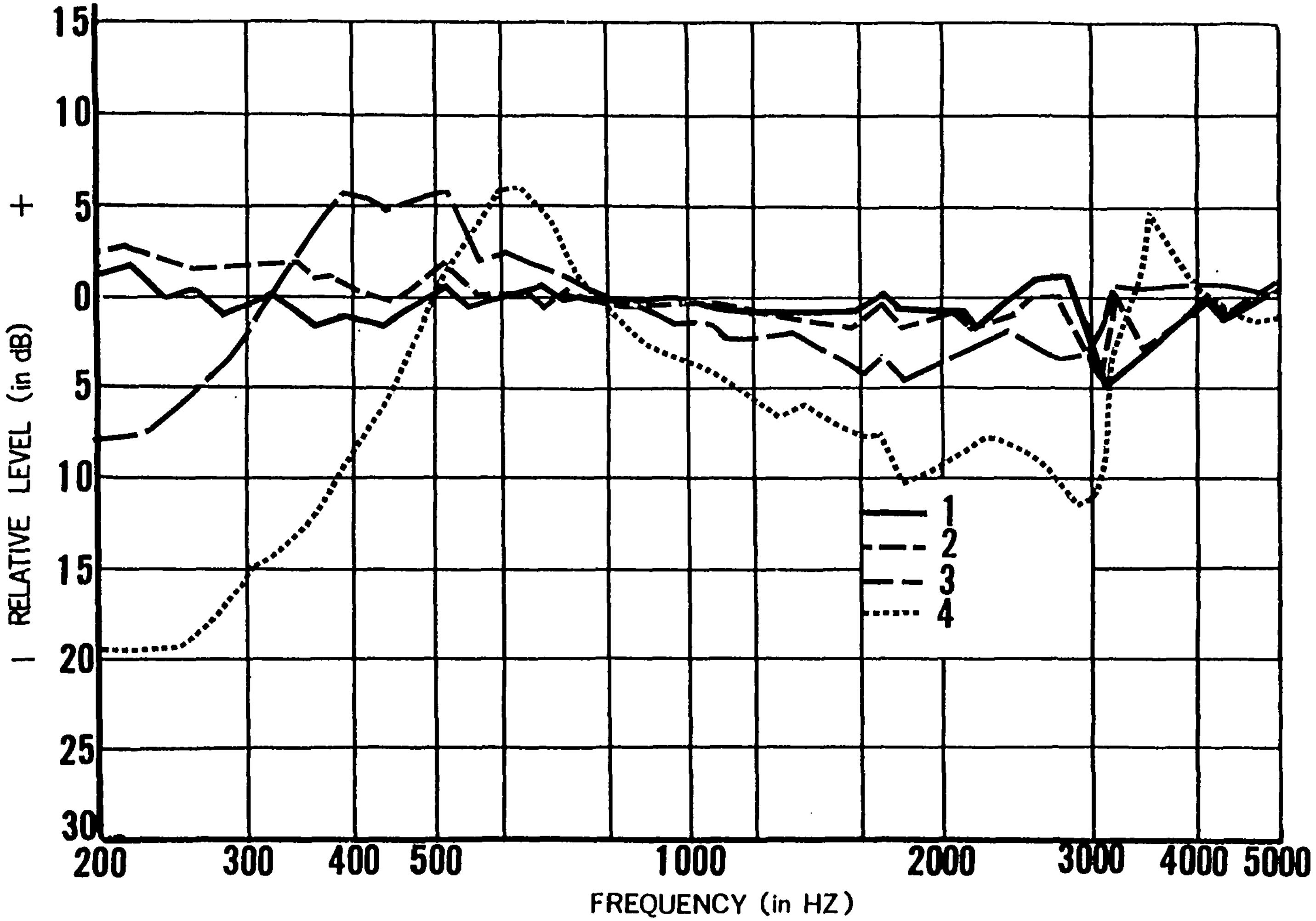

Figure 6.--The results for molds 1 through 4 obtained in Phase II plotted relative to the results for the hearing-aid-receiver on the standard 2-cc coupler.

frequency filtering effect below about 500 Hz of approximately 20 dB/ octave. Between 520 and 720 Hz there is a relatively sharp resonance. Above about 800 Hz, the curve gradually drops to approximately -10 to -12 dB, reaching a minimum at approximately 2900 Hz (Figure 6). The curve for mold 4 then shows a sharp resonant peak at 3520 Hz.

Of particular interest in Figure 6 are the results obtained with the unvented mold. This curve deviates from the frequency response curve obtained on the standard coupler (and thereby from the special coupler with the metal slug attached as well--see Figure 5) by less than 2-dB and usually by less than 1 dB over the entire frequency range below about 2900 Hz. It is concluded on the basis of this evidence that the standard coupler frequency response at the frequencies below 2900 Hz is representative of that which would be obtained with an unvented earmold having the same bore dimensions attached to a 2-cc cavity.

Figure 7 records the results for molds 2, 3 and 4 (vented molds) plotted relative to the results for the unvented earmold. This depiction clarifies the influence of the vents on the sound level in the 2 cc cavity.

Mold 2 shows a broad low frequency resonant area between 200 and 600 Hz which appears to peak around 300 to 250 Hz. From 600 to 3040 Hz, mold 2 shows a drop of generally less than 1 dB from the zero line. At 3200 Hz, there is an apparent resonant peak relative to mold 1.

Mold 3 (with a vent diameter of 1.5 mm) shows a low frequency filtering effect of up to 10 dB below 320 Hz (Figure 7). From 320 to 800 Hz, mold 3 shows a resonant frequency area which is somewhat sharper

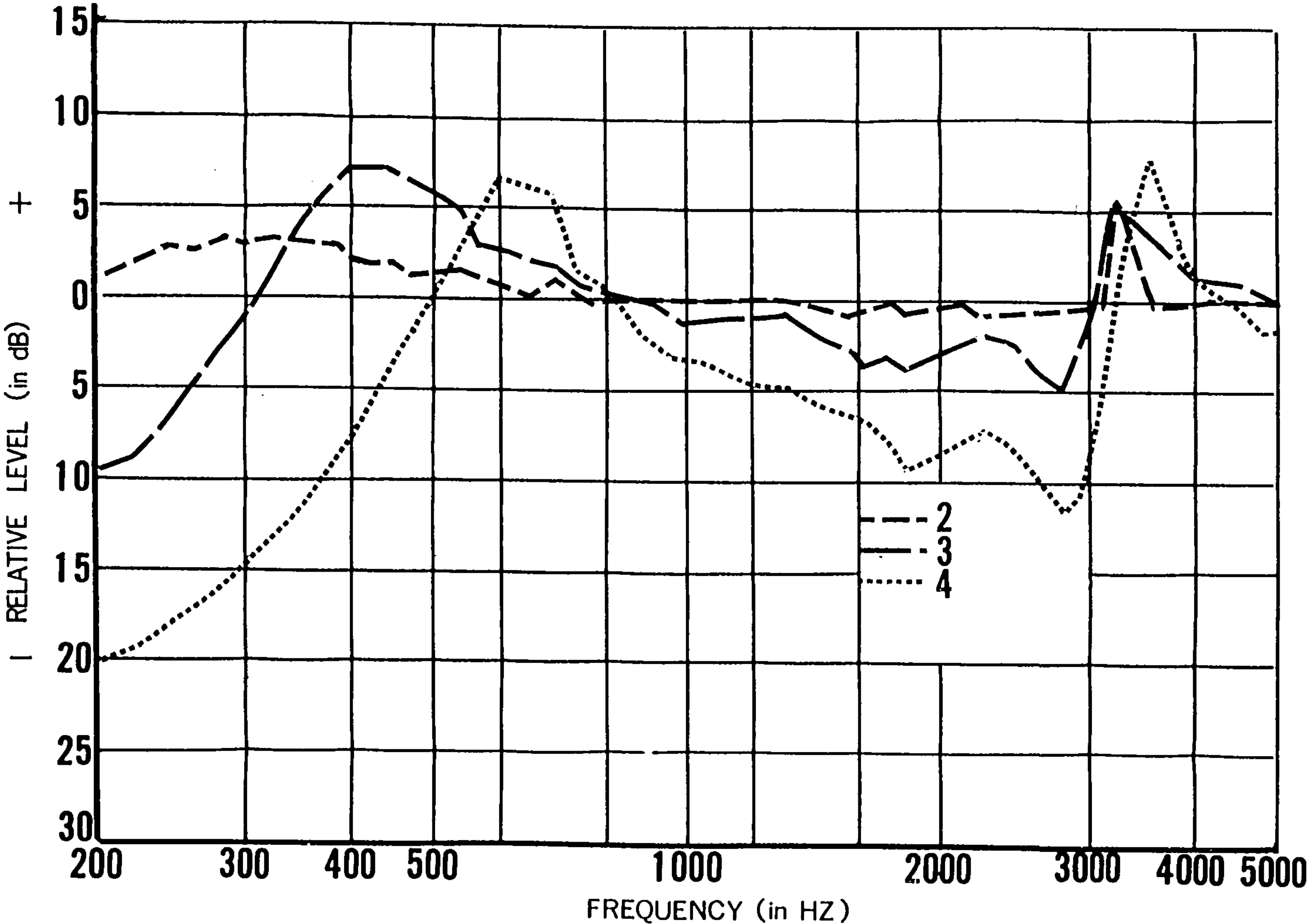

Figure 7.--The results for molds 2 through 4 obtained in Phase II plotted relative to the results for mold 1 obtained in Phase II.

than the resonant frequency area for mold 2. From 800 to 2800 Hz, mold 3 shows a progressive drop, reaching a minimum about -4 dB at 2720 Hz. Mold 3 also shows a resonant peak at 3200 Hz relative to mold 1.

Mold 4 (with a vent diameter of 3 mm) shows a low frequency filtering effect of up to 21 dB below 520 Hz when plotted relative to mold 1. From 520 to 800 Hz, mold 4 shows a resonant frequency area which is more sharply defined than that of molds 2 and 3. From 800 to 2720 Hz, the results for mold 4 drop below the zero line to a minimum of about -12 dB. As in the case of mold 3 (with a vent diameter of 1.50 mm), mold 4 shows a small but sharp drop at about 2800 Hz. Mold 4 then shows a sharp and large resonant peak at 3520 Hz.

The principal features of the curves in Figures 6 and 7 may be explained, in large part, by acoustical network theory. Four principal features are evident: the low frequency filtering effect; the low frequency resonances; the gradual downslope above the low frequency resonant areas; and the high frequency resonant peaks.

In the following pages, three acoustic principles are given brief exposition in order to clarify the discussion. These are (1) the theory of side branches and power transmission ratio, (2) Helmholtz resonator theory, and (3) tube length resonance theory.

In discussing the theory of side branches, Kinsler and Frey (<u>22</u>, p. 220) state that when the length of the side branch is much smaller than the wavelength (a condition met by the vents used in this study) the side branch may be treated as an orifice. Thus, 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 = 3.142,

a = the radius of the side branch (in this investigation vent diameters are 0.75, 1.50 and 3 mm),

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 = wavelength.

Figure 8 records calculated power-transmission ratios expressed in dB loss for the bores and vents used in this study. It can be readily seen in this figure that the power transmission loss in dB is greatest for the largest vent (3 mm in diameter) and least for the smallest vent (0.75 mm in diameter). In comparing the obtained curves reported in Figures 6 and 7 with the calculated power loss in Figure 8, it is evident that the power losses past the vents alone do not explain the configuration of the curves. Two suggestive features, however, are noted. First, at the lowest frequencies (200 to 220 Hz) the observed and calculated curves are in close agreement for molds 3 and 4 and second, the slope of the curves for these two molds decrease in steepness just above the lowest frequency measured. These features suggest the possibility of resonances superimposed on the power transmission

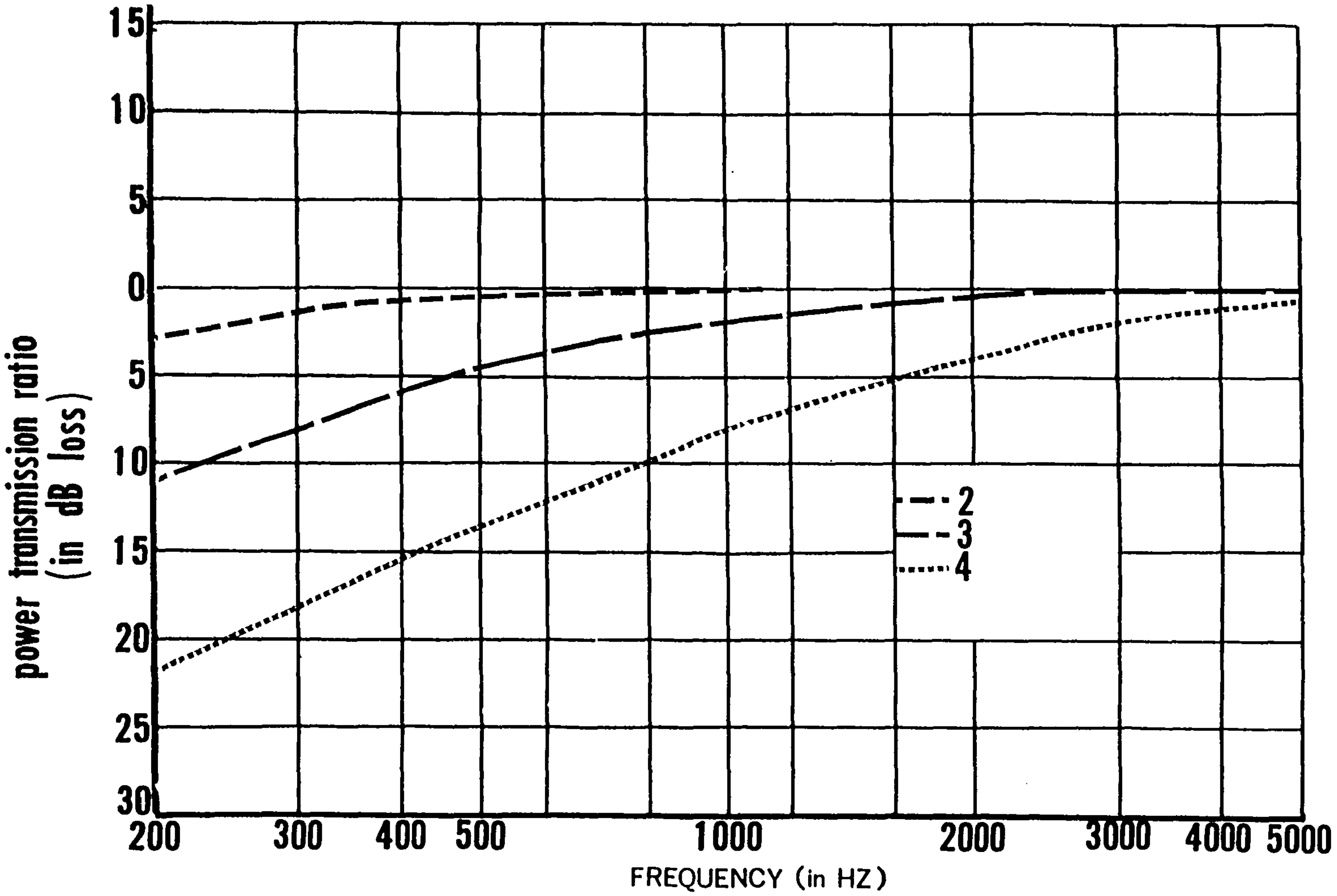

Figure 8.--Calculated power transmission loss curves for molds 2 through 4.

loss curves. In order to visualize better the hypothesized resonances the curves of Figure 7 were plotted relative to the respective power transmission loss curves of Figure 8. The result is depicted in Figure 9. All three of these curves are strikingly like those expected of resonant circuits.

Further support for this hypothesis is obtained when the earmolds mounted on the coupler are considered as Helmholtz resonators with the 2 cc cavity acting as a compliance and the air in the tube extending from orifice of the bore at the 2 cc cavity to the orifice of the vent at the open air acting as the inertance.

The resonant frequency of a Helmholtz resonator may be calculated by the formula (Baranek 5, p. 69):

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

where = radians/second,

$$M = \frac{\rho_o l}{S}$$

where ρ_o = the density of air in Kg/m^3,

l = the length of the resonator neck in meters, and

S = the cross-sectional area of the neck, and

$$C = \frac{V}{\gamma P_o}$$

where V = the volume in cubic meters of the compliance,

P_o = barometric pressure in meters of mercury = 0.751 mHg,

and γ = the ratio of specific heats of the transmission medium (1.4 for air).

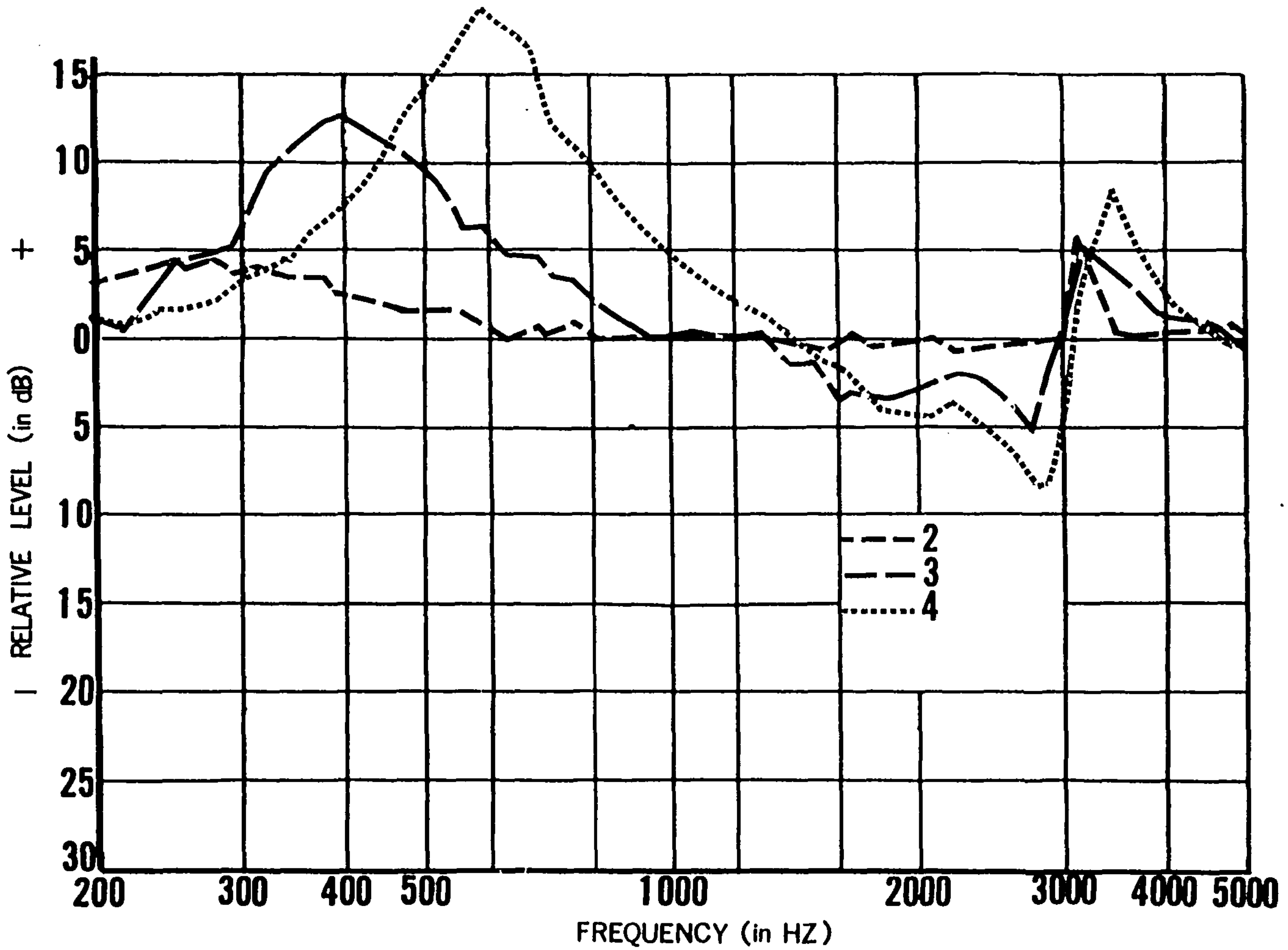

Figure 9.--The results from Figure 7 elevated by the amount of the calculated power transmission ratio reported in Figure 8.

On the basis of these formulas the resonant frequency was calculated for the molds with each of the vent sizes. For mold 4 the vent had the same diameter as the bore and thus M was calculated on the basis of a resonator neck of a constant diameter and a length of 26.5 mm. (The measured distance from the bore orifice at the 2 cc cavity to the vent orifice at the open air.) For the smaller vents, however, the resonator neck consisted of a tube of two different diameters. In this instance M was calculated separately for each neck segment and then added as appropriate for self inductances in series.

The calculated values were as follows: mold 2 (.75 mm vent), 242 Hz; mold 3 (1.5 mm vent), 428 Hz and mold 4 (3 mm vent), 624 Hz. It is evident from inspection of Figure 9 that all of these calculated values fall very near the observed maximums.

One further feature which distinguishes these curves is the relative heights of the resonant peaks with differing size vents. According to resonant circuit theory, the greater the resistance in a circuit, the smaller will be the height of the resonant peaks. This is also true of acoustical circuits. The resistance of a tube or pipe is given by the formula:

$$R = \frac{8\mu l}{\pi r^4}$$

It is apparent that as the radius (r) of a pipe is decreased the resistance increases. Therefore, the observation that the smaller vents produce smaller resonant peaks is an expected one.

On the basis of the evidence and the calculations reported above it is concluded that the configuration of the low-frequency segments of the curves reported in Figures 6 and 7 result from the superimposition of two essentially independent effects of the vents. The vent produces a filtering effect by acting as a side branch and at the same time completes a series resonant circuit in acting as a part of the neck of a Helmholtz resonator.

These low-frequency resonances associated with vents have also been observed by Lybarger (16) and by Dalsgaard et al. (7). These writers, however, did not calculate theoretical values to support their results.

Above the low-frequency resonance area but below 3040 Hz two of the vent sizes produce curves which gradually decrease until reaching the frequency region from 2240 to 2400 Hz. The curves then drop more sharply in the 2720 to 2880 Hz region. The similarities and differences between the curves can be seen most clearly in Figure 9 where the power-transmission loss has been mathematically restored as discussed earlier. The decrease in level above resonance may be explained as follows. Below resonance, resonant circuits (including acoustical) are stiffness controlled and the response is independent of frequency (4). At resonance, where the reactances cancel, the circuit is resistance controlled whereas above resonance the system is inertance (mass) controlled. Since mass reactance acts as a low-pass filter there will be a steady reduction in transmission of energy through the system as frequency is increased (4).

Between about 2200 and 2900 an apparent anti-resonance is observed with the two largest vents. Then at 3200 to 3520 Hz a sharp resonance appears which is somewhat larger and higher in frequency for the largest vent. A number of hypotheses were considered for this pattern but most were rejected for one or more reasons. Among the considered hypotheses was that of tube-length resonances. All tube lengths, however, are too small since half wavelengths are required in this instance (open tubes). Also considered was the possibility that the recess volume under the snap ring acted as a compliance and the bore and vents acted respectively as inertances. Using the bore as the inertance and the recess volume as a compliance, in fact, produces an answer of 3538 Hz as the resonant frequency. However, if this explanation is to be used to explain the positive peak at 3200 to 3520 Hz it seems necessary to find a shunt resonance to explain the anti-resonance just below 3040 Hz. The vents are available as the shunt inertances. However, calculation shows this resonance to fall at 4380 Hz which is not only too high in frequency but is on the wrong side of the series resonance. (The shunt resonance should fall below the series resonance if the total configuration is to be explained on the basis of the recess volume as the compliance. However, this cannot occur because the vents are shorter than the bore.)

Another possibility involves the volume of air over the diaphragm within the hearing aid receiver. (The resonant frequency of the diaphragm itself is probably not involved since this resonance is normally below 2000 Hz.) According to Lybarger (16) the air volume in front of the receiver diaphragm is highly important in the region around 3000 Hz and is selected by manufacturers to produce a certain cut-off frequency. This cut-off frequency and the frequency location of the peaks are dependant upon how the receiver is acoustically loaded. For example, increasing the diameter of the bore increases the frequency of the highest resonant peak and the cut-off frequency (Lybarger [16, 17] and Dalsgaard et al. [7]). The addition of vents as in this study in effect increases the effective bore size into which the receiver must work. Further, the larger the vent the smaller the resistance. When the results are plotted relatively, as in this study, a shift in the resonant peak will appear as an antiresonant-resonant configuration. The larger the bore the more the peak is shifted. The smaller the resistance the larger the resonance pattern will appear.

It is not possible, on the basis of the available evidence, to explain definitely what mechanism may produce the effects noted in the 3000 Hz region. Further procedures are needed to arrive at a definite conclusion. However, the evidence suggests a reduction in resistance (the increasing size of the pattern) and a shift upward of the frequency of the resonant peak similar to that associated with larger bore diameters. Both of these conditions are satisfied by the addition of vents of increasing size.

In summary, the overall configuration of the curves reported in Figures 6 and 7 may be accounted for on the basis of side-branch filtering, compliance-inertance resonance, high-frequency filtering above the resonance, and finally, by shifts in the high frequency resonance associated with the air volume over the receiver diaphgram produced by changes in the acoustic load into which the receiver works.

Table 3 presents the intrasubject and intersubject standard deviations obtained at selected frequencies in Phase II of the

TABLE 3

SELECTED INTRASUBJECT AND INTERSUBJECT STANDARD DEVIATIONS FROM PHASE II IN dB

Hz	Mold 1 (No Vent)					Mold 2 (0.75 mm in Diameter Vent)				
	Intrasubject				Inter-Subject	Intrasubject				Inter-Subject
	Subject 1	2	3	4		Subject 1	2	3	4	
200	0.25	0.25	0.10	0.63	0.53	1.10	0.93	0.90	0.86	0.91
520	0.17	0.22	0.51	0.50	0.46	0.41	0.31	0.30	0.40	0.34
1040	0.14	0.30	0.44	0.40	0.37	0.96	0.91	1.20	1.10	0.97
1520	0.37	0.22	0.54	0.52	0.50	0.51	0.50	0.46	0.52	0.49
2080	0.10	0.34	0.50	0.44	0.42	0.61	0.73	0.44	0.56	0.59
2560	0.40	0.37	0.10	0.20	0.20	0.10	0.34	0.31	0.22	0.28
3040	0.30	0.10	0.45	0.54	0.45	0.63	0.65	0.61	0.53	0.59
3520	0.31	0.34	0.30	0.20	0.33	0.52	0.41	0.34	0.61	0.46
4160	0.33	0.12	0.10	0.12	0.19	0.48	0.46	0.52	0.53	0.48
5000	0.22	0.30	0.50	0.52	0.40	0.51	0.43	0.32	0.41	0.40

TABLE 3--Continued

Hz	Mold 3 (1.5 mm in Diameter Vent)					Mold 4 (3 mm in Diameter Vent)				
	Intrasubject				Inter-Subject	Intrasubject				Inter-Subject
	Subject 1	2	3	4		Subject 1	2	3	4	
200	0.81	0.72	0.60	0.72	0.75	1.13	0.92	1.20	0.12	1.17
520	0.73	0.85	0.82	0.77	0.79	0.51	0.53	0.31	0.23	0.48
1040	0.75	0.74	0.72	0.71	0.73	0.20	0.16	0.13	0.21	0.19
1520	0.36	0.32	0.34	0.22	0.30	0.21	0.34	0.13	0.15	0.20
2080	0.21	0.14	0.25	0.22	0.23	0.54	0.13	0.22	0.25	0.47
2560	0.31	0.36	0.30	0.33	0.31	0.72	0.53	0.55	0.61	0.67
3040	0.52	0.73	0.64	0.60	0.61	0.72	0.65	0.83	0.70	0.76
3520	0.51	0.46	0.45	0.55	0.50	0.61	0.40	0.54	0.63	0.51
4160	0.23	0.20	0.21	0.24	0.21	0.21	0.43	0.40	0.33	0.40
5000	0.26	0.20	0.24	0.20	0.23	0.41	0.35	0.42	0.53	0.40

investigation.

Intrasubject and intersubject[1] standard deviations greater than 1 dB were observed at only the lowest frequency (200 Hz) and only for molds 2 and 4. The remaining standard deviations are less than 1 dB at any frequency for all subjects and earmolds. Two conclusions seem justified on the basis of these values. First, test-retest reliability is very high and second, the variability across molds of given type is of the same order of magnitude as the test-retest variability, justifying the use of means to describe the performance of all four molds of a given type, *i.e.*, unvented, small vent, *etc*.

Phase III

Phase III of the investigation is concerned with the insertion of a probe tube (24 mm long with an inside diameter of 1.45 mm) in the earmolds, recording the influence of the probe tube's presence on the 2-cc coupler readings and comparing the frequency-response recordings taken from the one inch (coupler) and one-half inch (probe tube) condenser microphones.

Comparisons between the frequency-response recordings from the 2-cc coupler (one inch) microphone in Phase III (probe tubes inserted in the earmolds) and the frequency response recordings from the 2-cc coupler microphone (one inch) in Phase II (no probe tubes in the earmolds) revealed differences of less than ± 1 dB at all frequencies. The small size of these differences demonstrates that the presence of these

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[1] The terms "intrasubject" and "intersubject" are used to refer to the molds for a subject in Phases II and III although actual human subjects are involved only in Phase IV.

probe tubes in the earmolds has little influence on the sound pressure levels in the coupler between 200 and 5000 Hz.

In order to illustrate the differences obtained between frequency response recordings taken from the coupler microphone (one inch) and the probe-tube microphone (one-half inch), the frequency-response recordings for the earmolds in Phase III (one-half inch microphone) were plotted relative to the frequency-response recordings from the same earmolds in Phase II (one inch microphone). These results are shown in Figure 10. The reference line in each instance is based on the frequency-response recordings from the same earmold in Phase II. Therefore, each curve represents a separate estimate of the calibration corrections to be applied to the one-half inch microphone measurements in order to determine the sound pressure levels at the orifice of the probe tube. It is evident that the four estimates differ to a significant extent. The extent of the differences in the curves represents an interaction between the method of measurement and the acoustical circuit through which the sound passes in arriving at the respective microphones. Two principal deviations across mold type are evident. First, the results for mold 3 in the low frequencies are peculiarly high. No satisfactory explanation has been found for this result. Second, in the 1920 to 3840 Hz region the mold 1 results do not drop as do those of the other molds. This deviation in the high frequencies will be discussed further in subsequent paragraphs.

The general configuration of the probe-tube response is one which suggests a compliance-inertance resonance over a broad frequency region between 400 and 1520 Hz which is more sharply tuned with the

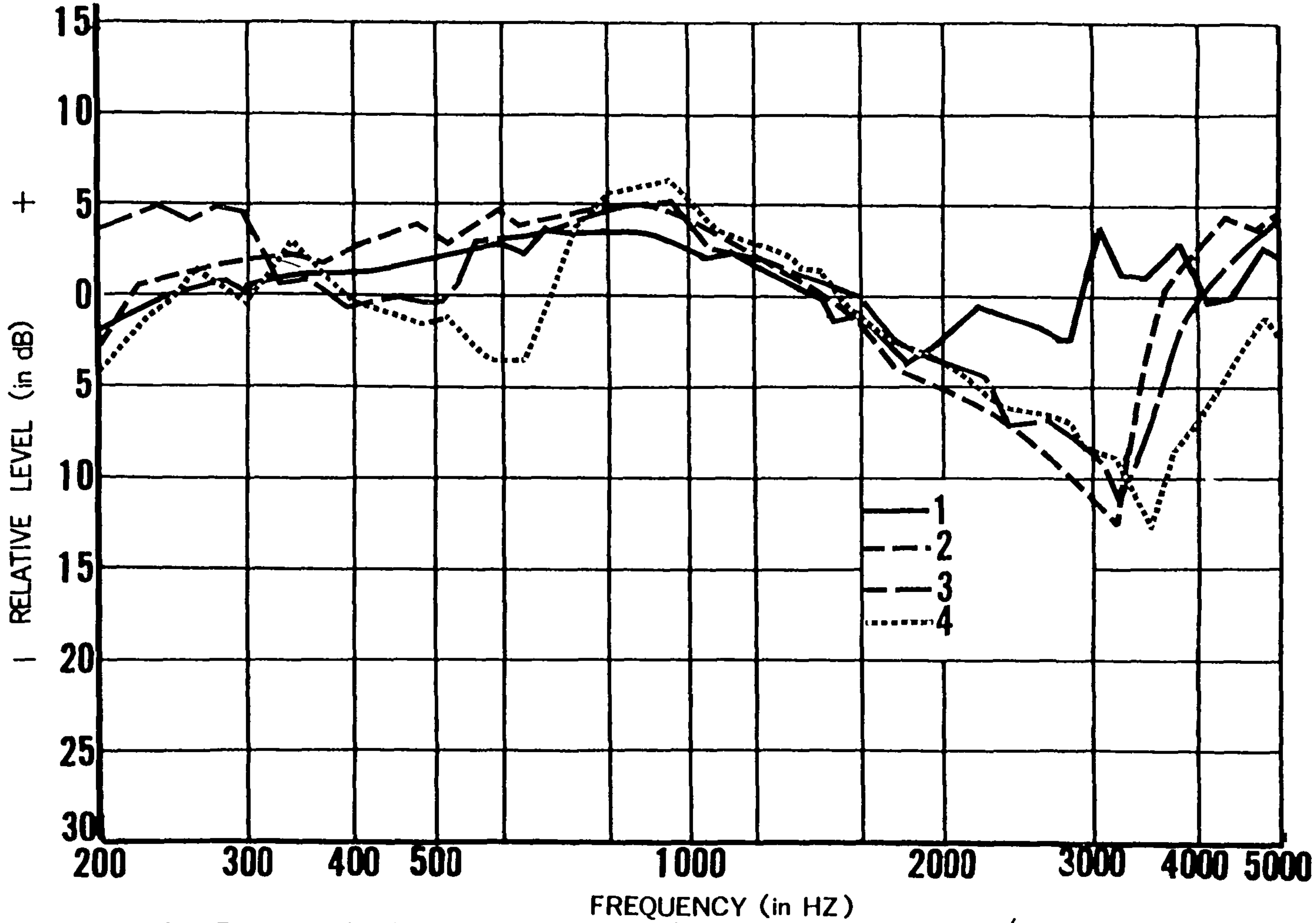

Figure 10.--The results for molds 1 through 4 obtained in Phase III (one-half inch microphone) plotted relative to the results for molds 1 through 4 obtained in Phase II (one inch microphone).

larger vents in the 800 to 880 Hz region. This sharpening is suggestive of decreased damping in the total network: a condition that is met by the larger vents above the resonance is the gradual drop normally seen in probe-tube response and which is associated with an inertance controlled circuit (4). In spite of this evidence, calculations failed to produce results to support an inertance-compliance resonance in the 800 to 880 region. The calculated resonance and/or the inertance factors are such that the calculated resonance is too high in frequency when assuming the space over the one-half inch microphone as the compliance and too low when assuming the 2 cc volume as the compliance. It appears possible that the use of plastic tubing instead of metal tubing may increase the effective compliance of the circuit and/or the effective diameter of the tube above the measured values.

The results for the three vented molds at the highest frequencies probably are produced by a dimensional resonance which becomes apparent with the reduction in damping produced by the introduction of the vents. Above 3000 Hz the quarter wavelengths of the signal are not substantially smaller than the dimensions of the cavity probe tube and bore. Under these circumstances the asymetrically placed probe tube may record different sound pressure levels than the one inch microphone. It is not possible at this time to interpret adequately the results above 3000 Hz because of the highly complex acoustic situation at these frequencies.

In order to demonstrate the effects of earmold vents on frequency response as seen from the probe-tube microphone, the results for molds 2 through 4 (vented) in Phase III were plotted relative to the results for the unvented mold in Phase III (mold 1 equals the zero line). These results are recorded in Figure 11. Molds 2 (0.75 mm in diameter) and 3 (1.5 mm in diameter) are markedly similar throughout the frequency range above 520 Hz. Below 520 Hz, molds 2 and 3 are discrepant by as much as 5 dB. The previously discussed low-frequency resonant areas are present, although smaller, and appear to modify the frequency responses obtained with these molds below 520 Hz. Mold 4 (3 mm in diameter) shows a filtering effect of approximately 23 dB below 600 Hz and the low-frequency resonant area is evident for this mold.

In Figure 11, as noted in Figure 10, the results for molds 2 and 3 show a moderate drop of about 10 dB from 1440 to approximately 3000 Hz. Mold 4 shows a larger drop beginning at approximately 1000 Hz, reaching a minimum of -17 dB at 3040 Hz. This is a further reflection of the differences between the vented molds and the unvented molds noted in the previous figure. The marked increase in the magnitude of the pattern seen for mold 4, however, apparently illustrates again the effect of decreased damping, and further, that the effects produced by vents are not limited to the low frequencies.

The results reported in Figure 11 may be compared to results reported in Figure 7 which compare earmold vent influences in Phase II. The differences in these two figures are evident and indicate that the apparent influence of vents is dependent upon how these differences are observed. This interaction is undesirable and under some circumstances, misleading. It was felt that a means of removing it would help clarify the effects of the vents in this phase.

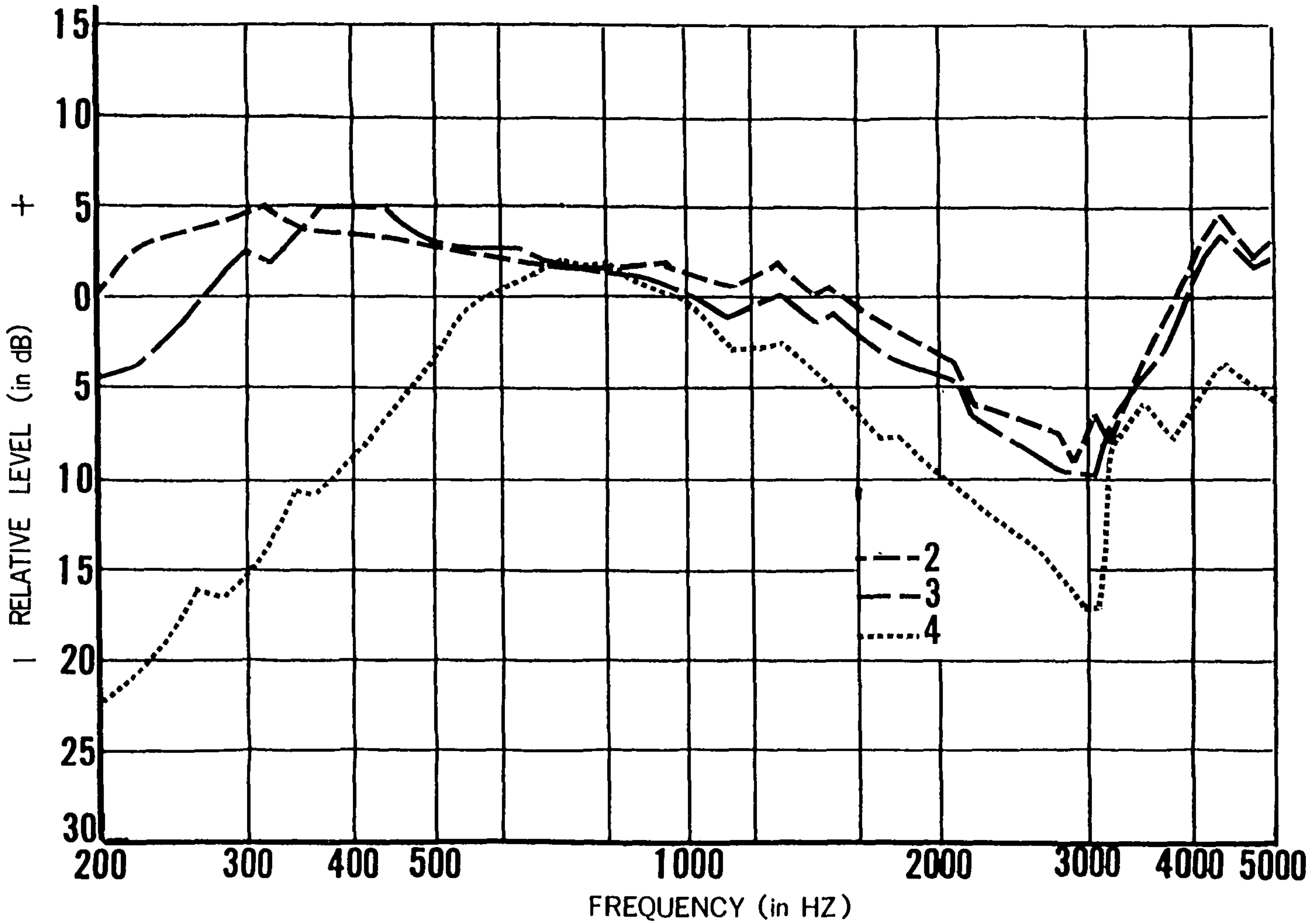

Figure 11.--The results for molds 2 through 4 obtained in Phase III plotted relative to the results for mold 1 obtained in Phase III.

Figure 12 represents an effort to compare the results for the various earmolds with influence of the probe tube removed. The procedure was to "correct" the curves of Figure 11 (the differences between molds 2 through 4 and the unvented molds as seen from the probe-tube microphone) by the difference between the two microphone readings under identical conditions (Phase II results minus Phase III results, Figure 10), thereby removing the interaction between microphone and test condition. The results in Figure 12 are clearly more nearly like those of Figure 7.

Two conclusions are reached on the basis of the results reported in Figures 10 through 12. First, significant interactions exist between the test variable (vents) and the method of measurement and second, for this reason, separate calibration corrections must be used for each test condition when the measurements are made on a coupler. However, it is probable that these interactions will not remain the same when the molds are placed in the human ear. The data in Phase IV, in fact, suggest that this interaction is much smaller when measurements are made in real ears. This factor will be discussed further.

Table 4 presents intersubject and intrasubject standard deviations at arbitrarilly selected but representative frequencies obtained in Phase III. None of the observed standard deviations obtained in Phase III is larger than the largest reported in Table 4. Only molds 2 and 3 produce standard deviations in excess of 1.5 dB and these larger values are located at the lowest frequencies. This result is explained by the need to measure levels near the "noise floor" with the vented molds at the lowest frequencies. Otherwise, it can be seen that the

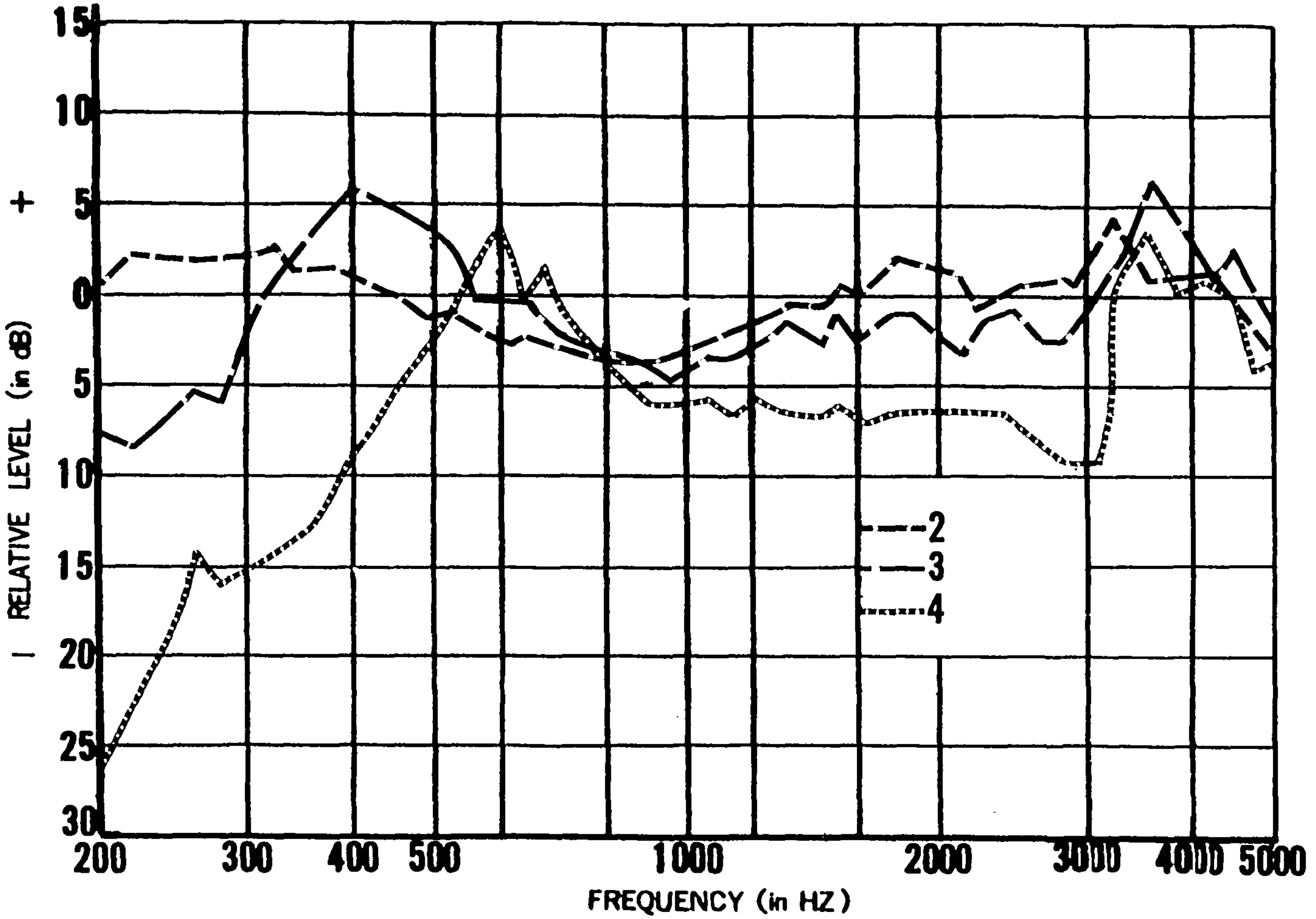

Figure 12.--The results for molds 2 through 4 obtained in Phase III plotted relative to the results for mold 1 obtained in Phase III. These curves are plotted with the correction for the differences between the one-half inch microphone (Phase III) and the one inch microphone (Phase II) removed.

TABLE 4

SELECTED INTRASUBJECT AND INTERSUBJECT STANDARD DEVIATIONS FROM PHASE III IN dB

Hz	Mold 1 (No Vent)					Mold 2 (0.75 mm in Diameter Vent)				
	Intrasubject				Inter-Subject	Intrasubject				Inter-Subject
	Subject					Subject				
	1	2	3	4		1	2	3	4	
200	0.63	0.82	0.54	0.57	0.75	0.64	0.80	0.81	0.70	0.72
520	0.43	0.65	0.63	0.51	0.64	0.84	0.84	0.91	0.93	0.86
1040	0.43	0.31	0.30	0.32	0.37	0.41	0.44	0.25	0.23	0.30
1520	0.21	0.21	0.16	0.25	0.20	0.40	0.50	0.52	0.54	0.50
2080	0.55	0.46	0.71	0.60	0.60	0.21	0.20	0.36	0.30	0.33
2560	0.51	0.54	0.55	0.63	0.50	0.31	0.30	0.24	0.30	0.26
3040	0.71	0.64	0.51	0.50	0.54	0.73	0.64	0.60	0.60	0.61
3520	0.83	0.70	0.80	0.71	0.74	0.74	0.71	0.60	0.63	0.65
4160	0.83	0.81	0.67	0.73	0.80	0.41	0.44	0.53	0.40	0.42
5000	0.71	0.66	0.85	0.91	0.83	1.31	0.95	0.95	0.90	1.20

TABLE 4--Continued

Hz	Mold 3 (1.5 mm in Diameter Vent)					Mold 4 (3 mm in Diameter Vent)				
	Intrasubject				Inter-Subject	Intrasubject				Inter-Subject
	Subject 1	2	3	4		Subject 1	2	3	4	
200	1.91	0.95	2.93	1.94	2.84	1.51	0.91	0.73	0.70	1.30
520	0.97	1.50	1.00	0.91	1.10	0.84	1.83	1.81	0.00	1.72
1040	1.10	0.95	0.81	0.91	0.91	1.11	0.76	0.83	0.82	0.93
1520	0.43	0.61	0.53	0.50	0.50	0.91	0.74	0.80	0.70	0.76
2080	0.96	0.90	0.83	0.91	0.94	0.70	0.80	0.71	0.63	0.70
2560	0.43	0.25	0.31	0.33	0.40	0.75	0.71	0.60	0.73	0.71
3040	0.75	0.62	0.44	0.51	0.64	0.91	0.95	0.61	0.41	0.82
3520	0.60	0.51	0.53	0.55	0.53	0.94	0.83	0.84	0.52	0.81
4160	0.93	0.91	0.84	0.73	0.90	0.61	0.54	0.61	0.71	0.64
5000	0.75	0.66	0.94	0.90	0.90	0.93	0.80	0.71	0.82	0.81

variability is not large in this phase, although tending to be somewhat larger than the variability observed in Phase II. Also, the intersubject variabilities are of the same order of magnitude as the intrasubject variabilities in this phase as was also observed in Phase II.

Phase IV

Phase IV of the investigation was concerned with recording of frequency response with the earmolds situated in the ears of the subjects. The recordings were taken with the one-half inch probe microphone attached to a probe tube (24 mm long with a 1.4 mm inside diameter) which was inserted in the earmolds approximately parallel to the bore.

Figure 13 compares the mean frequency response obtained with each mold type in Phase IV with that obtained in Phase III. The results obtained with each mold show the same general rising configuration. In the frequencies below 1000 Hz each of the molds produce a configuration of "inverse resonances." In these relative plots this is felt to represent the reduction of the resonances produced on the coupler due to increased resistance in the real ear. In the 3000 Hz region and above mold 1 appears in Figure 13 to have the configuration given for molds 2 through 4 in Figure 10. The slope of the curves in the low frequencies is approximately that which would be produced by a 1.5 mm vent and may result from leakage around the molds. This leakage also apparently permits mold 1 to produce a high-frequency pattern like that obtained with the other molds on the coupler (Figure 10). It appears that some of the interaction between microphones and vents is removed when measurements are made on the real ear.

The results recorded in Figure 14 confirm this conclusion. In

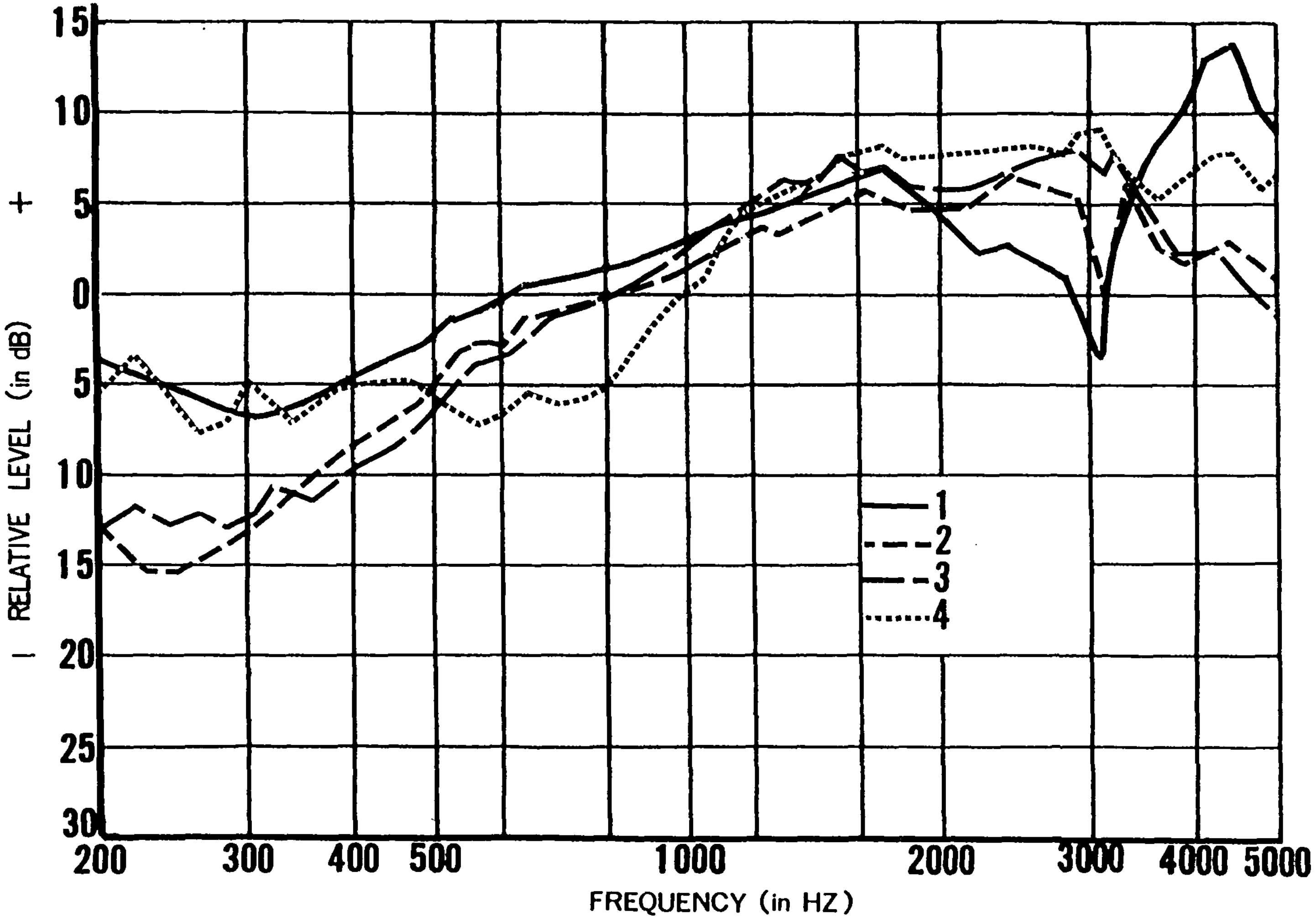

Figure 13.--The results for molds 1 through 4 obtained in Phase IV plotted relative to the results for molds 1 through 4 obtained in Phase III.

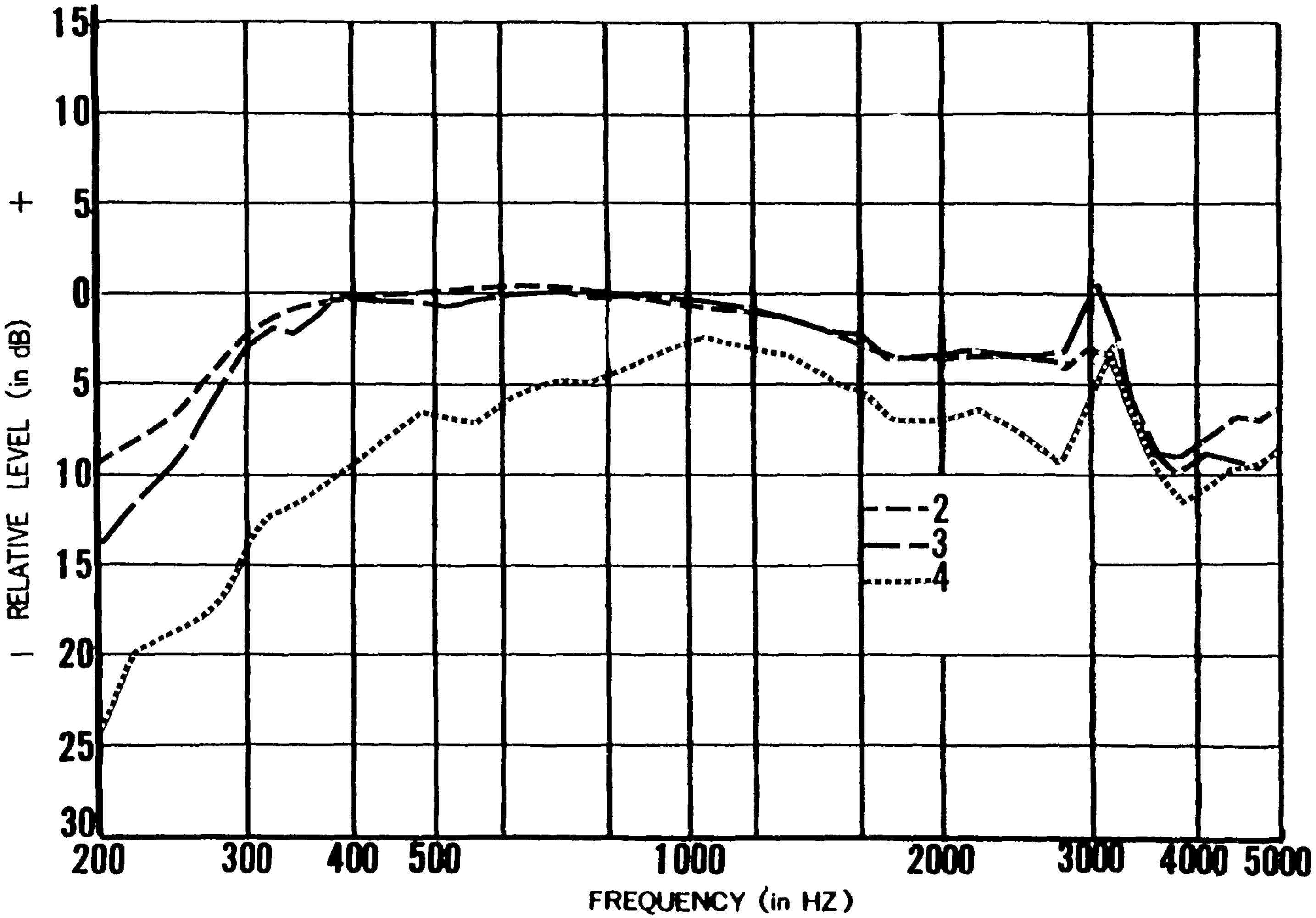

Figure 14.--The results for molds 2 through 4 obtained in Phase IV plotted relative to the results for mold 1 obtained in Phase IV.

Figure 14 the results obtained in Phase IV for molds 2 through 4 are plotted relative to the results for mold 1 obtained in Phase IV. The smoothness of the curves is remarkable when compared with the curves obtained on the coupler in Phase III. The vents produce the expected low-frequency filtering but the resonances noted on the coupler are not so apparent. (They are present, however, as revealed when the curves are elevated by the theoretical power transmission losses as shown in Figure 15.) Each of the curves in Figure 14 are somewhat lower at 200 Hz than the theoretical power loss curves probably because of leaks around the mold and/or because of viscous damping by the real ear. Finally, a small resonance appears at 3040 Hz. The resonances above 4000 Hz do not appear prominantly here because under this condition the resonance is relatively similar for all earmolds.

Inspection of the variability in this phase, reported fully in Table 5, reveals that the intrasubject standard deviations are of the same order of magnitude as those reported for Phases II and III except at the lower frequencies. The larger variability at the lower frequencies is attributable to the relatively low sound levels produced in the ear at these frequencies and the inevitable slight movements of the subjects which confounded, to some extent, these low sound level readings. It is notable that the results for the unvented mold and the mold with the smallest vent are most affected, suggesting that very low frequency pressure changes in the ear canal associated with movement is responsible for the larger standard deviations.

The intersubject variability in this phase is distinctly larger than that of any other phase and is distinctly larger than the intra-

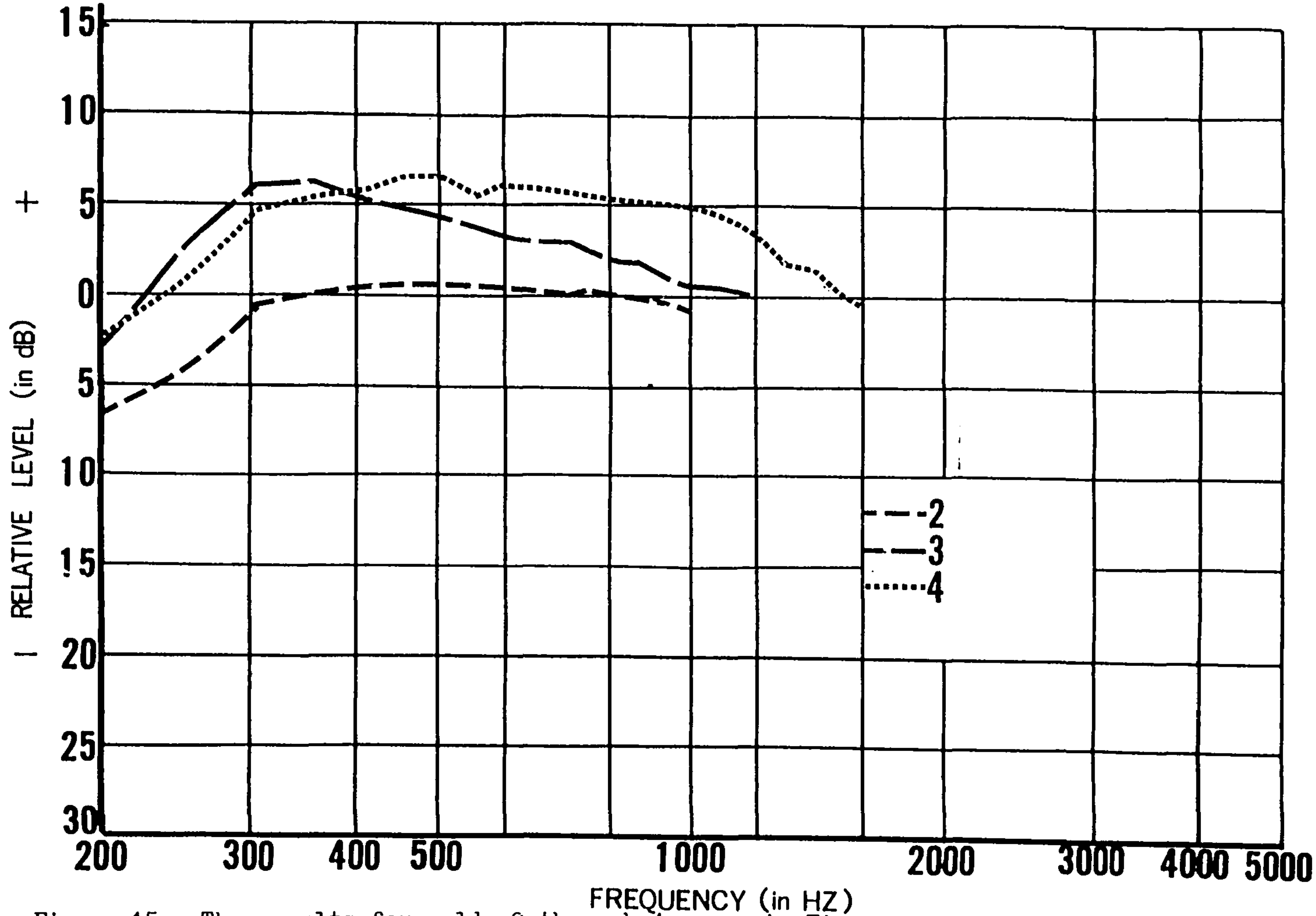

Figure 15.--The results for molds 2 through 4, seen in Figure 14, elevated by the power transmission loss seen in Figure 8.

TABLE 5

THE INTRASUBJECT AND THE INTERSUBJECT STANDARD DEVIATIONS ACROSS FREQUENCY IN PHASE IV OF THE INVESTIGATION (IN dB)

Mold 1 (No Vent)

Hz	Intrasubject				Inter-subject	Hz	Intrasubject				Inter-subject
	Subject 1	2	3	4			Subject 1	2	3	4	
200	1.18	.71	.94	.37	7.39	1040	.17	.41	.29	.43	.55
220	.79	.39	.61	.29	7.90	1120	.10	.31	.22	.47	.55
240	1.07	.76	.77	.33	7.44	1200	.31	.47	.38	.26	.59
260	.35	.38	.54	.41	7.63	1280	.42	.17	.37	.33	1.04
280	.26	.24	.33	.46	8.23	1360	.61	.26	.37	.48	.62
300	.08	.31	.53	.38	8.58	1440	.49	.38	.46	.55	.79
320	.24	.28	.22	.41	8.48	1520	.36	.33	.29	.38	1.04
340	.24	.29	.19	.44	7.84	1600	.33	.58	.33	.29	1.21
360	.08	.17	.37	.32	7.19	1760	.42	.37	.29	.39	1.03
380	.17	.39	.39	.61	6.67	1920	.49	.17	.36	.34	2.21
400	.25	.33	.35	.22	5.98	2080	.41	.13	.37	.29	2.30
440	.17	.25	.35	.28	5.26	2240	.55	.68	.35	.29	2.11
480	.15	.31	.35	.30	4.38	2400	.53	.28	.34	.26	1.71
520	.15	.34	.50	.43	3.61	2560	.62	.33	.38	.22	1.62
560	.32	.24	.48	.46	3.53	2720	.73	.17	.43	.39	1.83
600	.43	.21	.39	.32	3.14	2880	.95	.53	.57	.54	1.41
640	.59	.48	.42	.43	3.18	3040	.48	.92	.47	.33	1.10
680	.31	.25	.33	.36	2.38	3200	.65	.43	.41	.43	1.81
720	.06	.26	.32	.35	1.56	3520	.50	.76	.33	.45	3.05
760	.13	.59	.22	.48	1.72	3840	.21	.34	.30	.31	5.20
800	.29	.10	.25	.25	1.50	4160	.23	.36	.28	.46	5.25
880	.19	.28	.29	.21	1.19	4480	.55	.36	.48	.31	5.80
960	.13	.47	.36	.37	0.95	4800	.24	.56	.46	.66	6.70
						5000	.99	.33	.35	.66	6.72

TABLE 5--Continued

Mold 2 (0.75 mm in Diameter Vent)

Hz	Intrasubject				Inter-subject	Hz	Intrasubject				Inter-subject
	Subject						Subject				
	1	2	3	4			1	2	3	4	
200	29.92	1.10	1.17	1.43	15.93	1040	.42	.42	.38	.58	3.91
220	1.30	.91	.97	1.45	6.40	1120	.39	.42	.67	.54	3.44
240	1.50	.41	.93	.71	5.75	1200	.68	.39	.32	.33	2.62
260	.93	1.54	.61	.83	7.53	1280	.25	.40	.38	.50	2.35
280	1.09	3.14	.57	.68	8.62	1360	.29	.41	.33	.79	1.69
300	.87	.57	.49	1.00	7.92	1440	.43	.50	.17	.57	1.22
320	.90	.86	1.04	1.31	7.24	1520	.45	.39	.24	.37	.82
340	.76	.47	.79	.85	7.75	1600	.29	.53	.53	.36	.76
360	1.00	.63	.51	.76	7.84	1760	.28	.86	.36	.35	.93
380	1.14	.88	.37	.47	7.96	1920	.34	.69	.26	.39	1.95
400	.87	.22	.37	.55	7.99	2080	.37	.35	.59	.44	2.41
440	.67	.41	.65	.44	7.86	2240	.32	.24	.28	.44	1.96
480	.82	.65	.48	.47	7.56	2400	.40	.31	.22	.60	1.63
520	.56	.53	1.05	.67	8.50	2560	.30	.53	.22	.39	1.51
560	.42	.42	.43	.77	9.21	2720	.28	.35	.41	.43	1.73
600	.83	.83	.27	.65	8.91	2880	.24	.31	.57	.21	2.04
640	.59	.90	.79	.15	9.10	3040	.41	.38	.54	.42	2.10
680	.51	.41	.22	.39	8.63	3200	.48	.41	.51	.32	4.04
720	.40	.39	.34	.24	8.81	3520	.38	.49	.35	.35	3.50
760	.37	.63	.15	.37	8.69	3840	.32	.67	.46	.50	1.50
800	.29	.43	.24	.33	8.71	4160	.40	.62	.18	.37	2.91
880	.25	.46	.55	.48	8.10	4480	.37	.35	.22	.21	5.05
960	.37	.58	.61	.77	4.51	4800	.37	.32	.42	.65	3.76
						5000	.29	1.41	.34	.31	3.50

TABLE 5--Continued

Mold 3 (1.5 mm in Diameter Vent)

Hz	Intrasubject				Inter-subject	Hz	Intrasubject				Inter-subject
	Subject						Subject				
	1	2	3	4			1	2	3	4	
200	.65	.34	.33	.34	7.17	1040	.27	.47	.85	.39	1.22
220	.29	.21	.40	.18	8.36	1120	.42	.37	.26	.37	1.50
240	.67	.17	.21	.24	7.75	1200	.31	.10	.37	.28	1.66
260	.56	.31	.24	.19	8.12	1280	.31	.22	.38	.32	1.44
280	.28	.05	.17	.37	8.17	1360	.33	.60	.39	.48	1.31
300	.42	.22	.44	.34	8.26	1440	.37	.22	.31	.36	1.24
320	.46	.17	.78	.28	7.40	1520	.43	.71	.25	.32	.79
340	.35	.44	.26	.51	8.76	1600	.39	.27	.35	.36	1.03
360	.30	.51	.24	.57	8.59	1760	.34	.29	.33	.29	.79
380	.29	.30	.17	.31	6.46	1920	.36	.21	.17	.24	1.79
400	.47	.39	.43	.41	5.98	2080	.42	.29	.53	.33	1.96
440	.26	.56	.63	.21	5.30	3340	.25	.41	.36	.15	1.91
480	.44	.31	.24	.26	5.14	2400	.52	.46	.41	.21	1.65
520	.42	.29	.81	.13	3.26	2560	.42	.31	.24	.17	2.23
560	.37	.50	.13	.24	3.36	2720	.43	.43	.13	.31	2.83
600	.69	.36	.15	.26	3.10	2880	.47	.15	.31	.17	2.87
640	.29	.22	.33	.31	3.11	3040	.50	.16	.51	.17	3.23
680	.32	.41	.31	.32	2.28	3200	.61	.43	.32	.29	4.00
720	.31	.25	.29	.28	1.71	3520	.39	.35	.32	.39	3.34
760	.33	.19	.32	.17	1.66	3840	.38	.19	.31	.24	2.68
800	.43	.26	.32	.32	1.56	4160	.33	.11	.68	.21	3.62
880	.13	.39	.39	.28	1.41	7780	.43	.40	.62	.32	4.74
960	.29	.75	.46	.38	1.02	4800	.29	.26	.36	.26	3.42
						5000	.45	.36	.48	.44	3.55

TABLE 5--Continued

Mold 4 (3 mm in Diameter Vent)											
Hz	Intrasubject				Inter-subject	Hz	Intrasubject				Inter-subject
	Subject						Subject				
	1	2	3	4			1	2	3	4	
200	.55	.31	.45	.42	7.30	1040	.37	.51	.43	.31	.91
220	.51	.24	.34	.60	9.02	1120	.24	.13	.37	.44	.76
240	.42	.34	.51	.31	8.24	1200	.18	.30	.49	.22	.87
260	.76	.10	.29	.17	8.63	1280	.43	.13	.25	.17	1.22
280	.59	.22	.57	.29	8.32	1360	.54	.37	.25	.31	1.06
300	.44	.49	.74	.22	7.88	1440	.42	.14	.22	.29	.70
320	.51	.46	.46	.23	7.66	1520	.22	.22	.17	.62	.85
340	.22	.13	.63	.37	7.54	1600	.26	.11	.37	.26	1.23
360	.48	.05	.18	.28	6.79	1760	.58	.31	.37	.50	1.49
380	.34	.14	.34	.36	6.34	1920	.51	.33	.31	.24	2.50
400	.38	.22	.56	.42	6.13	2080	.25	.51	.31	.13	2.79
440	.48	.28	.26	.33	5.18	2240	.22	.45	.26	.26	3.14
480	.39	.13	.26	.28	4.42	2400	.37	.17	.49	.17	2.60
520	.51	.10	.25	.13	3.59	2560	.44	.43	.50	.26	2.54
560	.22	.21	.13	.22	3.85	2720	.31	.35	.25	.28	3.19
600	.22	.32	.55	.25	3.52	2880	.33	.11	.45	.26	3.97
640	.21	.22	.34	.17	3.27	3040	.40	.42	.26	.42	4.24
680	.34	.26	.29	.36	2.97	3200	.42	.54	.31	.31	3.93
720	.33	.34	.19	.52	2.37	3520	.45	.17	.54	.33	2.61
760	.38	.35	.45	.65	2.39	2840	.22	.45	.37	.54	2.11
800	.24	.29	.24	.25	2.00	4160	.67	.26	.35	.28	3.81
880	.28	.17	.57	.39	1.81	4480	.39	.25	.50	.38	6.15
960	.37	.15	.33	.28	1.24	4800	.36	.26	.59	.44	5.62
						5000	.45	.45	.49	.51	5.26

subject variability obtained in this phase. The variability is also distinctly larger apparently than that observed by Ewertsen et al. (8) who reported "measurements were made on 6 different persons, and the results were exactly identical" (8, p. 313). The pattern of the inter-subject variability across frequency suggests that the differences between subjects varies with frequency. In order to further evaluate the individual differences, Figures 16 through 18 are presented. Each figure compares the results for one of the vented molds with those for the unvented mold for each of the four subjects individually. Through the mid-frequencies all subjects fall within a fairly small range of levels. However, at the higher and lower frequencies large differences between subjects are apparent in each figure. This is particularly true in the lower frequencies. It is also apparent that there is a great deal of overlap of results in that, for example, the results for subject 4 with the smallest vent show a greater low-frequency filtering effect than do the results for subject 3 with the largest vent. Further, note in each figure that the results in the low frequencies for the four subjects are in the same order from top to bottom. (The result at 200 Hz for subject 1, earmold 4, is the only exception. An explanation for this result is not apparent.)

The individual differences at the high frequencies are smaller but tend to follow similar patterns. Subject 1 consistently differs from the other three above 3520 Hz and there is a tendency for subject 2 to produce higher values in the 1520 to 3520 Hz region.

Whatever factor or factors produced the differences in the results across subjects, they appear common to the results for all vented

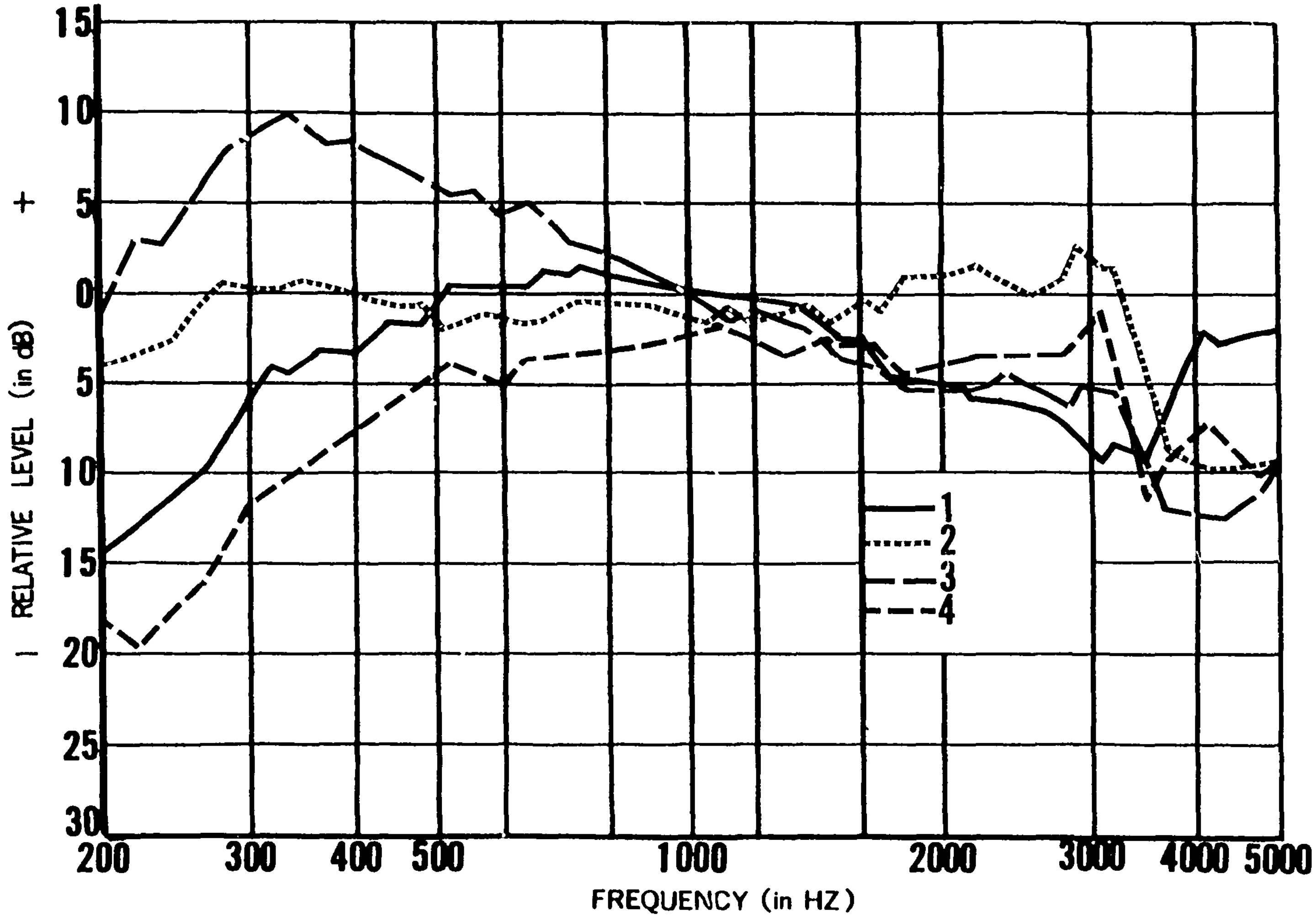

Figure 16.--The results for mold 2 obtained on each of the four subjects in Phase IV plotted relative to the results for mold 1 obtained on each of the four subjects in Phase IV.

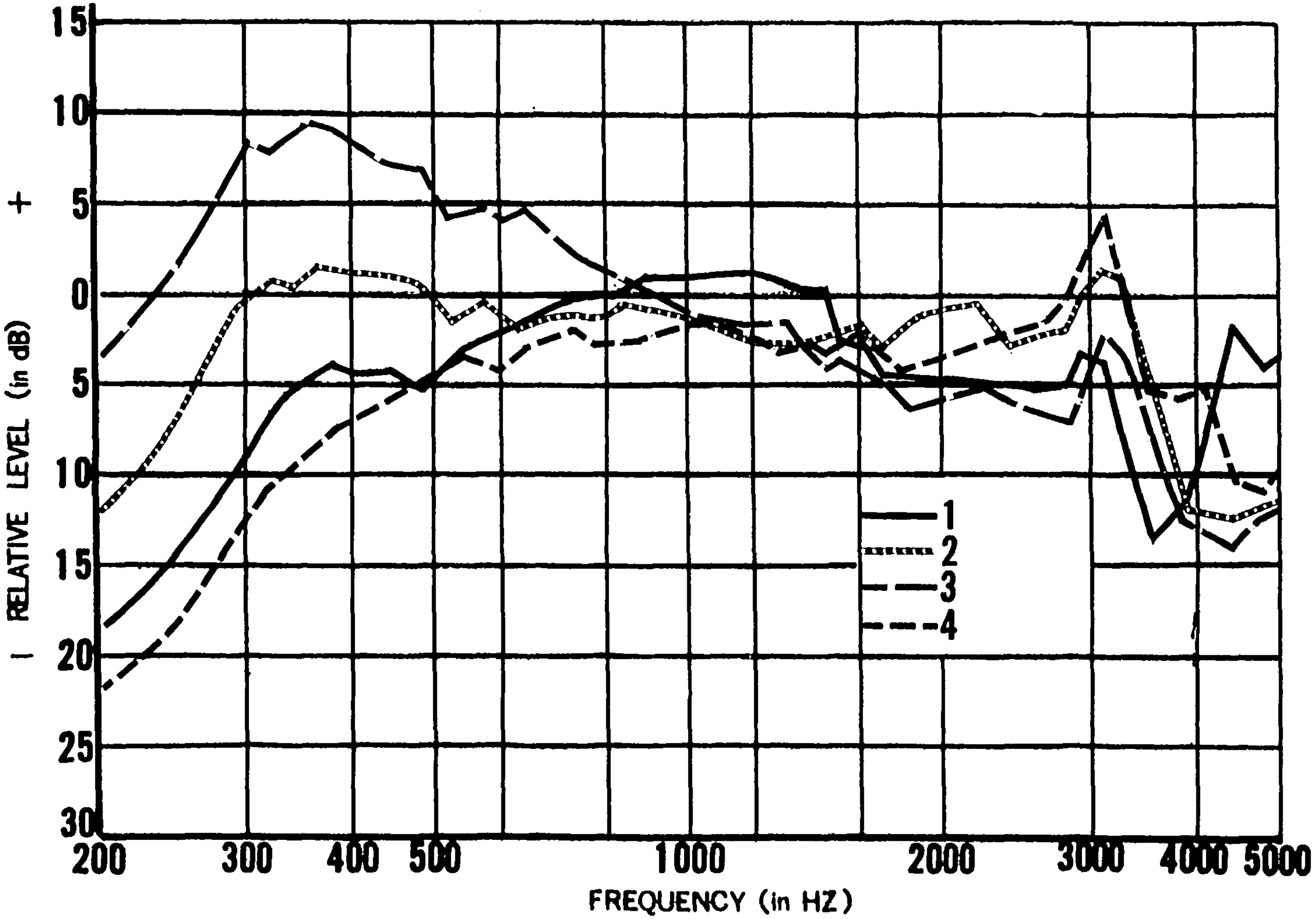

Figure 17.--The results for mold 3 obtained on each of the four subjects in Phase IV plotted relative to the results for mold 1 obtained on each of the four subjects in Phase IV.

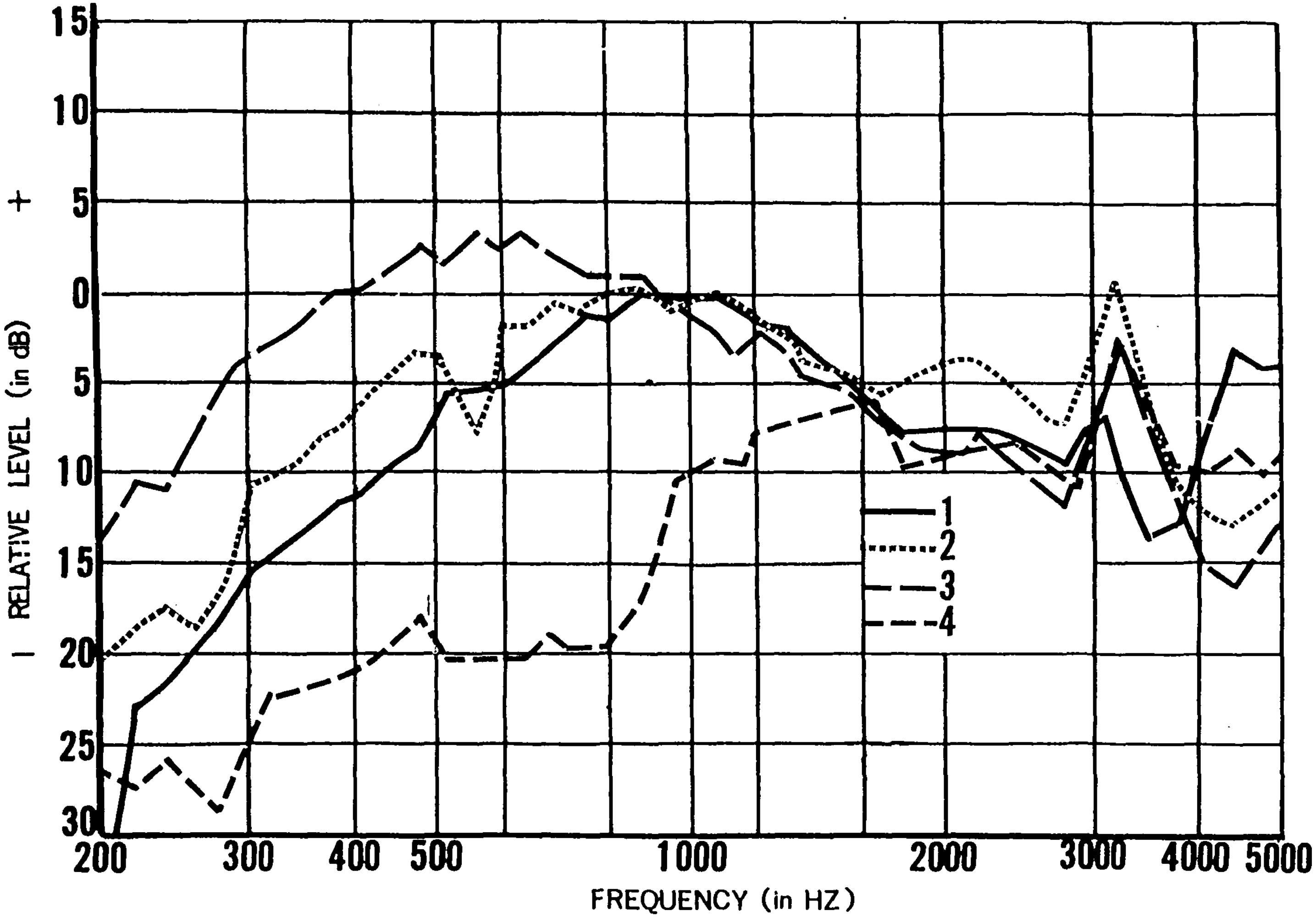

Figure 18.--The results for mold 4 obtained on each of the four subjects in Phase IV plotted relative to the results for mold 1 obtained on each of the four subjects in Phase IV.

molds. These factors may fall into one or both of two general categories. First, since all molds were made from a single impression it is possible that all molds for a given subject will produce common effects on the basis of how they fit the ear. A second set of factors may be those associated with the ears of the subjects. That is, the acoustic load provided by the subjects' ears may differ sufficiently to produce these differences. Close inspection of the data suggests that both of the above two sets of factors may be involved. However, further investigation will be required to identify the mechanism producing these individual differences.

A principal objective of this study was to measure the sound pressure levels developed in the human ear canal by a receiver working through various earmolds. The key issue in carrying this out successfully is the calibration of the probe-tube microphone. Achieving this calibration proved difficult because of the interaction between the acoustic network and the measurement microphones as noted earlier (Figure 10). Evidence from Phase IV suggests that the greater damping in the real ear reduces this interaction.

One of the most evident considerations is the difference between the unvented mold and the vented molds in the 3000 Hz region reported in Figure 10. The results from Phase IV suggest that this difference is greatly reduced when the molds are placed in the ear canal. Actually, the resonance pattern for the unvented mold in this region appears larger than those for the vented molds when all the molds are placed in the human ear. Therefore, it was felt that the high frequency pattern seen for the vented molds in Phase III would be a better calibration of the probe tube inserted in mold 1 when placed in the real ear than the results actually obtained for this mold in Phase III. Also the mold 3 results reported in Figure 10 at the lowest frequencies appear to differ from the results for the other molds. The Phase IV results suggest that this difference is also reduced when the molds are placed in the ear canal. For these reasons it was decided to use a single calibration curve for the probe-tube microphone. This curve is shown in Figure 19 and represents a fit by eye of the results for molds 1, 2 and 4 in the low frequencies, the results for all molds through the mid range and the results for molds 2, 3 and 4 in the high frequencies. This curve is thought to represent only the best available approximation of the calibration of the probe-tube microphone placed in the ear canal.

The mean results obtained from the probe-tube microphone with earmold placed in the real ear were corrected for probe tube response (Figure 19). The resulting sound pressure levels obtained for each earmold type are recorded in Figures 20 (molds 1 and 2) and 21 (molds 3 and 4). The frequency response of the receiver obtained on the standard coupler is repeated in each figure for comparison. A systematic relationship is noted between the curves at both high and low frequencies. In the low frequencies the higher damping provided by the real ear is evident in that at no frequency do the results for the vented molds in the real ear rise above those for the unvented mold on the standard coupler. What appears to be a receiver-standard-coupler resonance in the 300-400 Hz region is not present in the real-ear measurements.

Above this frequency region the results for the unvented mold

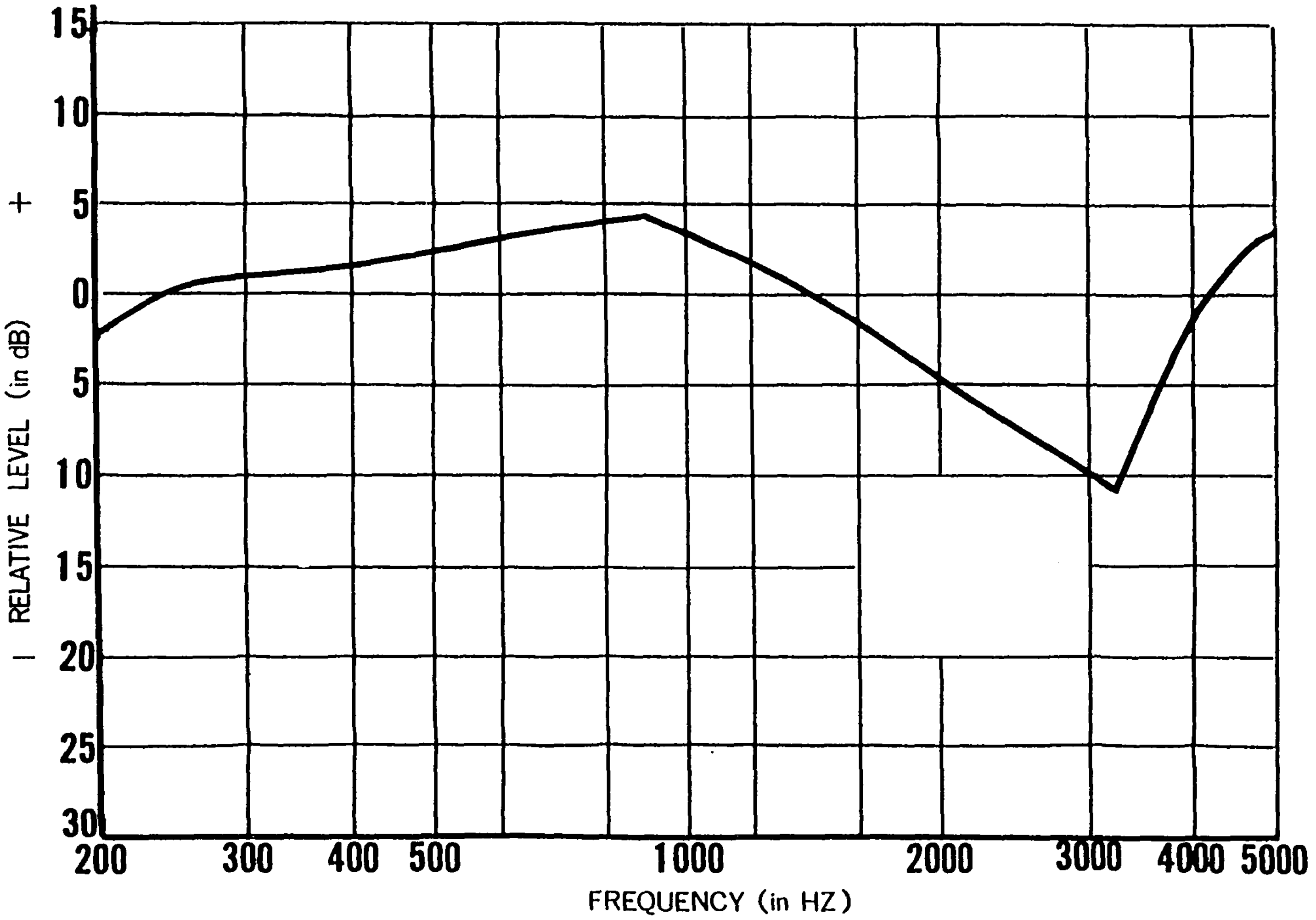

Figure 19.--Curve "fitted by eye" from the data reported in Figure 10 and used as a correction for the calibration of the one-half inch microphone.

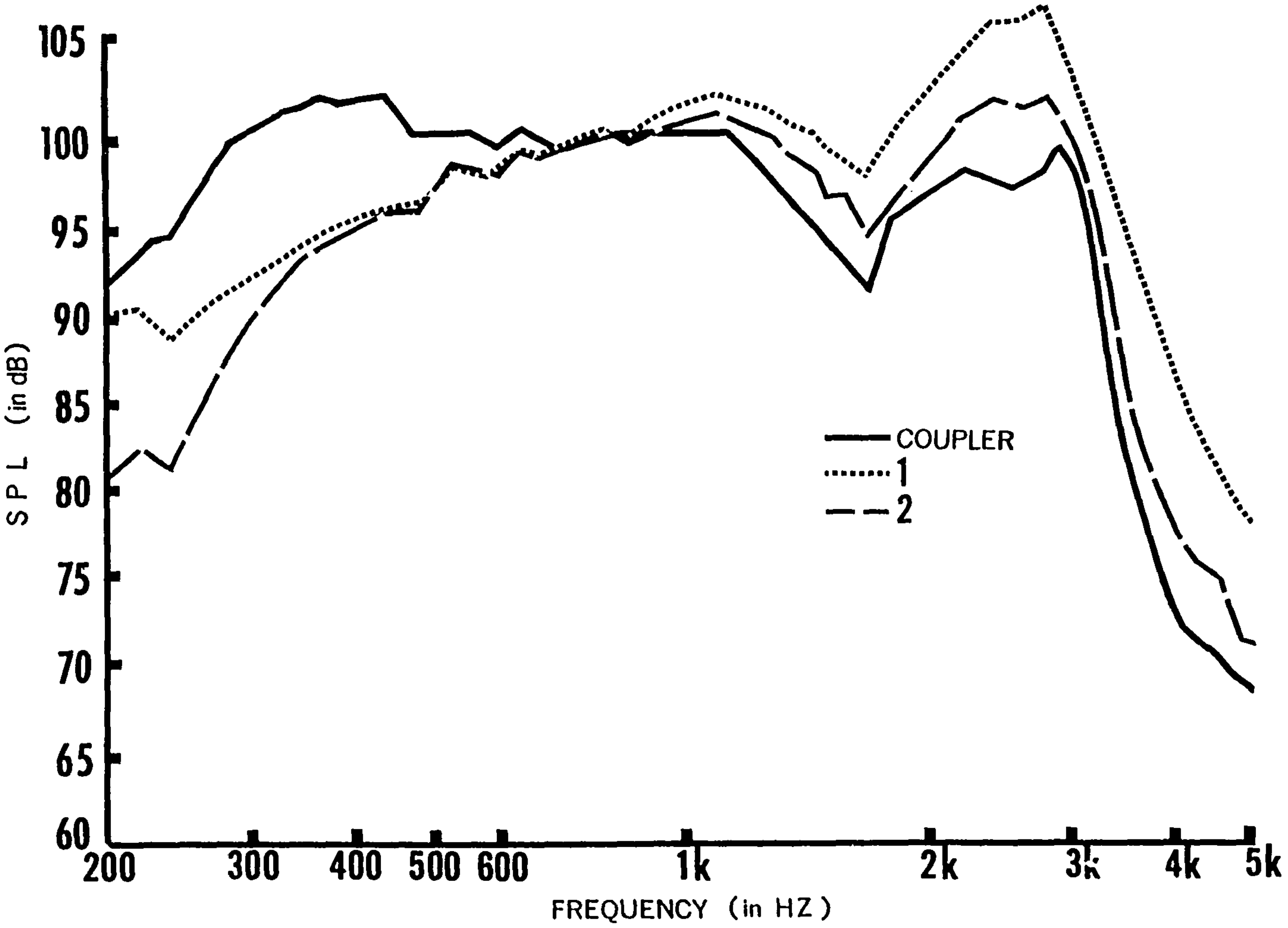

Figure 20.--The results for the hearing-aid-receiver obtained from the standard 2-cc coupler. The results for molds 1 and 2 obtained in Phase IV corrected by the curve in Figure 19 and plotted in S.P.L. values.

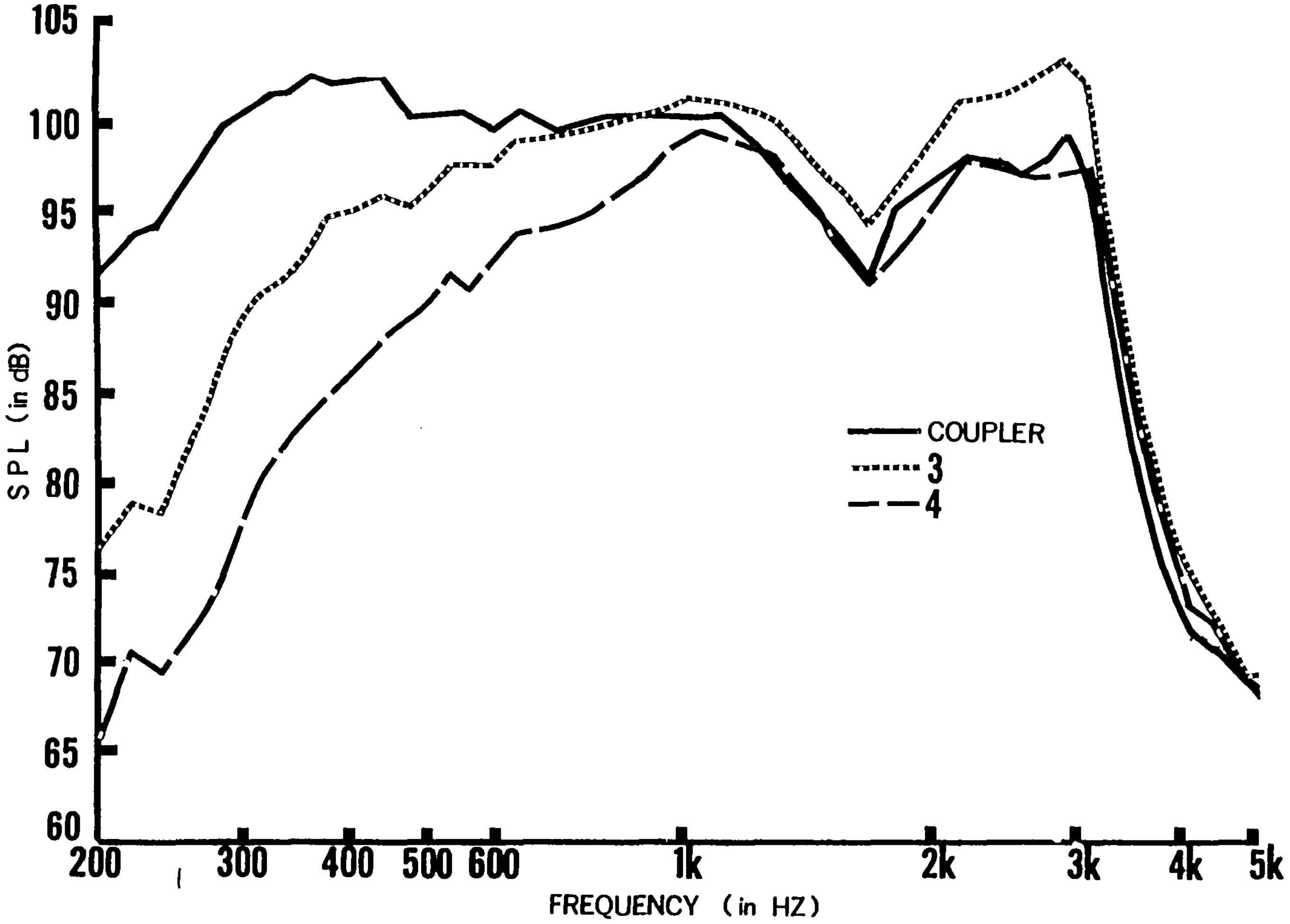

Figure 21.--The results for the hearing-aid-receiver obtained from the standard 2-cc coupler. The results for molds 2 and 3 obtained in Phase IV corrected by the curve in Figure 19 and plotted in S.P.L. values.

increase at a rate of four to five dB per octave relative to the standard coupler results until reaching a maximum of about 8 dB above the coupler results. This same trend was noted by Nichols et al. in 1946 (5). These workers used procedures much like those of this study including sealing the earmolds in the ear with a viscous substance. Ewertsen et al. (8) also made a similar comparison between ear canal and 2-cc coupler readings and found the ear-canal readings to be higher at all frequencies with sealed earmolds. Only when using a relatively loose fitting mold did they obtain lower readings in the ear canal and then only at frequencies below 300 Hz.

As in other figures, the effect of the vents is observed at the lowest frequencies. Above this the results for the two smaller vents in the real ear increase relative to standard-coupler readings until they are about 4 to 5 dB higher in 2000 to 3000 Hz region. The results for the mold with the largest vent also increase in the low frequencies as expected but in the high frequencies the results for this mold superimpose the results obtained on the standard coupler.

The source of the relatively high levels in the ear canal at the high frequencies is not clear at this time. It may occur because the relatively small size of the space remaining in the ear canal relative to that in the 2-cc coupler which would increase the observed level as suggested by Ewertsen et al. (8). The low-frequency filtering would then be explained by damping of the low-frequency resonance and leaks around the mold when placed in the real ear. Whatever may produce the high-frequency tilt of the ear-canal data these results along with those of Nichols et al. (5) suggest that the high-frequency emphasis provided by hearing-aid receivers on the real ear may be 4 to 5 dB per octave steeper than standard-coupler frequency-response curves indicate. The steepness of this slope would be further enhanced by molds not sealed with Vaseline or by poorly fitting molds.

CHAPTER V

SUMMARY

The effects of earmolds on the frequency response of hearing aids has received only limited attention during the past thirty years. Experimental data concerning the differences between frequency-response curves with vented and unvented earmolds mounted on a 2-cc coupler and situated in real ears are particularly limited. This study was undertaken to increase the information in these areas.

The investigation was divided into four phases:

Phase I: This segment involved a comparison of frequency-response recordings from the hearing-aid receiver mounted on a standard 2-cc coupler with frequency response recordings taken with the hearing-aid receiver mounted on the metal slug (taken from the standard 2-cc coupler) which was fixed to a special 2-cc coupler.

Phase II: This segment involved a comparison of frequency-response recordings from the hearing-aid receiver mounted on the standard 2-cc coupler with frequency-response recordings obtained using the hearing-aid-receiver-earmold(s) mounted on the special 2-cc coupler.

Phase III: This segment involved frequency-response recordings taken from the probe-tube microphone (the probe tubes were inserted in the earmolds and recordings were taken with a one-half inch microphone) with the molds mounted on the special 2-cc coupler. These frequency response recordings were compared with recordings taken from the coupler microphone (one inch microphone). The coupler microphone recordings obtained with the probe tube present were compared with the coupler microphone recordings of Phase II to determine the effects of the presence of the probe tube on coupler sound-levels. The differences between the probe-tube frequency-response recordings in this phase and the coupler frequency-response recordings in the previous phase were subsequently used as a calibration factor for the probe-tube microphone assembly.

Phase IV: This segment involved a comparison of probe-tube microphone frequency-response recordings from the earmold(s) situated in the ear(s) of the subject(s) with frequency-response recordings from the standard 2-cc coupler in Phase I. A comparison is also made of the results obtained across subjects with the various earmolds. In each of Phases II, III and IV a comparison is made of the results obtained with each of the three vented earmolds and the unvented earmold.

Results

Phase I: The differences in frequency response between the hearing-aid receiver mounted on the standard 2-cc coupler on the one hand and the metal slug fixed to the special 2-cc coupler on the other were observed to be no greater than 1 dB at any test frequency.

Phase II: The curve for the unvented mold varies by no more than 2 dB from the frequency response obtained on the standard 2-cc coupler out to 2900 Hz. The results obtained with the vented earmolds mounted on the special 2-cc coupler when plotted relative to the hearing-aid-receiver mounted on the standard 2-cc coupler show a progressive low frequency filtering effect with increased vent diameters. The vented molds show a resonant peak between about 300 and 700 Hz which is progressively sharper and higher in frequency with increased vent diameters. In the mid-frequencies, the vented molds show a progressive drop, reaching a minimum in the 3000 Hz region. The magnitude of this drop is increased with the larger vent diameters. In about the 3000 to 3500 Hz region, the vented molds, as well as the unvented mold, show resonant peaks.

When plotted relative to the unvented mold, the vented molds clearly show a low-frequency filtering effect as well as low-frequency resonant peaks. In the mid-frequencies, the vented molds show a progressive drop with increased vent diameters and in the high-frequency region (about 3000 to 3500 Hz) the resonant peaks are somewhat more pronounced.

Four principal features are evident in the curves: the low-frequency filtering; the low-frequency resonances; the downslope above the low-frequency resonances; and the high-frequency resonant peaks. Calculated power transmission ratios for the bores and vents of the molds show the transmission loss to be greatest for the largest vent and least for the smallest vent. The low-frequency resonant areas, however, tend to alter the power transmission loss of the molds. Low-frequency inertance-compliance resonant frequencies were calculated for the vented molds and found to be in close agreement with the observed low-frequency resonant areas.

The mid-frequency drop seen with the vented molds is explained by mass reactance acting as a low-pass filter. This mass reactance causes a steady reduction with a frequency increase above the low-frequency resonant areas.

The apparent high-frequency resonant peaks seen when the curves are plotted relatively are thought to represent shifts in the receiver's high-frequency resonance produced by changes in the acoustic load into which the receiver is working. The frequency shift appears as an antiresonant-resonant pattern in the relative plots.

Phase III: The frequency-response results taken from the probe-tube microphone (one-half inch microphone), when compared to the special 2-cc coupler frequency response (one inch microphone), show that the presence of the probe tube had little effect on the coupler readings.

Comparing the results obtained in Phase III from the probe-tube microphone with each of the four earmold types with the results obtained from the one inch microphone with each of the earmold types produces four separate estimates of probe-tube microphone calibration. These four estimates differed substantially in certain frequency regions. The differences represent an interaction between the method of measurement and the acoustical circuit through which the sound passes between the source and the measuring instrument.

Phase IV: The frequency response curves seen from the probe microphone with the molds in the ears of the subjects, when plotted relative to the probe microphone frequency-response recordings in Phase III, suggest that the interactions between the acoustic network and the measurement microphone are reduced. The curves in this phase also show a smoothness not seen in Phase III where the 2-cc coupler and probe tube were employed.

The intrasubject variability seen in this phase is quite small and not dissimilar to that seen in previous phases. The intersubject variability, however, is large when compared to the intersubject variability observed in the other phases.

Using a single calibration curve for the probe-tube microphone for all earmold types based on the differences between the responses recorded with the one-half inch probe microphone in Phase III and the one inch 2-cc coupler microphone in Phase II, the mean results in Phase IV were plotted in S.P.L. values. These curves were related to the hearing-aid-receiver response from the standard 2-cc coupler in Phase I. There appears to be a systematic relationship between the results obtained with molds in the ear and the hearing-aid-receiver response on the 2-cc coupler. The increased damping of the real ear is evident in that in the low-frequency resonance areas noted on the coupler the curves for the vented molds do not rise above the curves for the unvented mold. There is a general increase in level with increases in frequency for all of the molds with the results obtained with the two smaller vents rising above the hearing-aid-receiver response curve beyond the 800 Hz region. The curve for the mold with the largest vent also rises beyond 400 Hz but superimposes the curve obtained with the standard coupler in the high frequencies.

Conclusions

1) When compared with the standard 2-cc coupler, the special 2-cc coupler with the standard metal slug attached appears to be an essentially equivalent device for the measurement of the frequency response of a hearing-aid-receiver system.

2) When vents are added to the molds the changes in frequency response can be explained by side branch filtering, compliance-inertance resonances and high-frequency filtering above the low-frequency resonances. Above 2900 Hz, each of the molds appears to modify the high-frequency resonance pattern of the receiver.

3) Substantial differences are noted in the real-ear measurements across subjects. Further research is needed to clarify the reasons for these differences.

4) The metal two-cc 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 2-cc 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.

5) This study has illustrated that measurements can be made on couplers and on real ears with a high degree of consistency. While many of the principal features of the results, particularly those obtained on couplers, can be explained adequately by acoustic theory, certain other features require further investigation. Of particular interest are the differences between real-ear and coupler measures and the differences between real-ear measures on different subjects.

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