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ACOUSTIC ASPECTS OF HEARING AID-EAR CANAL COUPLING SYSTEMS

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CONTENTS

INTRODUCTION

This discussion focuses on the acoustic behavior of the coupling system which connects the receiver of a modern (circa, 1978) over-the-ear hearing aid to the wearer's ear canal. An attempt has been made to emphasize those aspects of the coupling system which are accessible to the individual fitting the hearing aid and may therefore be manipulated to achieve a more desirable output. The topic is discussed under two general headings: issues relating to the sound input system (sections III and IV); and issues relating to the acoustic seal (section V). Much of the discussion applies equally well to eyeglass type hearing aids, but only the acoustic seal section is relevant to in-the-ear models (the sound input system is not accessible to the fitter of in-the-ear instruments). Many of the earmold-related considerations apply to coupling systems utilized with body worn hearing aids, but no attempt has been made to cover this topic in depth. For a discussion of issues involved in coupling systems for body worn hearing aids see Lybarger (1972).

No information is included about the various earmold styles and materials. This information may be found in many sources (Langford, 1976; Smith, 1971; Staab, 1978).

BASIC CONCEPTS

The transmission of an acoustic signal from an over-the-ear or ear-level hearing aid to the user's eardrum is accomplished via a system of tubes, holes, cavities, screens, and/or porous acoustical materials. Typically, this system consists of the following elements: (1) an ear canal; (2) an earmold (which may contain a vent); (3) 40-45mm of polyvinyl chloride tubing having an internal diameter of 1.93mm; (4) an "earhook" (the curved, plastic part which attaches to the nozzle of the hearing aid); (5) 8-10mm of flexible rubber tubing inside the hearing aid (internal diameter = 0.5-1.0mm) coupling the receiver outlet to the hearing aid nozzle; and (6) an air-filled cavity in front of the receiver diaphragm. This system is illustrated in Figure 1. Taken together, these elements make up an acoustical system which affects the propagation of sound waves by the particles of air within the elements in a number of ways. In addition, any discussion of the behavior of this system must take into consideration some of the mechanical aspects of the receiver itself, particularly the effective mass and compliance of the receiver diaphragm system.

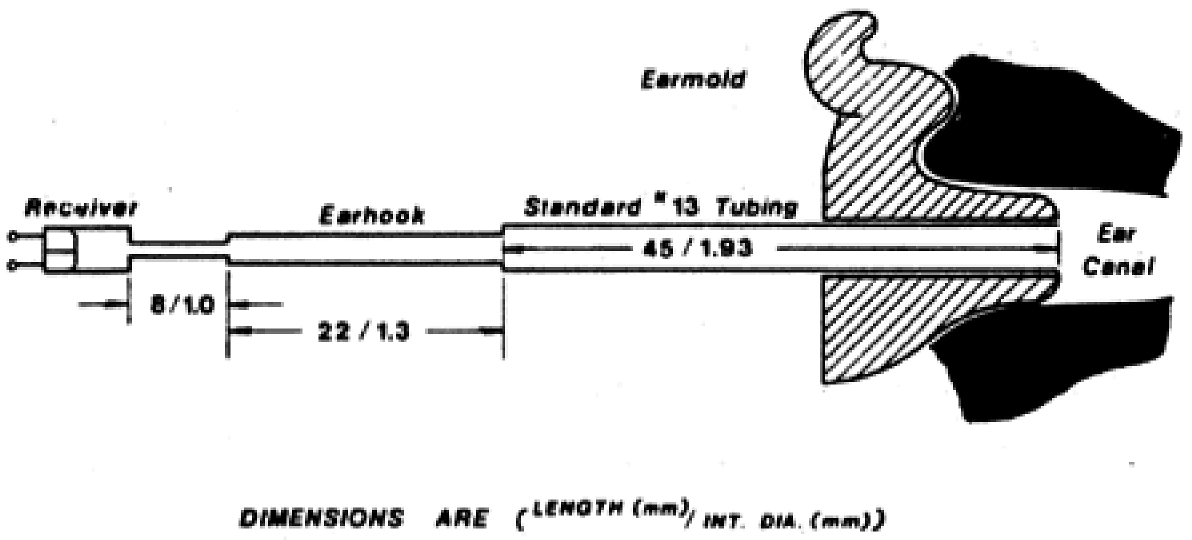

Fig. 1 Schematic illustration of a typical hearing aid-ear canal coupling system.

Much of the behavior of this mechano-acoustic system can be understood and predicted within reasonably close tolerances in terms of a limited number of fundamental concepts: acoustic mass, acoustic compliance, acoustic resistance, acoustic transformers, and resonances. The notion of acoustic impedance is fundamental to all of these concepts. In general, acoustic impedance can be thought of as the opposition to the flow of acoustic energy through a system or element. A system or element may oppose the flow of acoustic energy in one or both of two ways: (1) energy may be temporarily stored within the element and then returned to the source; or (2) the energy may be dissipated through conversion into heat. Either process results in less energy appearing at the output of the system or element than at its input. When energy is stored and returned, rather than dissipated, the impedance of the system or element is called "reactive" or "imaginary". When the energy is actually dissipated, the impedance of the system or element is called "resistive" or "real". Most systems or elements have an impedance which is comprised of both a resistive component and a reactive component. The resistive component is almost the same at all frequencies, but the reactive component changes with frequency.

Acoustic Mass

An acoustic mass, also called an acoustic inertance, exists when a volume of air which is subjected to a vibratory force is set into oscillatory motion as a unit by this force without being compressed to any significant extent. The air inside a length of tubing behaves in this manner as long as the frequency of the driving force is low enough such that the length of the tube is less than about 1/16 of the wavelength (Beranek, 1954). At higher frequencies, some compression of the air in the tube begins to occur in addition to the oscillatory motion, and the behavior of the air in the tube begins to take on some of the characteristics of an acoustic compliance as well as those of an acoustic inertance. The value of inertance of a mass of air in a section of tubing is directly proportional to the length and inversely proportional to the cross-sectional area of the tubing. Hence, inertance increases as length increases or diameter decreases.

The acoustic impedance of an acoustic inertance (i.e., the opposition which the acoustic mass offers to the flow of acoustic energy) is reactive and is directly proportional to the frequency of the signal. At low frequencies, therefore, the acoustic impedance is relatively low and acoustic energy flows into and through the tube with minimum decrease in level. As frequency increases, however, the impedance increases and the signal encounters greater opposition traversing the length of the tube with resultant further decreases in level at the output.

The total length of tubing (about 75mm) from the hearing aid receiver to the medial tip of the earmold (called hereafter the sound input tubing) behaves predominantly as an acoustic inertance up to about 600 Hz. As frequency increases above 600 Hz, the behavior of the tubing is potentially complicated by the appearance of wavelength resonances. At off-resonance frequencies, however, the impedance is primarily reactive and proportional to frequency. In general, low frequency energy flows into and through the sound input tubing with relative ease, whereas high frequency energy encounters considerably greater opposition.

Another element of the hearing aid-ear canal coupling system which behaves as an acoustic inertance is the bore of the earmold vent, if one is present. Since a vent does not usually exceed about 17mm in length, it is safe to anticipate that this element will behave predominantly as an acoustic inertance up to about 2500 Hz. At higher frequencies the effects of wavelength resonances may be seen under certain conditions (see Figure 25).

Finally, the effective mass of the receiver diaphragm acts in a manner which is analagous to the behavior of an acoustic mass. On occasion, this mechanical component enters into the behavior of the system as if it were another length of air filled tubing (i.e., an acoustic mass).

Acoustic Compliance

An acoustic compliance exists when air is enclosed within a cavity having rigid walls. When such an enclosed volume of air is subjected to a vibratory force, the air within the cavity will undergo compression and expansion at the frequency of the driving force, but the volume of air will not execute oscillatory motion as a unit. The air inside a cavity behaves in this manner as long as the frequency of the driving force is low enough such that the longest dimension of the cavity is less than about 1/16 of the wavelength (Beranek, 1954). At higher frequencies the air in the cavity begins to undergo oscillatory motion in addition to compression, and its behavior begins to take on some of the characteristics of an acoustic inertance as well as those of an acoustic compliance. The value of compliance of the air in a cavity is directly proportional to the volume of the cavity. Hence, compliance increases as volume increases.

The acoustic impedance of an acoustic compliance is reactive and is inversely proportional to the frequency of the signal. Here, as frequency increases, acoustic impedance decreases and the signal flows into the cavity with less opposition. Conversely, an acoustic compliance offers a relatively high impedance to low frequency signals.

Cavities within the hearing aid-ear canal coupling system which behave predominantly as acoustic compliances within the frequency range of interest for hearing aids are: (1) The tiny volume of air in the front of the receiver diaphragm; and (2) any cavities which exist within the earmold. In addition, the occluded ear canal is an enclosed cavity and should be expected to behave as an acoustic compliance within some range of frequencies. An investigation of the acoustic behavior of ear canals occluded by earmolds (Studebaker, 1974b) indicated that the maximum effective length of occluded ear canals is probably about 16mm. On the basis of this estimate, one would predict that the occluded ear canal behaves predominantly as an acoustic compliance at frequencies below about 3000 Hz. At higher frequencies the effects of wavelength resonances may begin to be seen.

Finally, the mechanical compliance component of the receiver-diaphragm system acts in a manner similar to the behavior of an acoustic compliance. It presents a reactive impedance which is greater at low frequencies than at high frequencies.

Acoustic Resistance

Acoustic resistance exists whenever acoustic energy is dissipated by frictional losses due to collision of air particles with each other, with the sides of the "waveguide" (e.g., the tube), or with other obstacles. Resistance within an element increases whenever molecules are forced to collide with each other more frequently; for instance, when the sound wave encounters an obstacle which restricts the pathway available for energy flow. Several types of these "bottlenecks" are intentionally used in hearing aid-ear canal coupling systems in order to induce various amounts of acoustic resistance. Mesh screens, sintered metal pellets and lambswool are probably the most frequently employed.

The acoustic resistance element is usually placed within the tubing of the coupling system and its effect on the output of the system depends upon its exact location within the system as well as on the amount of resistance that it offers. The acoustic impedance of an acoustic resistance element is a "real" or "resistive" impedance and is independent of frequency as long as the element does not also contain a significant component of acoustic inertance. Sintered metal pellets and small tubes do incorporate significant acoustic inertance, mesh screens do not (Beranek, 1954). As a result, the acoustic resistance offered by a mesh screen is constant across frequency, whereas the acoustic resistance of tubes and sintered metal pellets increases as a function of frequency. The behavior of pure acoustical resistances is in many ways analogous to that of electrical resistances.

Within the hearing aid-ear canal coupling system there may be several components which provide acoustic damping (i.e., reduction in the level of the signal due to the dissipation of energy by an acoustic resistance element). In a smooth-walled tube of 2mm internal diameter there is a small acoustic resistance due to the collision of particles with the tubing walls. This resistance is inversely proportional to the tube's diameter, and directly proportional to frequency (i.e., resistance of the tube is greater for signals of higher frequency and for tubes of smaller diameter; Beranek, 1954). Additionally, the impedance of the eardrum contains a resistive component (Shaw, 1975). Furthermore, "damping elements" (mesh screens, lambswool, or sintered metal pellets) are often added to the system to reduce the size of unwanted peaks.

The Acoustic Transformer

A principle which is well understood in musical acoustics is the acoustic transformer action provided by a horn which can be defined simply as a pipe with a gradually increasing cross-sectional area. The characteristic configuration of the hearing aid-ear canal coupling system resembles a horn in that it consists of at least three sections of tubing with a gradually increasing cross-sectional area. In the musical realm, the use of a horn-shaped instrument, instead of a cylindrical pipe of the same length, has at least two major effects on the spectrum of the sound emerging from the end (or "mouth") of the instrument. First, the low frequency resonant modes of the musical instrument are at higher frequencies in the horn than in the pipe because the flaring cross-section of the horn makes it appear shorter than the pipe at these frequencies. The higher frequency resonant modes are at approximately the same location in both the horn and the pipe (Benade, 1976). If the circumference of the mouth of the horn is small relative to a wavelength, however, the horn will have resonant modes at the same locations as those observed in a cylindrical pipe of the same length (Beranek, 1954). The exact location of resonant modes for any particular horn depends upon factors such as its length and its flare constant (Benade, 1976).

Second, at frequencies where the length of the horn is greater than a half wavelength, the gradually increasing cross-section functions as an acoustic transformer which causes the output impedance at the mouth of the horn to be more like the impedance of the surrounding air. The result is that acoustic energy is able to flow more easily from the horn into the air. Thus, there is improved transmission of the higher frequency components of the signal into the medium (Beranek, 1954).

In a hearing aid-ear canal coupling, the "horn", which is formed by several sections of tubing, is of such small dimensions in both length and diameter that the full effect of the factors described above may not be seen at frequencies which are of interest in hearing aid work. Even though the dimensions of the typical earmold bore are quite small relative to a wavelength, however, wavelength resonances occuring above about 5000 Hz tend to be located at slightly higher frequencies than anticipated from calculations using the actual measured length of the system. Moreover, since the acoustic transformer action of the horn occurs only at frequencies where the length of the horn is equal to a half wavelength or greater, and since the length of the coupling system is typically about 75mm, the anticipated improvement in transmission should begin to occur for frequencies greater than about 2300 Hz. The impedance change from one end of the horn to the other has a maximum value of S_2/S_1: where S_2 = cross-sectional area of the mouth, and S_1 = cross-sectional area of the receiver end of the horn (Beranek, 1954). Hence, the larger the cross-sectional area of the opening at the medial end of the earmold, the better the transmission of higher frequencies through the coupling system and into the ear canal. It is important to note that the increase in cross-section of the tube must be accomplished in several small increments rather than a single large increment.

Resonant Behavior

A resonance will occur in an acoustic system at a frequency where the reactive component of the impedance decreases to a minimum for a particular element or combination of elements. When this occurs, the opposition offered by that element or combination of elements to the flow of acoustic energy (i.e., its acoustic impedance) is at its lowest and is comprised entirely of its acoustic resistance. At resonance, sound pressure increases and the flow of air particles becomes very great in some portions of the involved element(s). The various resonant peaks which may be seen at the output of the hearing aid-ear canal coupling system are attributable either to resonances between elements (Helmholtz resonances) or within an element (wavelength resonances), or to a co-occurence of, or interaction between, two resonances.

Helmholtz Resonances

A Helmholtz resonance will occur in the system when an element of acoustic mass (e.g., a length of tubing) is adjacent to an element of acoustic compliance (e.g., the volume of air in front of the receiver diaphragm). Recall that the acoustic impedance of an acoustic mass is reactive and increases as frequency is raised. The acoustic impedance of an acoustic compliance is also reactive, but it decreases as frequency is raised. At some frequency, therefore, the reactive component of impedance of the mass element will be equal in magnitude to that of the compliance element, but opposite in direction. At this frequency the reactive components of impedance for these two elements cancel and the total acoustic impedance is comprised only of the acoustic resistance within the elements. Under these conditions the sound pressure within the elements becomes maximum. If this frequency is within the pass band of the hearing aid-ear canal coupling system, a resonant peak will be observed in the ear canal whenever the ear canal is in series with, or one of, the resonating elements. A "simple" Helmholtz resonator is comprised of elements with dimensions which are small relative to a wavelength of the signal frequencies of interest. If either element has a dimension which is a significant proportion of a wavelength, a resonance may be seen which displays a combination of Helmholtz and wavelength resonance characteristics.

The typical hearing aid-ear canal coupling system generates one "simple" Helmholtz resonance. This resonance is observed only when the earmold incorporates a vent, and involves the acoustic compliance of the volume of air in the ear canal as the compliance element and the acoustic mass of the air in the vent bore as the mass element. This applies only for a parallel vent. If the vent is of a side branch configuration, the mass element includes the mass of air in the vent bore plus the mass of air in the part of the earmold main bore which is medial to the intersection of the vent with the main bore. In addition, the typical coupling system generates three resonances which exhibit characteristics of both Helmholtz and wavelength resonances. (These "combination resonances" will be discussed in some detail under Traditional Coupling Systems.)

Wavelength Resonances

A wavelength resonance will occur in the system at any frequency where the input impedance of one of the elements is at a minimum. The simplest wavelength resonances can be defined in terms of elements which have very high or very low resistive impedance at their ends (termination). For example, when an element such as a length of tubing is terminated at both ends by a low impedance as when it opens at each end into free air, the condition of minimum input impedance occurs when the wavelength of the signal frequency is equal to twice the effective length of the tubing element. It is necessary to think in terms of "effective" length rather than actual length since various factors, such as the tubing diameter and the nature of the terminating impedances, often cause a length of tubing to behave acoustically as if it were longer or shorter than its actual measured length. This frequency is the "fundamental" resonant frequency (or first resonant mode) for that element. Other resonant modes occur at all frequencies which are whole number multiples of the fundamental. Hence, if the effective length of the tubing element is 75mm, and the tube is terminated at both ends by a low impedance, the fundamental resonant frequency would be approximately 2300 Hz and higher modes would be seen at approximately 4600 Hz (second mode) and 6900 Hz (third mode). This section of tubing is a "half wave" resonator and is described as being "open at both ends."

When the tubing element is terminated by a very low impedance at one end and a very high impedance (such as a rigid wall) at the other end, a condition of minimum input impedance occurs when the wavelength of the signal frequency is equal to four times the effective length of the element. This frequency is the first resonant mode for that element. In this case, higher resonant modes are seen only at frequencies which are odd number multiples of the fundamental. Thus, if the effective length of the tubing is 75mm and the tube is terminated by a low impedance at one end and a high impedance at the other end, the fundamental resonant frequency would be at approximately 1150 Hz and higher modes would be seen at 3450 Hz (1150 Hz x 3 = second mode) and 5750 Hz (1150 Hz x 5 = third mode). This section of tubing is a "quarter wave" resonator and is described as being "closed at one end".

Wavelength resonances occur because reflections of acoustic energy from the far end of the tube combine with the input signal to result in the formation of a "standing" wave within the tube at that frequency. Reflections of acoustic energy occur whenever an impedance discontinuity exists at the end of the tube. An impedance discontinuity occurs whenever there is a sudden transition from one value of impedance (such as the characteristic impedance of the tubing) to a higher or lower value (such as the low impedance of a fairly large cavity). If the tubing is terminated by an impedance which closely matches its own characteristic impedance, there will be no impedance discontinuity, no reflections of energy, and consequently no wavelength resonances.

When a standing wave develops within a section of tubing, the flow of air particles in the tubing is maximum in one or more locations (antinodes) and minimum in one or more locations (nodes). The number of nodes and antinodes which exist depends upon the resonant mode. The distribution of nodes and antinodes for a length of tubing 75mm long and closed at one end is shown in Figure 2 for the first three resonant modes. This figure will be discussed further with respect to damping in the coupling system.

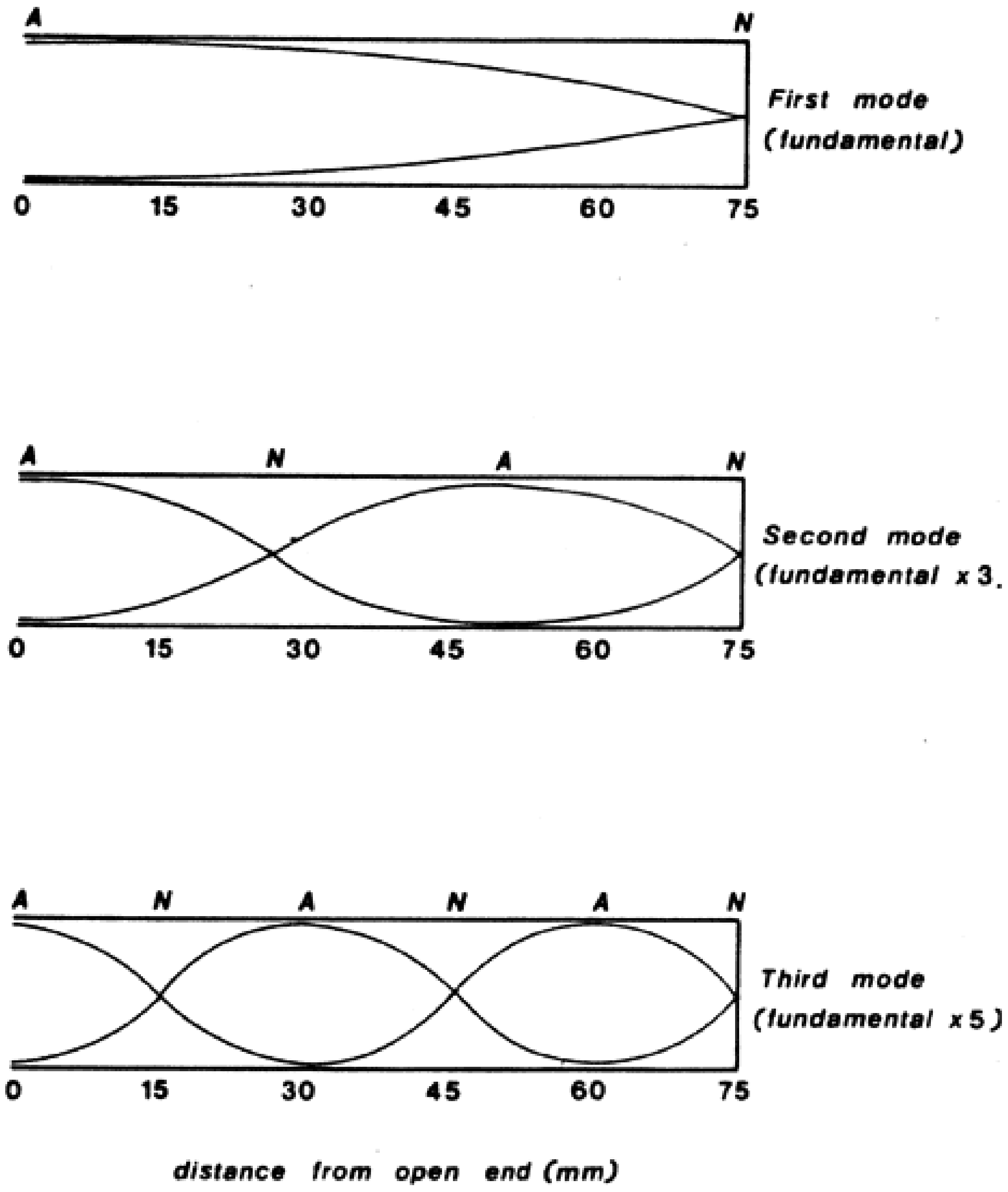

Fig. 2 Schematic illustration of particle flow nodes (N) and antinodes (A) for the first three resonant modes of a 75mm pipe which is closed at one end.

In the hearing aid-ear canal coupling system, the main element which generates wavelength resonances is the total length of tubing which extends from the receiver output to the medial end of the earmold. The terminating impedances for this tubing are not as easy to define as in the examples given above. The ends are neither free air (open) nor hard walls (closed). As shown in Figure 1, the tubing is terminated at one end by the cavity of the ear canal/eardrum and at the other end by the cavity in front of the receiver diaphragm, and the mechanical components of the receiver impedance. Both terminating impedances are therefore reactive and changing with frequency. The ear canal/eardrum termination presents a low impedance throughout the frequency range usable for hearing aids. The termination at the receiver end of the tubing, however, may be either high or low impedance depending on the particular receiver and frequency region involved. If this termination is a high impedance, the length of tubing should behave as a quarter wave resonator. If this termination is a low impedance, the length of tubing should behave as a half wave resonator. The situation is further complicated by the observation that the effective length of this section of tubing may be considerably different from its measured length and is difficult to predict. As Studebaker (1974a) has shown, button type (external) hearing aid receivers present a low impedance to the tubing to which they are attached, and hence produce half wave and multiples of half wave resonances. Knowles and Killion (1978) have indicated that the miniscule dimensions of modern subminiature (internal) receivers cause them to present a high impedance to the tubing to which they are attached and that this results in the production of quarter wave resonances in the tubing system.

Another factor which may influence the production of wavelength resonances in the coupling system is the presence of impedance discontinuities within the sound input tubing which extends from the receiver to the medial end of the earmold. In the typical coupling system there may be two or three such impedance discontinuities where a tubing of smaller diameter joins with a section of larger diameter tubing. As tubing diameter increases, acoustic impedance of the tubing decreases. Whenever such a discontinuity occurs, a portion of the sound wave arriving at the discontinuity will be reflected back towards the source and the remainder will be transmitted onward. If the two impedances are almost equivalent, only a small proportion of the incident sound energy is reflected. As the difference between the two impedances increases, a greater proportion of the incident energy is reflected and less is transmitted. Since energy is reflected at a discontinuity, the potential exists for the establishment of standing waves in the uniform sections between successive discontinuities. In the typical coupling system, each small section of tubing of a given diameter can potentially function as a quarter wave resonator since the impedance at one end is higher and at the other end is lower than the characteristic impedance of the section of tubing involved. Under certain circumstances, therefore, effects of quarter wave resonances for individual sections of the sound input tubing may also be observed in the signal transmitted into the ear canal.

TRADITIONAL COUPLING SYSTEMS

Measurement Procedures

It is considerably more convenient to obtain measurements of sound level in a simple metal coupler such as a 2cm^3 cavity than in a real ear canal. However, several studies have shown that a given input signal will usually produce a level and spectrum in a 2cm^3 cavity which differs in several respects from the level and spectrum produced by the same signal in a real ear canal. One such study by Wiener and Filler (1945) reported results which demonstrated the differences typically observed between real ear and 2cm^3 coupler measurements. They concluded that: (1) resonant peaks which are prominent in coupler measurements are reduced in size or even absent when the same input signal is working into a real ear canal; (2) the frequency location of resonances may vary somewhat between coupler and real ears and from individual to individual; (3) real ears often exhibit acoustic leakage which is not found in coupler measurements and which may result in spectral changes.

The search for a simple replicable "ear simulator" coupler which will produce acoustic results like those seen in a median ear canal, particularly with respect to appropriate location and damping of resonant peaks, has been in progress for many years. The four branch "earlike" coupler designed by Zwislicki (1970) seems to satisfy these requirements very well (Studebaker and Cox, 1977). Since it is not simple and, therefore, relatively expensive, its use has been restricted primarily to research endeavors.

Some of the data reported in this paper were obtained using a simple, cylindrical cavity of 1.5cm^3. These data should be interpreted as showing more prominent resonant peaks than would be seen in a real ear canal with the same sound input system. The location of resonant peaks, however, will tend to be more appropriate in a 1.5cm^3 coupler than in a 2.0cm^3 coupler, since 1.5cm^3 is closer to the equivalent volume of the median ear canal/eardrum occluded by an earmold. Again, the assumption of an excellent acoustic seal in the simulated real ear system is necessary.

In obtaining most of the data presented here, a subminiature wideband hearing aid receiver, biased at 1mA, and electrically driven with a high impedance (essentially constant current) source was substituted for the acoustically driven hearing aid. The resultant data do not show, therefore, the effects of the hearing aid microphone, amplifier, and/or tone controls on the frequency response. Furthermore, although most modern hearing aid amplifiers present a high source impedance to their receiver (Killion, 1978b), some present a low or equal impedance. While these factors would operate to modify the absolute output spectrum of a given hearing aid-ear canal coupling system to some extent, the relative effects which are the main focus of this discussion are validly represented using this simpler instrumentation and may be interpreted as applying to most modern post-auricular hearing aids.

*A Typical System Output**

The dotted line in Figure 3 shows the spectrum measured at the output of a coupling system identical to the one illustrated in Figure 1 with the exception that a Zwislocki coupler was substituted for the real ear canal/eardrum. This system will be referred to hereafter as a "typical" coupling system.

These data demonstrate the five resonant peaks which are observed in the output when a subminiature, wideband receiver is coupled to this system. The peaks have been labelled R1 through R5. The number and location of resonant peaks are specific to this receiver-coupling system combination. However, the coupling system is similar to the most commonly encountered arrangement, and since the three subminiature wideband receivers used in the collection of these data (Knowles BP, BR and BK series) all performed similarly with the various coupling systems, it is hoped that the data shown as the dotted line in Figure 3 are an adequate representation of all such data.

It is instructive to attempt to identify the origins of the various resonant peaks in this spectrum. Such information provides a framework for understanding and predicting the changes in the spectrum which occur when changes are made in the coupling system.

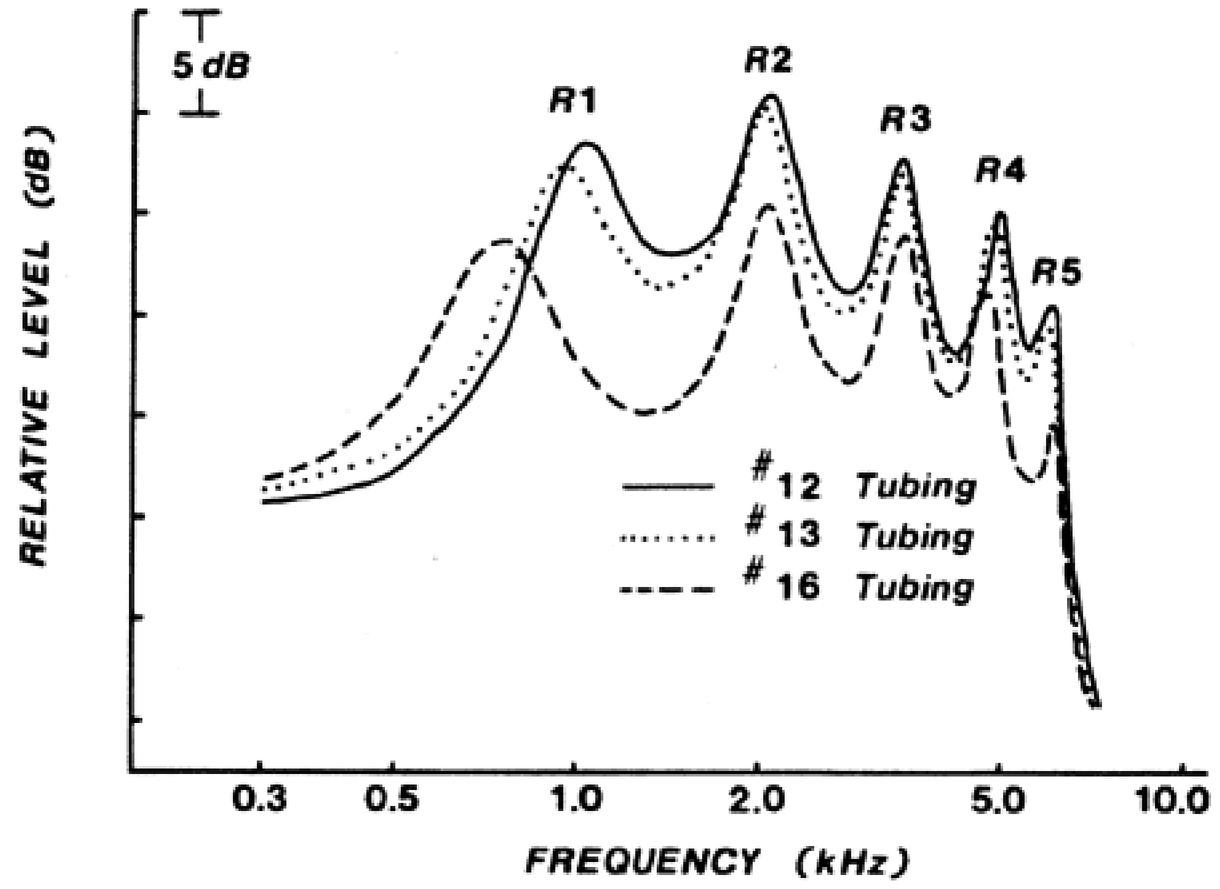

Fig. 3 Effect of changing tubing diameter in a typical coupling system. Data are shown for three standard tubing sizes.

The origin of each resonant peak must be inferred from a study of its behavior when aspects such as length, inertance, or damping of the coupling system are varied. The actual behavior of a resonant peak is compared with the expected behavior under the same conditions, given a particular hypothesis about its origin. The hypothesis is developed on the basis of well understood acoustical phenomena. If a particular hypothesis consistently results in predictions which are fulfilled, the origin of the resonance under study is tentatively identified according to that hypothesis. This approach has been described and utilized by Studebaker (1974a).

When the length, inertance, or damping of the coupling system is varied, the behavior of the resonant peaks identified as R3 and R5 is consistent with the hypothesis that they are the second and third resonant modes of the sound input tubing. The sound input tubing appears to function basically as a quarter wave resonator (Knowles and Killion, 1978). Hence, R3 = fundamental x 3 and R5 = fundamental x 5 as illustrated in Figure 2. The location of R3 (3400 Hz) is consistent with an effective length of 76mm (the measured length of the system was 75mm), whereas R5 is seen at approximately 6000 Hz and is consistent with an effective length of 72mm. The apparent decrease in effective length in this frequency

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*The author wishes to acknowledge the contribution made by Gerald Studebaker in the formulation of this discussion. His suggestions following a review of the first draft resulted in considerable modification of the content.

region is a characteristic finding and is probably due to the effects of the horn shaped coupling system. (See the section on the Acoustic Transformer, page 4.)

When length or inertance of the coupling system are varied, the behavior of R4 is consistent with the hypothesis that it is a Helmholtz resonance produced between the acoustic compliance of the air in the cavity in front of the receiver diaphragm and the acoustic mass of the air in the sound input tubing. Since the length of the inertance element producing R4, the sound input tubing, is a significant proportion of a wavelength in this frequency region, R4 cannot be thought of as a "simple" Helmholtz resonance. Indeed, when the damping of the coupling system is varied, the behavior of R4 displays characteristics typical of both Helmholtz and wavelength resonances. For most purposes, however, it is satisfactory to characterize R4 as a Helmholtz resonance.

A phenomenon which reduces the predictability of resonance peaks in the output from hearing aid-ear canal coupling systems appears to be demonstrated in R2 and R1. When two resonances, for example, a Helmholtz resonance and a wavelength resonance, occur in the system at approximately the same frequency, the two resonances often appear to cancel, partially resulting in resonant peaks appearing at the output of the system at frequency locations which are somewhat higher or lower than their predicted location. It also may be possible for the two resonances to combine, producing a single resonance which is located at an intermediate position between them, and which displays characteristics of both types of resonance.

When aspects of the coupling system are varied, the behavior of R2 displays features which are strongly indicative of both Helmholtz and wavelength resonances. Subminiature wideband receivers appear to have a resonant peak at approximately 2000-2500 Hz which is relatively independent of the coupling system. This resonance may be seen when the receiver is coupled directly to a cavity without added tubing. It may also be seen when the receiver is coupled to any length of tubing as long as the standing waves are removed from the system by "terminating" the tubing at the coupler end with an acoustic resistance element which has an impedance equal to the characteristic impedance of the tubing. (This technique has been described in some detail by Knowles and Killion, 1978). This resonance has been identified by Killion (1978b) as principally a Helmholtz resonance between the mechanical components (mass and compliance) of the receiver diaphragm system.

In addition, data obtained when the length of the coupling system is varied indicate that when the receiver is working into a typical coupling system, as illustrated in Figure 1, the peak identified as R2 also incorporates a half wavelength resonance. The reader will recall that a half wave resonator is terminated at both ends by a low impedance whereas a subminiature receiver presents a high impedance termination and, hence, would not apparently support a half wave resonance. In the frequency region where the mass and stiffness of the receiver's mechanical system are passing through resonance, however, the impedance presented to the tubing coupled to the receiver is comprised of the resistance of the receiver's mechanical system shunted by the compliance of the volume in front of the receiver diaphragm. It is conceivable that this combination may be low enough to appear as a low impedance termination. Under these conditions the coupling system would be terminated by a low impedance at both ends and, therefore, potentially become a half wave resonator. This situation would exist only in the frequency range at or near the receiver's mechanical resonance (approximately 2000-2500 Hz). Hence, to produce a half wave resonance, the coupling system must be of a length appropriate to produce such a resonance in this frequency range. It happens that the fundamental resonant mode for a 75mm half wave resonator occurs near 2300 Hz.

It is suggested, therefore, that the resonant peak labeled R2 in Figure 3 is actually comprised of superimposed Helmholtz and half wavelength resonances. When a tapered coupling system is used (such as the typical system), the half wave resonance appears to be the dominating factor determining the exact location of R2 within the frequency range of approximately 2000-2500 Hz.

It is not possible to identify clearly R1 as either a Helmholtz or a wavelength resonance. When standing waves are removed from the coupling system by terminating the tubing at the coupler end with an acoustic resistance element equal to the characteristic impedance of the tubing, thus preventing reflections, this resonant peak disappears entirely. This finding seems to indicate that R1 is largely a wavelength resonance. Other evidence supports this conclusion. If the location of a damping element in the coupling system is varied systematically, the pattern of damping displayed by R1 is indicative of a quarter wave resonance (see the section on effects of damping); also, if the coupling system is made long enough such that more than one resonant peak appears below the mechanical receiver resonance (R2) these peaks appear at locations consistent with odd numbered multiples of a fundamental quarter wave resonance. R1 has been identified by Knowles and Killion (1978) as a quarter wavelength resonance. The effective length of the system producing this quarter wave resonance, however, is somewhat greater than the measured length of the sound input tube. It would appear that at frequencies below the mechanical resonance of the receiver (R2), the compliance-controlled termination at the receiver end of the sound input tubing functions as an additional length of tubing. By contrast, the location of R3 and R5 indicate that the effective length of the system at frequencies above R2 is quite close to its measured length.

On the other hand, the location of R1 is also influenced by the inertance of the coupling system. This is particularly true when a tapered coupling system (such as the typical system) is used. It has been suggested that the inertance of the mass of air in the sound input tubing may combine with the mass and compliance of the receiver diaphragm system to produce a Helmholtz resonance (Lybarger, 1972; Studebaker, 1974). Data obtained from electrical models of hearing aid receivers support the existence of such a resonance. A resonant peak with many behavioral similarities to R1 produced by a button type receiver was identified by Studebaker (1974a) as a Helmholtz resonance. In addition, certain data obtained with subminiature receivers support the hypothesis that the location of R1 is influenced by a Helmholtz resonance. If the inertance of the coupling system is changed without change in its length, as when the diameter of some or all of the tubing is varied, the location of R1 is clearly affected. This result would not be expected if R1 were a "simple" quarter wave resonance. Movements of R1 with changes in inertance are always in the direction which supports the hypothesis that R1 is a Helmholtz resonance (i.e., increased inertance results in a lower resonant frequency, and vice versa). However, predictions of the extent of movement in R1 based on the hypothesis that the air in the sound input tubing supplies the inertance element for a Helmholtz resonator, however, are almost always in error to some extent, thus indicating that such a simple hypothesis is not sufficient to predict fully the location of R1.

The inertance and the length of the coupling system may be varied at the same time, as when the length is shortened without change in diameter, resulting in both decreased length and decreased inertance. Under these conditions the change in location of R1 tends to be more than that predicted by a Helmholtz resonance hypothesis, and less than that predicted by a wavelength resonance hypothesis.

On the basis of the data reflecting the behavior of R1 when the length, inertance and damping of the coupling system are varied, it is concluded that both quarter wave resonance effects and Helmholtz resonance effects are operating to produce this resonant peak.

Effect of Tubing Diameter

Data illustrating the effects of changing tubing diameter have been reported by many investigators (Lybarger, 1967, 1972, 1978b; Studebaker, 1974a; Langford, 1975; Smith, 1977). In a typical hearing aid-ear canal coupling system, modification of tubing diameter can only be made on that portion of the system which extends from the ear hook to the medial tip of the earmold. The solid, dotted, and dashed lines of Figure 3 demonstrate the effects of changing the internal diameter (I.D.) of this portion of the sound input tubing without changing its measured length. Each data line represents the system output when a subminiature receiver was coupled to a Zwislocki coupler via a typical system incorporating #12 tubing (solid line, I.D. = 2.16mm); #13 tubing (dotted line, I.D. = 1.93mm); and #16 tubing (dashed line, I.D. = 1.34mm). The same electrical input was applied to the receiver in each case.

The main result of decreasing tubing diameter is to increase the inertance and the acoustic impedance of the sound input tubing. This has effects on the output level and on resonant peaks whose location is determined wholly or in part by the inertance of the coupling system. In addition, when tubing diameter becomes very small the acoustic resistance of the tubing becomes appreciable and resonant peaks may be considerably damped. No significant damping effect is seen, however, at the smallest diameter shown in Figure 3.

The increased acoustic impedance of smaller diameter tubing results in a reduction in the absolute level of the signal appearing at the ear canal end of the system. As Figure 3 illustrates, there is a 1-2 db drop in level when #13 tubing is used instead of #12 tubing and a further drop of up to 7 db occurs when #16 tubing is substituted for #13 tubing. One practical result of using a smaller diameter tubing, therefore, is a decrease in both gain and maximum output available from the hearing aid being used with the coupling system.

Recall from the earlier discussion of acoustic masses that the inertance of the air in a given length of tubing increases as the diameter of the tubing decreases. Since Helmholtz resonances are produced by the combined effects of an acoustic compliance and an acoustic inertance, when the inertance is increased and the compliance is held constant, the resonance occurs at a lower frequency. Hence, we anticipate that Helmholtz resonances in the system which involve the inertance of the sound input tubing will move downward in frequency as the diameter of the tubing is decreased. As discussed previously, the peaks labeled R1, R2 and R4 are all thought to be influenced by Helmholtz resonances. Only R1 and R4, however, are thought to be very sensitive to the inertance of the sound input tubing. The general location of R2 is probably determined by characteristics of the receiver's mechanical system, and its exact location seems to be more influenced by the length of the coupling system than by its inertance, especially when a tapered coupling system is used.

Examination of the data depicted in Figure 3 demonstrates that R1 and R4 both move downward in frequency as the inertance of the sound input tubing is decreased. This result is consistent with the hypothesis proposed earlier regarding the origin of these resonant peaks. These data also demonstrate that while the hypotheses are useful in predicting general trends in the behavior of a given resonant peak, they are not sufficiently complex to explain fully this behavior. To illustrate, consider that the inertance of the system incorporating the #16 tubing was approximately 1.5 times that of the system incorporating the #12 tubing. In a "simple" Helmholtz resonator this change in inertance would result in a lowering of the resonant frequency by approximately 18%. In Figure 3, R4 actually migrates 13% less than this prediction, whereas R1 moves 9% more. Clearly, neither R1 nor R4 is behaving like a "simple" Helmholtz resonance. The exact location of these peaks is influenced by other factors, probably including the effective length of each coupling system at the resonant frequency and/or the proximity to other resonant peaks.

Figure 3 indicates further that the locations of R2, R3 and R5 were unchanged when the system's inertance was increased, holding lengths constant. This is consistent with the hypothesis that these peaks reflect wavelength resonances in the typical coupling system.

Of the various changes which occur in the system output due to changing diameter of the sound input tubing, the most significant one from a practical point of view would appear to be the loss of gain and maximum output (with consequent decreased efficiency in battery use) which occurs as tubing diameter is decreased. The downward migration of R1 as tubing diameter is decreased might also be of some significance in certain types of hearing aid fittings, since this results in a relative low-frequency emphasis.

Effect of Tubing Length

Data illustrating the effects of changing tubing length have also been reported by numerous investigators (Lybarger, 1967, 1972, 1978b; Studebaker, 1974a; Langford, 1975; Smith, 1977). For a given individual, the length of tubing appropriate to couple a particular hearing aid to an ear canal is largely determined by the anatomy of the external ear. The only changes which can be made in the length of the coupling system in a real hearing aid fitting are accomplished through changes in earmold canal length; that is, a longer canal incorporates a longer length of sound input tubing and vice versa. An additional factor which requires consideration in this context is the residual volume of the ear canal which remains between the earmold and the ear drum. A corollary of a long canal earmold is a small residual ear canal volume. Earmold canal length and residual ear canal volume vary together in a real hearing aid fitting. They cannot be varied independently.

Figure 4 presents data which are indicative of the extent of change in system output which can be expected to occur due to alterations in earmold canal length. These data were obtained with a subminiature hearing aid receiver coupled to a Zwislocki coupler using a typical coupling system incorporating 38, 43, or 48mm of #13 tubing; the end of the #13 tubing was flush with the medial end of the earmold canal portion. The actual lengths of the canal portions of the earmolds were 15mm (long canal), 10mm (average canal) and 5mm (short canal).

The effects of changing the length of the coupling system by varying the length of the earmold canal portion may be divided into two categories: (1) the effects of decreased tubing length, and (2) the effects of increased residual ear canal volume.

As tubing length (i.e., earmold canal length) is decreased, the inertance of the enclosed air decreases. Consequently, we would expect any Helmholtz resonances which involve the inertance of the air in the sound input tubing to move to a higher frequency. Furthermore, as tubing length decreases, wavelength resonances move upward in frequency. The anticipated result of decreasing the length of the coupling system, therefore, is to move all five resonances upward in frequency. In Figure 4, since the length is changed by a factor of .87 between the longest and shortest system, and inertance is changed by a factor of approximately .92 between the same two systems, we would predict that "simple" wavelength resonances would be moved upward in frequency by approximately 15% and "simple" Helmholtz resonances would be increased in frequency by approximately 4%. Again, these data indicate that the hypotheses suggested previously can predict general trends but not exact results. In Figure 4, all five resonant peaks migrate upwards as system length is decreased. The three peaks which seem most sensitive to tubing length (R2, R3 and R5) show more movement on a percentage basis than the two peaks which seem sensitive to tubing inertance (R1 and R4). The exact change in resonance location, however, does not coincide closely with the predicted changes. The upper cut-off of the system is about 800 Hz higher for the short canal mold than for the long canal mold.

It has been demonstrated repeatedly (Wansdronk, 1962; Dalsgaard *et al*, 1966) that the sound pressure level developed in a cavity by a hearing aid receiver is inversely proportional to the volume of the cavity; that is, the larger the cavity, the lower the SPL for a given volume velocity

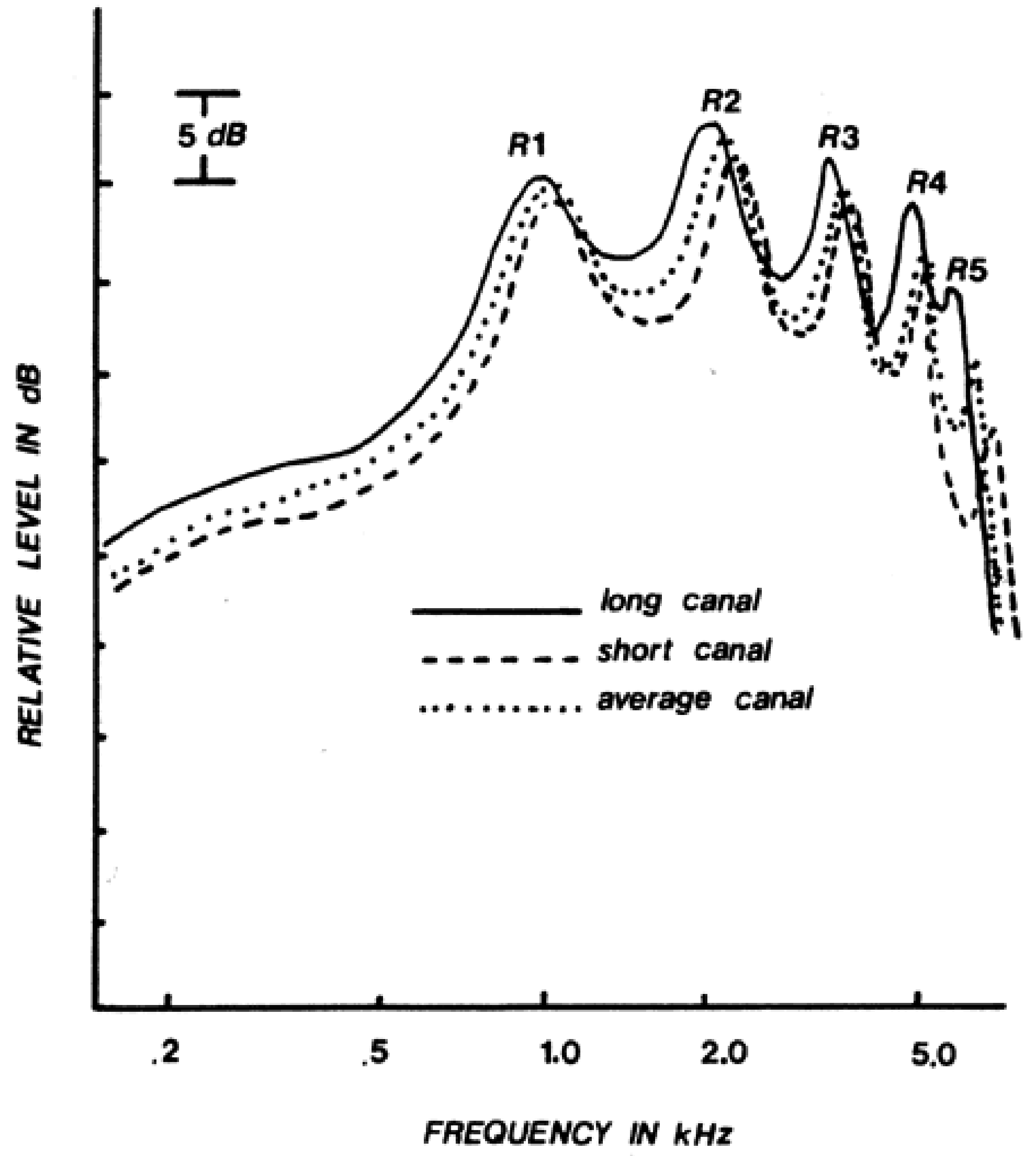

Fig. 4 Effect of simultaneous changes in tubing length and residual ear canal volume in a typical coupling system. Data are shown for short, average and long earmold canals.

input. Obviously a short canal earmold is concomitant with a large residual ear canal volume. We would anticipate, therefore, that as the earmold canal is made shorter the SPL developed in the ear canal (and, thus, at the eardrum) will decrease. This effect is also seen in Figure 4; the level developed at the microphone was about 3 dB less for the short canal earmold than for the long canal earmold. Because of the shifting of resonances, however, this difference varies from 0 dB to 10 dB in different frequency regions.

In summary, there are two main effects of changing the length of the hearing aid-ear canal coupling system: (1) the high frequency cut-off is higher for the short canal earmold, and (2) the SPL developed at the eardrum is lower for the short canal earmold.

Effect of the Earhook

In many hearing aids the earhook is a removable part of the instrument. The one supplied by the manufacturer can be removed and replaced if desired. Since the earhook forms an important element in the hearing aid-ear canal coupling, it is of some interest to examine the effect on the output of the system by changing the earhook. Earhooks supplied with current hearing aids range in length from about 20mm to 30mm, and in internal diameter from about 1.2mm to 1.5mm. Generally they can be classified as short narrow, short wide or long narrow. Comparisons of system output using each of these earhook types in a typical coupling system revealed no great differences attributable to them. The short narrow earhook seemed to perform best, resulting in a 2-3 dB higher output in the frequency range from 4500-6000 Hz.

One type of earhook, the "low-cut tone hook", did have a significant effect on the output of the coupling system. This is basically a long narrow earhook with a very small hole drilled just in front of the hearing aid nozzle. Figure 5 shows the output obtained from a typical hearing aid-ear canal coupling system in which either a long narrow earhook (solid line) or a "low-cut tone hook" (dotted line) was utilized. These data were obtained using a 1.5 cm^3 cavity rather than a Zwislocki coupler. The solid line shows the expected five peak pattern, very similar to that shown in Figure 3. The dotted line indicates that the low-cut tone hook resulted in a considerable change in the system output. Below 1000 Hz, for example, the small hole in the earhook functions very much like a side branch earmold vent (see discussion of venting effects). The vent associated resonance is seen at approximately 230 Hz. This is a Helmholtz resonance involving the volume of air in the coupler as the compliance element and the mass of air in the coupler system medial to the hole in the earhook plus the mass of air in the hole itself as the inertance element. The calculated location of this resonance is 212 Hz which agrees well with the measured location. Above this resonance, and below about 1000 Hz, there is a 10-15 dB, drop in the system's output level. Above 1000 Hz five resonance peaks are seen.

It is likely that the origin of some or all of these five peaks is considerably different from the five peaks seen in the output of the typical system. A tentative explanation is included in the appendix.

From a practical point of view, the major

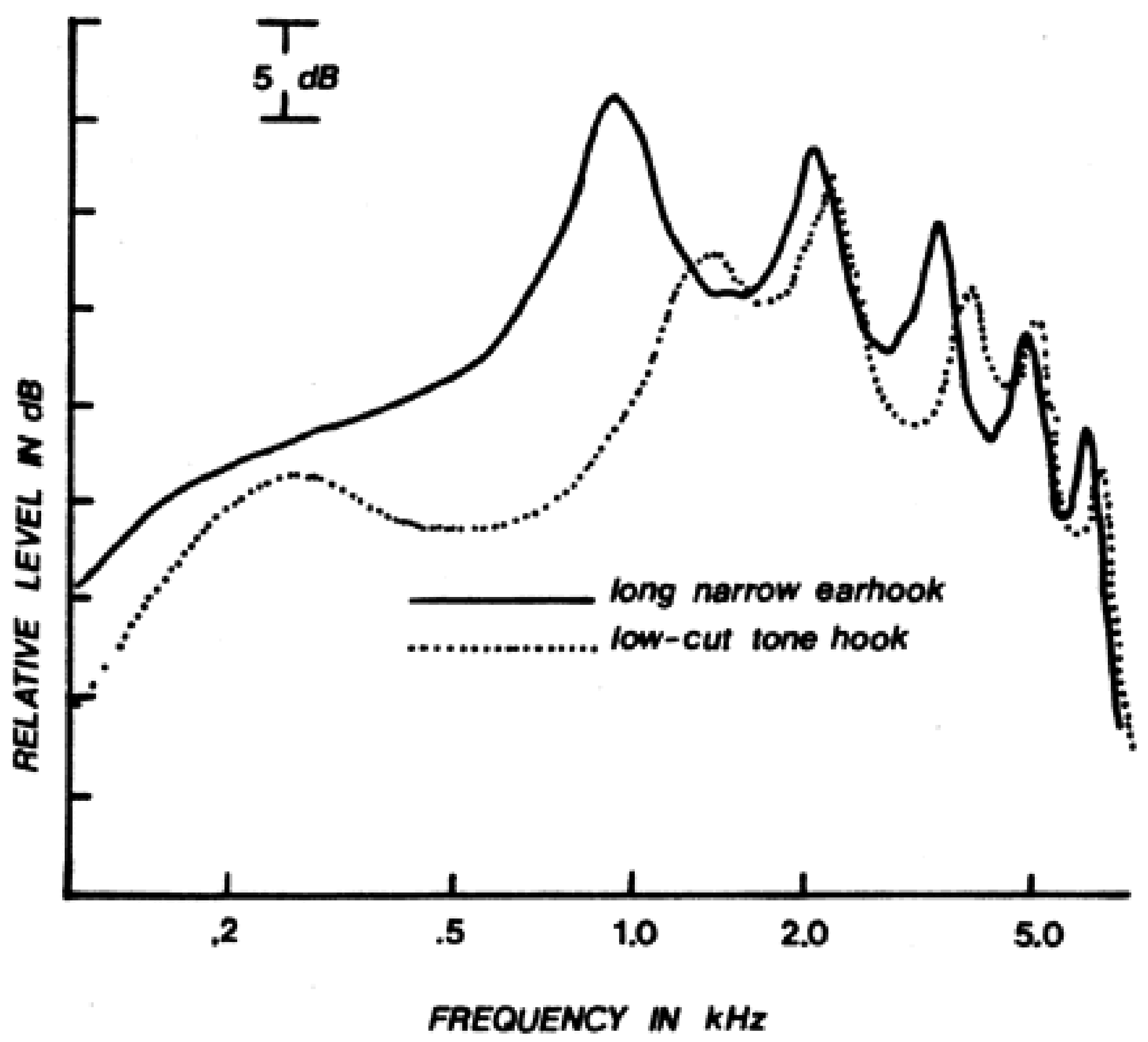

Fig. 5 Effect of substituting a "low-cut tone hook" for a typical earhook in an otherwise typical coupling system.

effect of this low-cut tone hook is a 10-15 dB drop in level from 500-1000 Hz. The resonance appearing at 230 Hz is probably too low in frequency to be of much significance in most hearing aid fittings.

Another factor which may be important in using a "vented" earhook in the coupling system is the lower gain available before audible acoustic feedback begins. Observations of this earhook on one hearing aid, however, did not indicate acoustic feedback to be a major problem.

Effect of Constrictions

A constriction occurs in the hearing aid-ear canal coupling system when the diameter of the sound input tubing becomes smaller instead of remaining uniform or becoming larger as it does in the typical coupling system. Usually the constriction consists of a short length of tubing which is used as a connector. It may be used to join two pieces of #13 tubing or to connect the #13 tubing to the earmold.

Figure 6 illustrates the effect of a constriction consisting of 9.0mm of tubing (I.D. = 1.1mm) inserted between two sections of #13 tubing (44mm and 22mm in length). The output of the coupling system incorporating the constriction is compared with the output obtained from a coupling system consisting simply of 75mm of #13 tubing. The constriction increased the total inertance of the sound input tubing by a factor of 1.25 (approximately) without changing the length of the system. This leads to the prediction that R1 and R4 should migrate downward in frequency by 11.7%, whereas R2, R3 and R5 should remain unchanged. In general, these predictions are verified by the data in Figure 6. R1 and R4, however, actually migrate by 6.9% and 7.3%, respectively.

From a practical point of view, the most significant effect of the constriction in the transmission path is the lowering of R4 since this results in lower high frequency cut-off in the system with the constriction. In general, decreased high frequency cut-off can be expected to result whenever a constriction is incorporated within the coupling system.

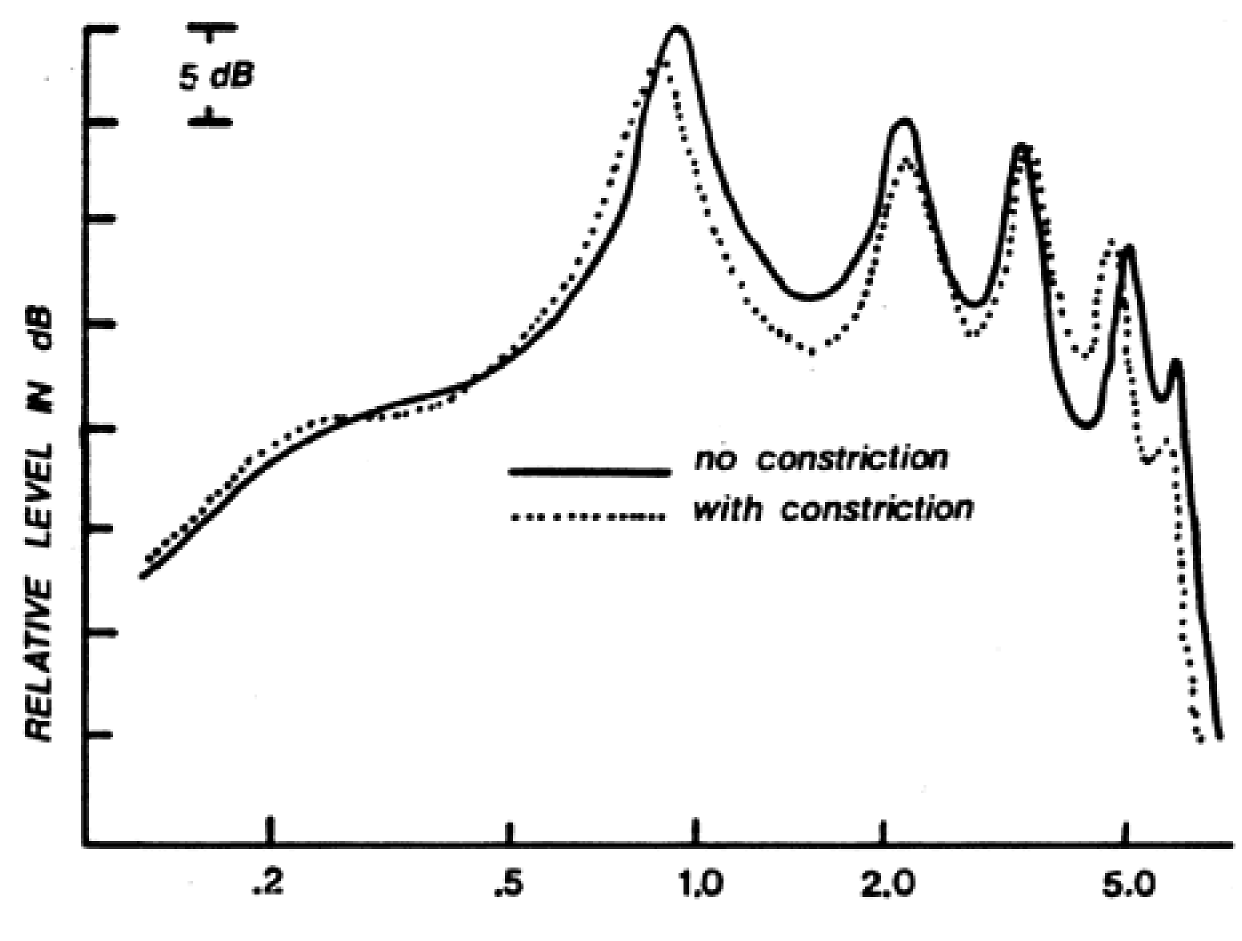

Fig. 6 Effect of a 9mm long constriction in a coupling system consisting of 75mm of #13 tubing.

Effect of Cavities

It has been amply demonstrated (Dalsgaard *et al,* 1966; Lybarger, 1972) that the size of the "recess cavity" in an earmold used with a body-worn hearing aid (the cavity behind the snap ring which accommodates the nubbin of the insert-type receiver) may affect the high frequency cut-off of the coupling system: if the recess cavity is too large the high frequency cut-off is decreased. Consequently, it has generally been recommended that the recess cavity in the earmold be kept as small as possible.

Constructing an earmold with a large recess cavity is equivalent to placing another Helmholtz resonator in the system. In this resonator the volume of air in the recess cavity provides the compliance element and the mass of air in the earmold tubing medial to the cavity provides the inertance element. The presence of the cavity has relatively little effect on the output of the system below the resonant frequency of the cavity-earmold bore combination. At the resonant frequency, a peak appears at the output of the system. Above this resonance the impedance of the earmold bore becomes large relative to the impedance of the cavity. Hence, much of the high frequency energy which would otherwise appear at the output of the system is filtered out by the cavity resulting in a decreased high frequency cut-off.

It has been suggested (Goldberg, 1977) that this principle could be utilized in the hearing aid-ear canal coupling for over-the-ear hearing aids to improve the high frequency output. The technique involves incorporating a cavity of controlled size into the earmold at a known location along the earmold bore. The cavity volume and bore length and diameter are chosen to give a resonant peak at the desired frequency. The presence of this peak effectively boosts the high frequency output. It should not be forgotten, however, that the output above the resonance will be decreased relative to the output of the same system without the cavity. Hence, the potential exists for decreasing the high frequency cut-off of the system and the cavity must be carefully "tuned" if this is to be avoided.

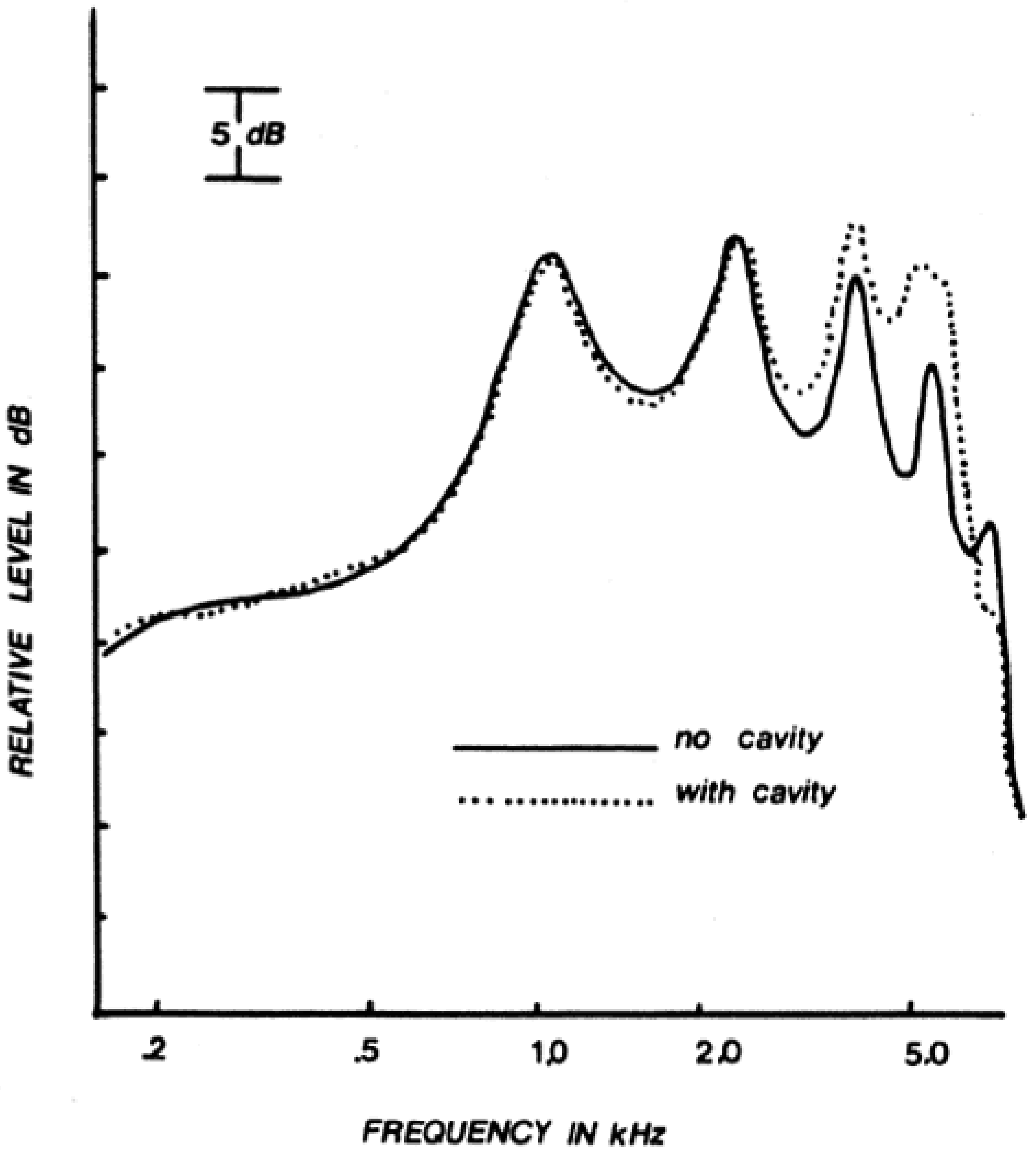

Fig. 7a Useful high frequency boost achieved by use of a cavity in the earmold.

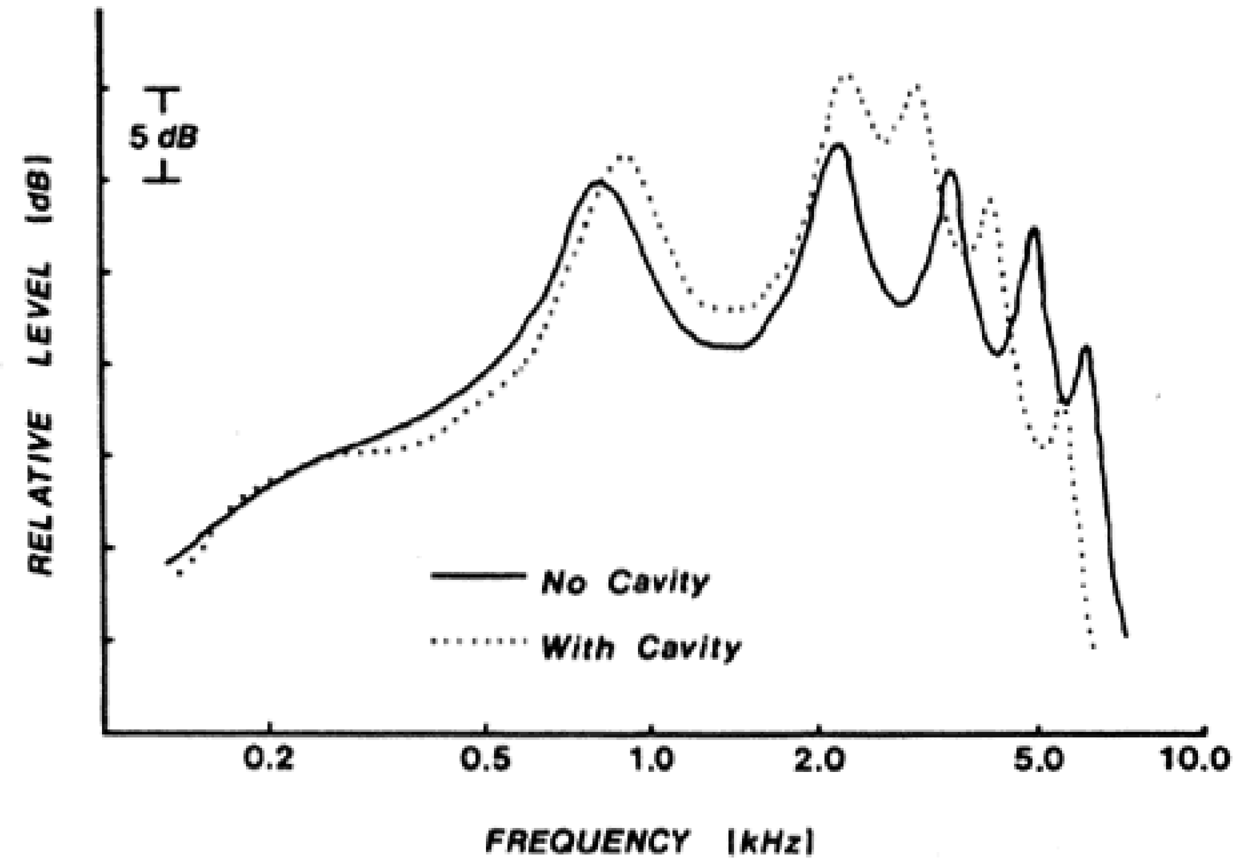

Fig. 7b Possibly detrimental high frequency boost achieved by use of a cavity in the earmold.

Figures 7a and 7b exemplify the use of this technique to boost high frequency output. In Figure 7a the solid line was obtained using a coupling system consisting of a subminiature receiver, approximately 69mm of #13 tubing, 6mm of earmold bore (I.D. = 2.5mm) and a Zwislocki coupler. The dotted line was obtained when a small cavity (volume approximately .042cm^3) was incorporated into the system at the beginning of the earmold bore section of the sound input tubing. The Helmholtz resonance between the cavity and the earmold bore medial to the cavity occurred at approximately 5000 Hz. The resonant peak imparted a satisfactory high frequency tilt to the output without significantly lowering the high frequency cut-off of the system.

The solid curve of Figure 7b was obtained using a coupling system consisting of a subminiature receiver, 75mm of non-standard tubing (I.D = 1.4mm) and a Zwislocki coupler. The dotted curve was obtained when the last 12.6mm of tubing was replaced by a cavity (volume approximately .075cm) and a bore section 9.5mm long (I.D = 2.0mm). The cavity/bore resonance in this system occurred at approximately 3000 Hz and resulted in a considerable boost in this region. However, unavoidable decrease in level above the resonance caused a lowering of the high frequency cut-off of the system by approximately 1000 Hz. It is conceivable that there may be some hearing aid fittings in which this lowering of the high frequency cut-off is of no consequence; however, this will not usually be a desirable outcome. In general, as long as the cavity/bore combination is tuned to resonate at or slightly above R4, a useful high frequency boost will be obtained without an undesirable lowering of high frequency cut-off.

Effect of Damping

As discussed previously, an element of acoustic resistance dissipates acoustic energy through frictional losses due to collisions of air particles. This results in less energy appearing at the output of the coupling system. Usually, acoustic resistance elements are employed in a hearing aid-ear canal coupling system with the intention of reducing the height of some or all of the resonant peaks in the output. Both the value of resistance used and its physical location within the system are important factors in determining the actual amount of damping achieved for any particular resonance. This issue has been discussed by several investigators (Studebaker, 1974; Lybarger, 1978a; Knowles and Killion, 1978).

To explain the behavior of an acoustic resistance element in a hearing aid-ear canal coupling system, it is helpful to consider a simple electroacoustic analogy in which electrical voltage is analogous to sound pressure, electrical current is analogous to the rate of flow of air particles through a small section of the tubing, and electrical resistance is analogous to acoustical resistance. A moment's consideration of Ohm's law (voltage = current x resistance) will result in the conclusion that for a given value of resistance, the voltage dropped across the resistor will increase in direct proportion to the current flowing through the resistor. In the analogous acoustical system, therefore, the sound pressure "dropped" in a given acoustic resistance element will increase in direct proportion to the flow of air particles through it. It fllows that effective damping of a particular resonant peak requires that the acoustic resistance element be placed in the system at a location in which the flow of air particles for that resonant mode is high.

Reference to Figure 2 shows that maximum flow of air particles (antinodes) occurs at specific locations within the tubing for the first three resonant modes of a quarter wave resonator. The reader will recall that the peaks designated R3 and R5 in the output of a typical coupling system are thought to represent the second and third quarter wave resonant modes of the sound input tubing, respectively. Furthermore, the peak designated as R1 is thought to be influenced by (or partly comprised of) the fundamental quarter wave resonance of the sound input system. In addition, the peak designated as R2 is considered to be partly comprised of a half wave resonance of the sound input tubing. Although not shown in Figure 2, resonant modes for a half wave resonator also may be described in terms of patterns of nodes and antinodes which represent regions of minimum and maximum particle flow, respectively. The fundamental resonant mode (which corresponds to R2) is characterized by an antinode at each end and a single node in the middle of the tubing element.

We would anticipate that an acoustic resistance element placed at an antinode for a particular resonant mode would cause the maximum possible damping (for that value of resistance) for that resonant peak, whereas the same element placed at a node would be relatively ineffective in damping that resonant peak.

In a "simple" Helmholtz resonator, the resonance is produced at a frequency for which the wavelength is much greater than any dimension of the resonating elements. Under these circumstances, the flow of air particles in the inertance element would be expected to be almost uniform throughout its length (i.e., there is no pattern of nodes and antinodes). These conditions occur, for instance, with the Helmholtz resonance associated with an earmold vent. One would anticipate, therefore, that a given acoustic resistance element within the vent would provide the same amount of damping regardless of its placement. When the length of the inertance element producing the Helmholtz resonance is a significant proportion of a wavelength of the resonant frequency, the flow of air particles is not uniform everywhere in the tubing. Consequently, placement of the resistance element is an important factor in determining the damping of such a resonance. Recall that R4 is thought to be primarily a Helmholtz resonance, but it is produced at a frequency which is between the second and third quarter wave resonant modes of the sound input tubing. It is difficult to predict *a priori* the damping of R4 which will be achieved by a resistance element at different locations within the sound input tubing. The same set of considerations applies to the damping of R1.

These principles are demonstrated in Figures 8a and 8b. These data were obtained using a coupling system consisting of a modern subminiature receiver, 75mm of #13 tubing and a 1.5cm^3 cavity. A 680 ohm mesh screen damping element was used and its effect on the height of R1 through R5 was measured with the damper located at the coupler end of the tubing (the 0mm position), and also at 15mm, 30mm, 45mm, 60mm and 75mm from this end. Figure 8a depicts the amount of damping (in decibels) observed in each damper position for the three resonant peaks designated R1, R3 and R5. Figure 8b shows the analogous data for the two resonant peaks designated R2 and R4.

The data in Figure 8a are perfectly consistent with the damping predicted from a consideration of the locations of nodes and antinodes shown in Figure 2. In Figure 2 the first node is shown to have a single location of maximum flow of air particles which occurs at the open end (analogous to the 0mm position). As one progresses towards the closed end of the tube, the flow of air particles decreases monotonically. One would predict, therefore, that for a given acoustic resistance, maximum damping of this resonant peak would occur with the resistance element placed at the 0mm position with progressively less damping occuring as the damping element is moved towards the 75mm position. This pattern appears very clearly in the R1 data in Figure 8a.

Similarly, the damping of R3 shown in Figure 8a reflects the two antinode pattern depicted in Figure 2 for the second resonant mode. Also, the damping shown for R5 reflects the three antinode pattern depicted for the third resonant mode. In general, when the damping element is placed at or near an antinode, maximum damping occurs; when the damping element is placed at or near a node, minimum damping occurs.

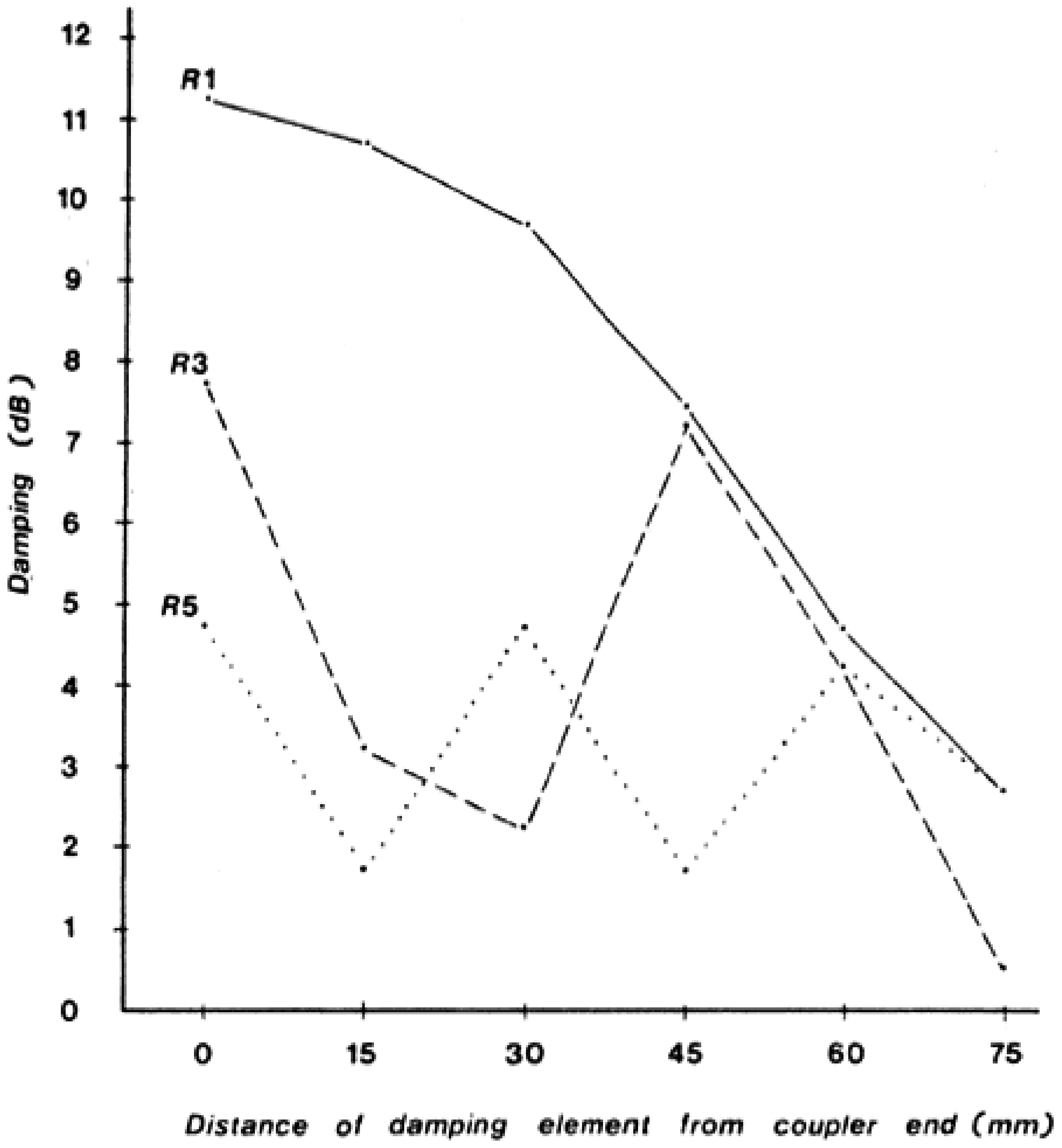

Fig. 8a Damping of R1, R3 and R5 achieved by a 680 ohm mesh screen damping element placed at six locations in a 75mm coupling system.

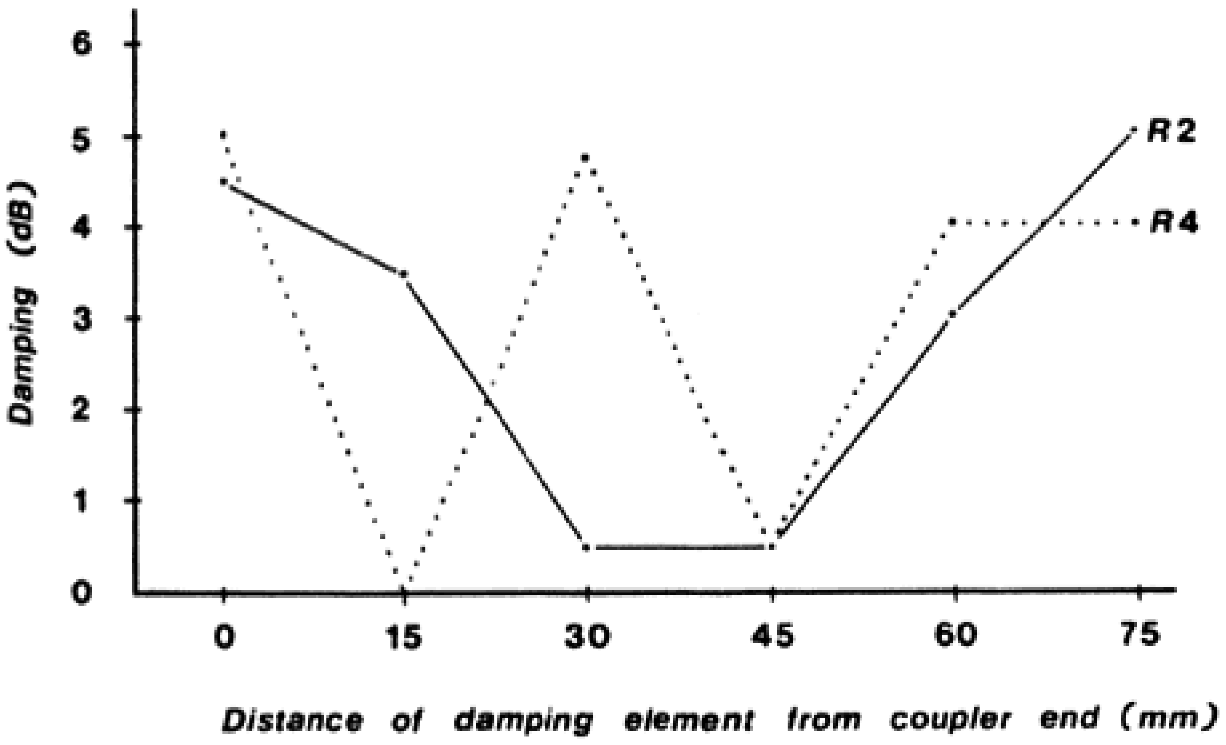

Fig. 8b Damping of R2 and R4 achieved by a 680 ohm mesh screen damping element placed at six locations in a 75mm coupling system.

Figure 8b demonstrates the damping achieved for R2 and R4 with the same 680 ohm damping element. The pattern of the results for R2 clearly suggests the influence of a fundamental half wave resonance since maximum damping is found with the damper located at either end (antinodes) and minimum damping found with the damper in the middle of the tubing (the only node location).

The damping achieved for R4, also seen in Figure 8b appears to be very much influenced by the distribution of antinodes which characterizes the third quarter wave resonant mode (see Figure 2): maximum damping is achieved when the damper is placed at predicted antinode locations. The result is a damping pattern very similar to that seen for R5. In fact, the only substantial difference in the results shown for R4 and R5 is in the amount of damping achieved at the 75mm position. With the damper in this location low damping is measured for R5 (this is consistent with expected behavior for a wavelength resonance) but high damping is measured for R4 (this is consistent with behavior expected for a Helmholtz resonance).

Several general statements may be made concerning the effectiveness of acoustic resistance elements in damping the resonances of a hearing aid-ear canal coupling system for ear-level hearing aids utilizing modern subminiature receivers. First, all resonances, regardless of their origin, are maximally damped (for a given acoustic resistance) when the damping element is placed at the 0mm position. This position would correspond to the tip of the earmold canal. Second, the peaks identified as R2 and R4 are equally well damped when the damping element is placed at the receiver end of the system (the 75mm postion), but R1, R3 and R5 are very poorly damped by a damper in this position. Third, when the damping element is placed in a position intermediate between 0mm and 75mm, its effect on the various resonant peaks will differ according to its exact location within the system and may be predicted reasonably well using the data in Figures 8a and 8b.

Figure 9 shows output curves for an undamped typical coupling system (dotted line); the same system with a 680 ohm damping element at the tip of the earmold (0mm position) (dashed line); and again with the 680 ohm damping element at the junction of the earhook and the #13 tubing (approximately a 42mm position). Observe that the damping obtained in both positions can be predicted in a relative sense from Figures 8a and 8b. The absolute values of damping are different in Figure 8 probably because the typical coupling system incorporates more inherent damping than does the simpler system used to obtain the data shown in Figures 8a and 8b.

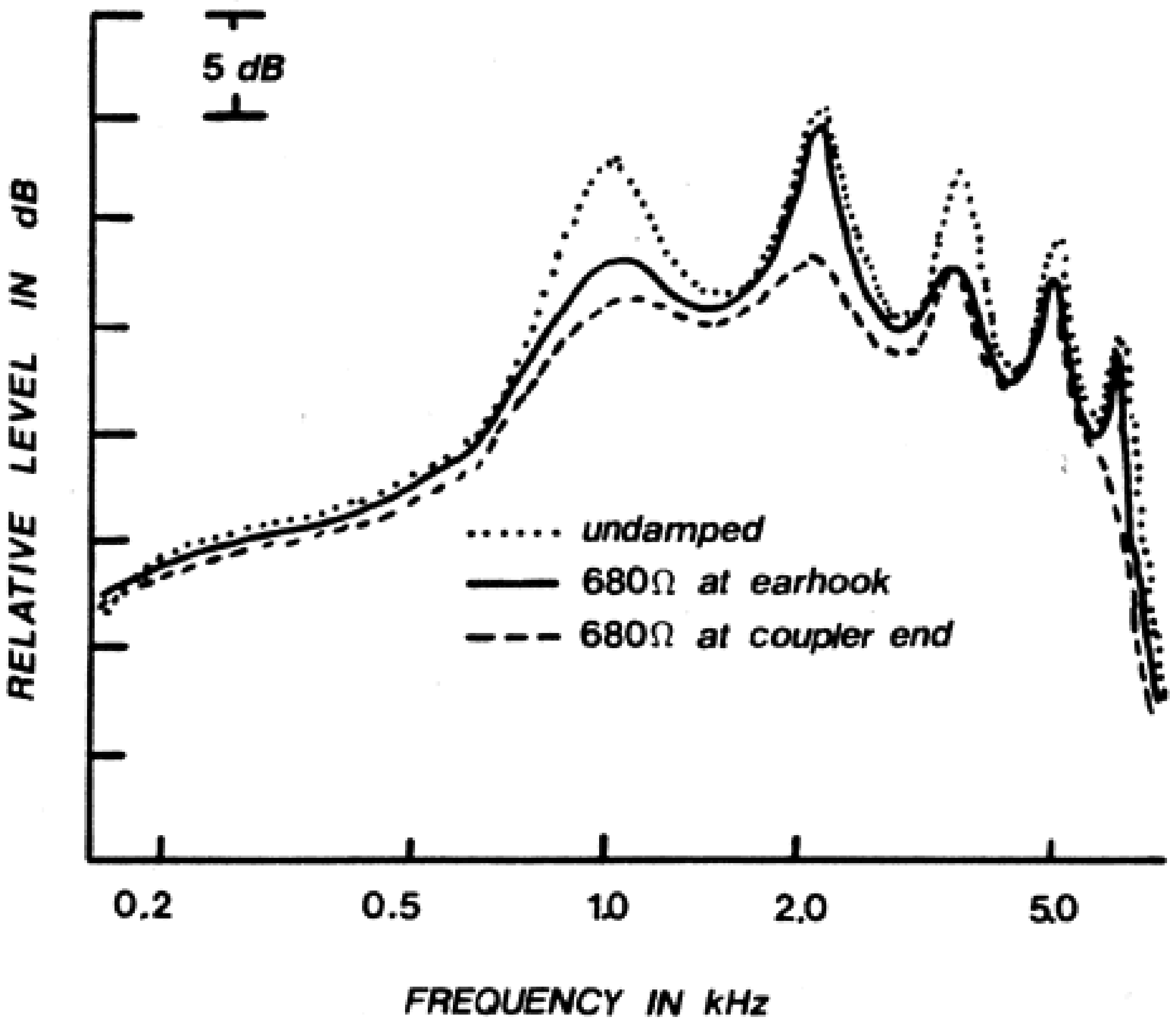

Fig. 9 Output curves for an undamped typical coupling system and for two damped coupling systems (with the damping element at a different location for each curve).

Clearly, the most effective location in the coupling system for a damping element is at the tip of the earmold canal. This fact has been known to hearing aid designers for many years. A damping element in this location is not a practical choice, however, since cerumen and moisture may accumulate in the damper resulting in a radical change in its properties, or complete blockage of the sound input tube. If a single damping element is to be placed within a typical coupling system, the optimal location will depend upon the desired outcome. For example, a damper at the 60mm position (within the earhook approximately 5mm from the nozzle of the hearing aid) will give approximately equal damping of all resonances although no peak will be maximally damped. A damper at the 15mm position (far enough back from the earmold tip to be protected from debris in the ear canal) will give relatively effective damping of low frequency resonances (R1 and R2) while providing little damping for the high frequency peaks R4 and R5, thus imparting some high frequency emphasis to the output.

It is important to note that the data shown in Figures 8a, 8b and 9 were obtained using a single 680 ohm mesh screen damping element. If a damper of larger or smaller value is used, a larger or smaller amount of damping will be seen, although the relative effects should remain the same as long as the damping element does not significantly exceed the characteristic impedance of the tubing in which it is located (approximately 1400 ohms for #13 tubing; 3000 ohms for the earhook). If the damper has an acoustic impedance greater than that of the tubing in which it is located, the damper takes on the characteristics of a high impedance termination and the resonance pattern of the tubing may be substantially changed.

Improving the Acoustic Transformer

The reader will recall the typical coupling system which incorporates three sections of tubing with progressively increasing internal diameter, has the properties of an acoustic transformer for higher frequencies: the increasing cross-sectional area of the sound input tubing results in better high frequency transmission through the system than would occur if the diameter of the entire length of tubing remained constant and equal to that of the first section, or if the receiver were coupled directly to the ear canal. An important aspect of the typical coupling system is the extension of the section of #13 tubing completely through the earmold to its medial tip. The acoustic transformer action of the coupling system can be improved by shortening this section and cementing it only a few millimeters into the earmold bore. The remaining length of the earmold bore then constitutes another section of tubing with slightly increased diameter (the internal diameter of a bore drilled to accommodate standard #13 tubing will be approximately 3.0mm). As a result, the sound input tubing will consist of four sections rather than the typical three; the mouth of the "horn" will be larger and the high frequency transmission will be better than seen with a typical coupling system. This technique for improving the acoustic transformer action of the coupling system (illustrated in Figure 10) has been recommended by at least one hearing aid manufacturer for several years. Lybarger (1978a) gives credit to Knowles for having first suggested this technique.

The amount of high frequency boost achieved by this earmold modification depends upon the [effective] length of the final section of tubing (i.e., the "earmold bore" section). The maximum effect is seen at the frequency corresponding to a quarter wave resonance for this section. Killion (1977) suggests a length of 17mm, and Lybarger (1978a) favors a range of approximately 16-19mm. Earmolds made to these recommendations have a maximum boost in the 4500-5500 Hz region. The increase in high frequency output relative to the output of the typical system is 5-7 dB.

As the length of the earmold bore section decreases, the region of maximum effect moves to higher frequencies and the effect seen in the frequency range useful for hearing aids (up to about 6000 Hz) is smaller. If the measured length of the bore section is as short as 10mm, the boost in the 4-6 kHz region is about 3 dB.

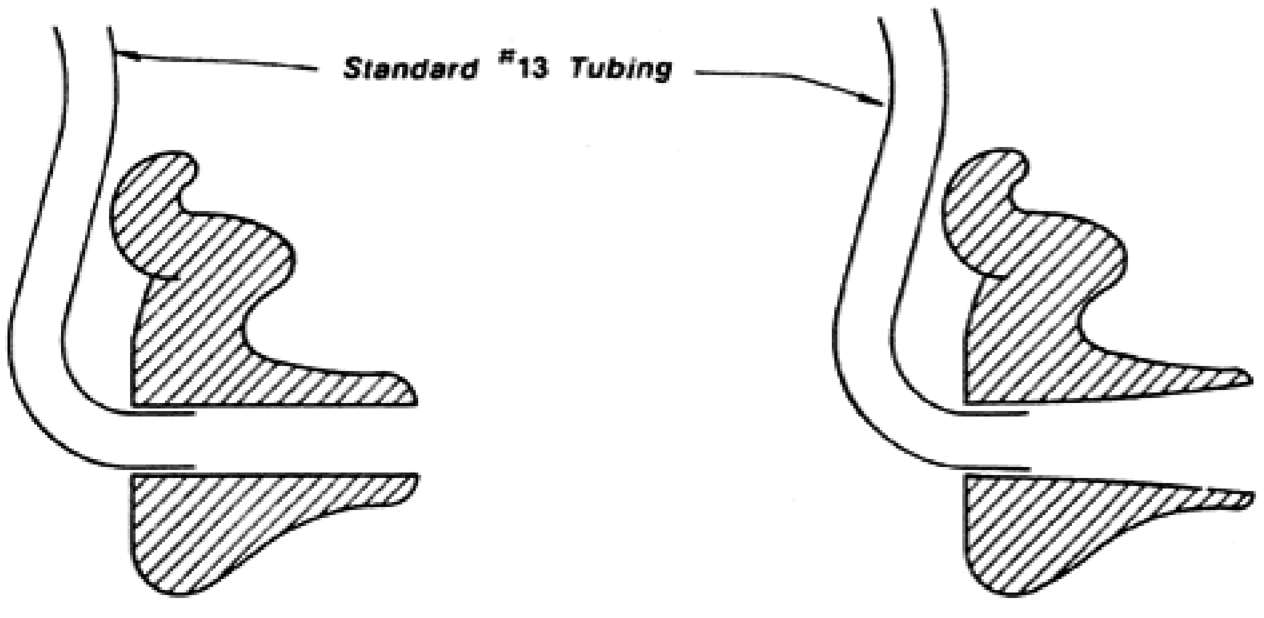

Fig. 10 Schematic illustration of the earmold portion of a four section coupling system with a uniform section of earmold bore (left) and with a "belled" section of earmold bore (right).

Figure 11 shows the effect of an earmold bore section of 14mm. The solid curve provides a reference condition: it was obtained using a coupling system consisting of a subminiature receiver, 75mm of #13 tubing, and a Zwislocki coupler. The dotted curve represents the output of the system when a section of #13 tubing was shortened to 61mm and the remaining 14mm of the sound input tubing was provided by the earmold bore (I.D. = 2.9mm). An average boost of about 4-5 dB is seen in the 4-6 kHz region and the high frequency cut-off is extended by approximately 500 Hz.

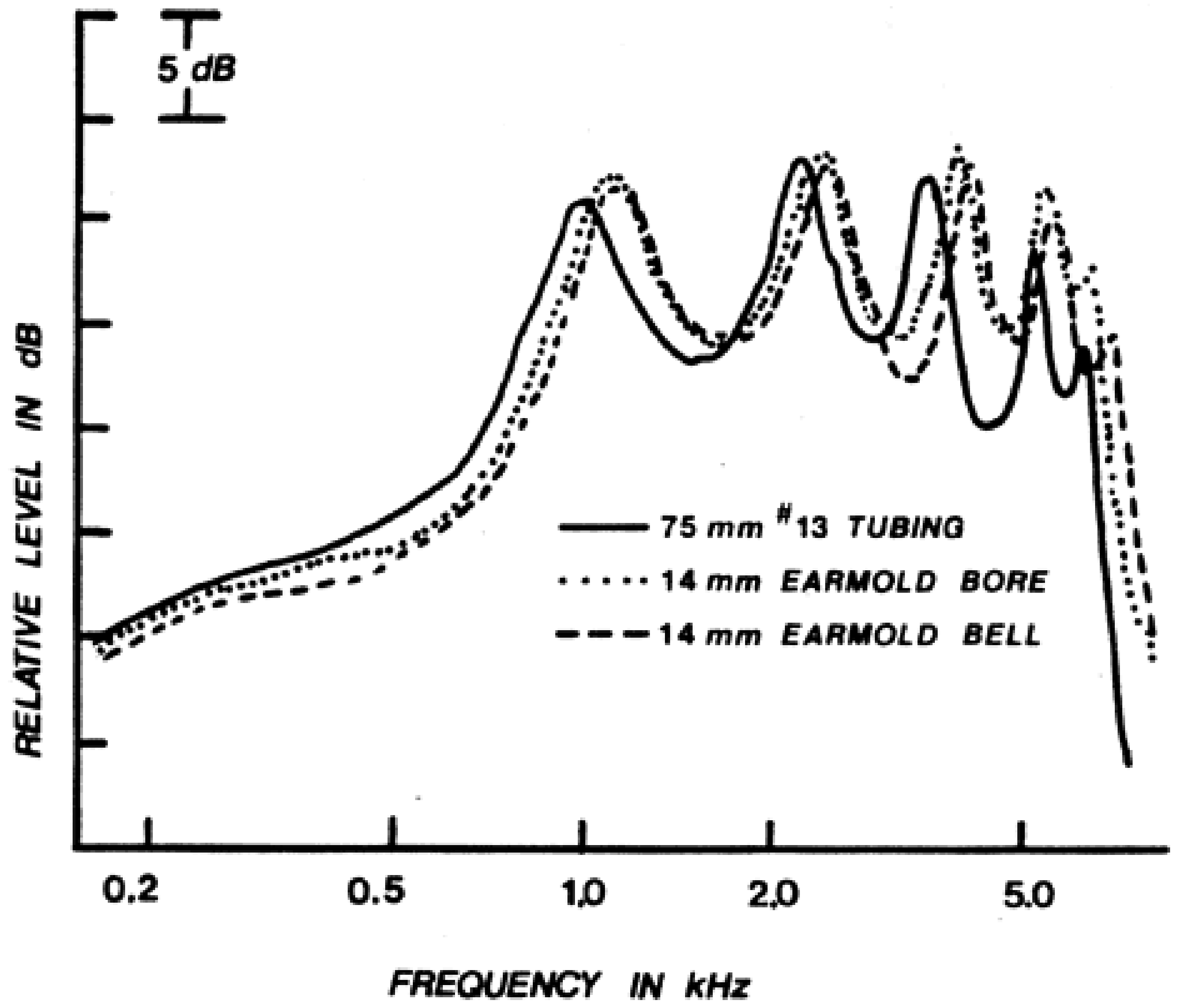

Fig. 11 Illustration of improvement in high frequency output due to use of wider earmold bore section in the coupling system. A uniform bore section (dotted) and a belled bore section (dashed) are compared with a coupling system consisting of 75mm of #13 tubing (solid).

The maximum length of this fourth section for any given coupling system is limited by the length of the earmold canal portion. Three to five millimeters of earmold bore are required for firm cementing of the section of #13 tubing. The remaining length of the earmold bore then determines the length of the fourth section.

To determine a typical length, the earmold bore was measured for each of a sample of 52 earmolds (mainly skeleton and shell types) fabricated by an earmold laboratory for over-the-ear hearing aids. Impressions for these earmolds had been taken by at least ten different audiologists. The average length of the earmold bore was 14.3mm and the standard deviation was 2.76mm. If these figures are representative of typical earmolds, it would appear that relatively few earmolds for post-auricular hearing aids have canal portions long enough to permit cementing of the #13 tubing and still permit a fourth section length of 16mm or more. Killion (1977) has suggested that this problem could be solved by the use of a piece of #9 tubing (I.D = 3.0mm) to extend the earmold bore laterally to the desired length. Another solution would be to employ a standard (full) earmold style rather than the skeleton or shell molds which are typically used with such hearing aids.

Another earmold modification which is basically an attempt to improve the acoustic transformer action of the coupling system is the "belled canal" (illustrated in Figure 10). This modification is accomplished by drilling the canal portion of the earmold into the shape of a funnel with the widest portion opening into the ear canal cavity. For this modification to be effective, the funnel shape should extend as far as possible into the earmold. Again, 3-5mm of earmold bore are needed for firm cementing of the #13 tubing. The dashed curve in Figure 11 shows the system output when the 14mm fourth section of the earmold used to obtain the dotted curve was "belled" to a diameter of 5.5mm at the tip of the earmold. The main result of this modification was to extend further the high frequency cut-off by approximately 500 Hz.

Finally, it is of some interest to note that although the traditional method of maximizing high frequency response has been to use a short earmold canal, this may not be the most effective technique. Figure 12 contrasts the output of a typical three-section coupling system utilizing a short earmold canal (solid curve) with the output of a four section coupling system utilizing a medium length earmold canal. The length of the fourth (earmold bore) section was 15mm (dotted curve).

The two curves have been matched on the height of R1. The total length of the system producing the solid curve was 68mm. The total length of the system producing the dotted curve was 73mm. Despite its longer measured length, the four-section coupling system clearly reveals a relatively better high frequency output than the three-section system. A further advantage of the four-section system is that the longer canal length reduces the likelihood of acoustic feedback problems as a consequence of leakage around the earmold.

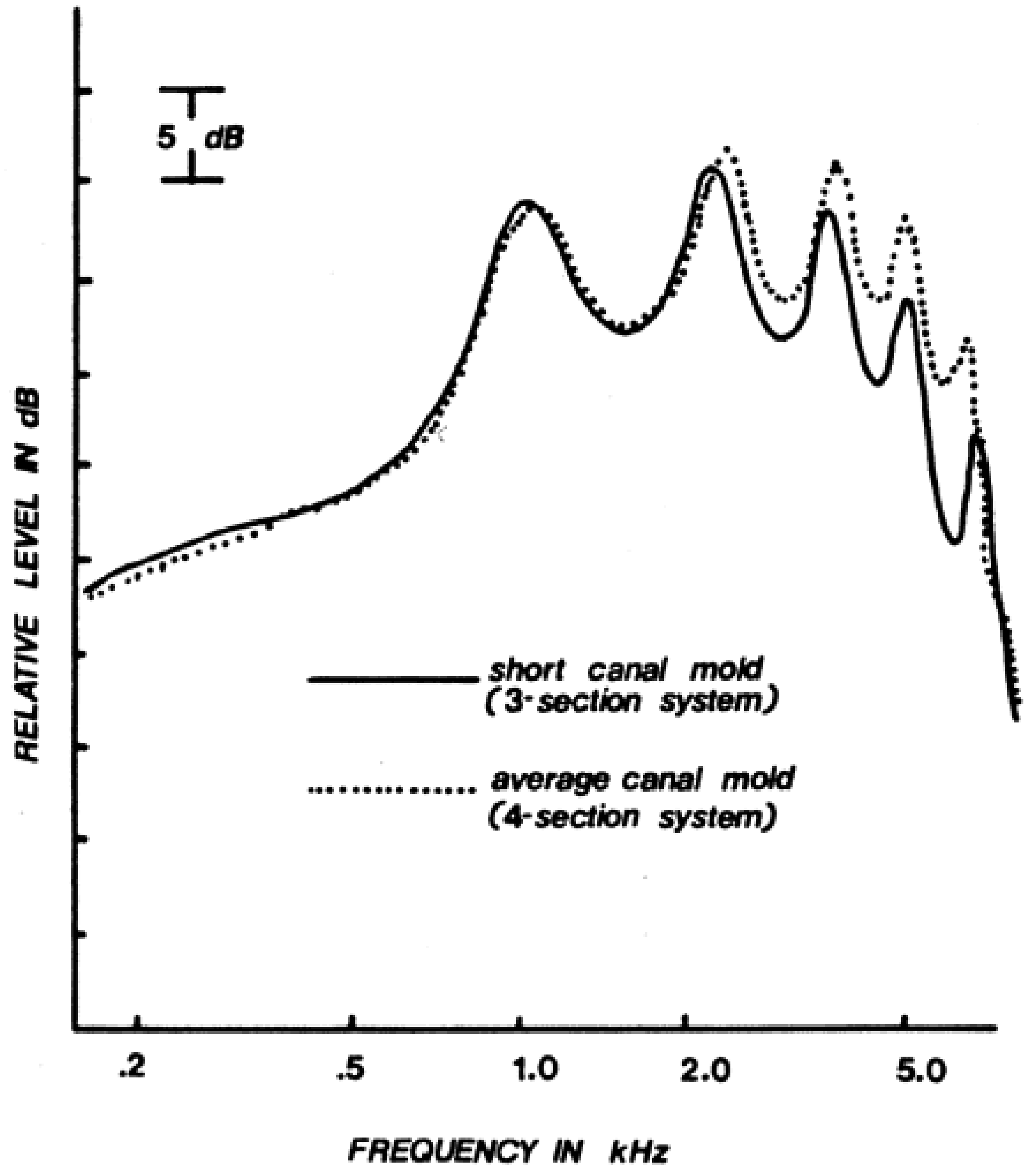

Fig. 12 Comparison of high frequency output achieved with a typical three section coupling system utilizing a short canal earmold (solid) and a four section coupling system utilizing a medium canal earmold (dotted).

INNOVATIVE COUPLING SYSTEMS

In recent years, two novel hearing aid-ear canal coupling systems have been proposed (Killion, 1976; Carlson 1974). Although the two systems are very different, they share a common approach which views the coupling system as a unit rather than a collection of discrete elements, each of which may be varied independently. Another aspect which is shared by both systems is that implementation of each proposed coupling system requires communication and cooperation between the manufacturer and the individual fitting the hearing aid. This represents a break with the traditional position in which the optimal coupling system has been chosen by the person fitting the hearing aid (it is recognized, of course, that manufacturers have always made recommendations regarding appropriate coupling for their hearing aids). Neither system can be employed entirely at the discretion of the hearing aid fitter; both require some participation by the manufacturer.

The Twin-Tube Approach

Carlson (1974) proposed the use of a coupling system which is specifically designed to eliminate peaks in the output which are due to wavelength resonances. He noted, as shown in Figures 8a and 8b, that modern subminiature receivers are not efficiently damped by acoustic resistance elements which are located near the receiver, whereas a damper location near the earmold tip, while effective, is not a practical choice for long term use. The system he proposed to solve this dilemma results in cancellation rather than damping of most wavelength resonances. Cancellation is achieved through the use of an additional length of tubing located as a side-branch on the typical coupling system. The length and internal diameter of the side-branch tube are equal to the length and internal diameter of the portion of the sound input tubing which extends from the sidebranch to the tip of the eamold. This sidebranch tube is terminated in a rigid cap. The result is a parallel combination of two identical lengths of tubing, one terminated in a low impedance (the ear canal), and the other terminated in a high impedance (the rigid cap).

As discussed in the previous section concerning wavelength resonances, pages 13-18, the input impedance of the tubing with the high impedance termination will be minimum at odd numbered multiples of the quarter wavelength frequency and maximum at even numbered multiples of the quarter wavelength frequency. The input impedance of the tubing with a low impedance termination will be minimum at even numbered multiples of the quarter wavelength frequency and maximum at odd number multiples of the quarter wavelength frequency. As a result, one parallel branch of tubing always presents a relatively low impedance and the impedance of the load seen by the receiver is thus controlled by dampers located in series with each branch. When these dampers are chosen to have an acoustic resistance equal to the characteristic impedance of the tubing, the total effect is to eliminate virtually all wavelength effects in the system; R1, R3 and R5 essentially disappear from the output, while R2 and R4 are still present but are damped. The resulting frequency response has the following properties: (1) it is much smoother than seen with a typical system as, for example, in Figure 3; (2) the high frequency output is decreased in the region where it would normally be boosted by R3 and R5; and (3) the overall output level is somewhat decreased due to energy losses associated with the damping elements. This system results in a frequency response with a smaller peak-to-dip ratio than that seen in the output of a typical system. In exchange for this smoother response, however, it is necessary to sacrifice output level, especially in the higher frequencies.

Carlson suggested methods which could be used to conceal the side branch tube in over-the-ear and eyeglass hearing aid styles. Provision for addition of the side branch tubing would have to be made by the hearing aid manufacturer. The actual installation of the side branch tube and damping elements would be made in some cases by the manufacturer and in other cases by the hearing aid fitter.

The "Earmold Plumbing" Approach

An approach which has been whimsically entitled "earmold plumbing" has been developed by Killion and discussed in several papers (Killion, 1976, 1977, 1978a; Knowles and Killion, 1978). The primary aim of this approach is to improve the acoustic transformer properties of the typical coupling system with the intention of increasing the high frequency output of the system. Secondarily, acoustic damping is strategically employed to reduce the height of resonant peaks.

As discussed earlier, the typical coupling system, consisting of three sections of tubing of gradually increasing diameter, reduces, to some extent, the impedance mismatch between the receiver and the ear canal. It was also noted earlier that the use of a four-section sound input tubing can provide better high frequency transmission than that of a three-section system. The earmold plumbing techniques discussed by Killion utilize sound input systems which consist of five or six sections resulting in greatly improved transmission of high frequency energy to the ear canal.

Several sound input systems have been described by Killion (1976, 1977, 1978a). These have been designated according to the high frequency cut-off and the increase in level from 1 kHz to the high frequency cut-off. The most recent papers have focused on a "6R12" design (6 kHz cut-off; rising 12 dB from 1 kHz to 6 kHz) and an "8.5R8" design. It is important to note that these designations describe the system output only when measured using an ear-simulator coupler such as the Zwislocki coupler. An ear simulator coupler will itself provide about 7 dB of gain at 6 kHz relative to 1 kHz. Hence, if 6R12 or the 8.5R8 systems are evaluated using a "flat" coupler such as 2cm^3 cavity, the high frequency slope will appear less steep.

There are two requirements of the earmold plumbing systems which can only be fulfilled by the hearing aid manufacturer; they are beyond the control of the individual fitting the hearing aid. First, these coupling systems are designed incorporating a small capacitor across the receiver terminals inside the hearing aid. This capacitor boosts the high frequency output by 1-3 dB and produces a smaller peak-to-dip ratio (i.e., a smoother frequency response curve). The coupling systems may be used without the capacitor at the expense of some high frequency output and slight increase in peak-to-dip ratio. Second, it is necessary for the hearing aid to utilize a modern subminiature receiver which presents a high acoustic source impedance at all frequencies of interest, and that this receiver be driven by an essentially constant current electrical source. These are engineering considerations which are controlled by the manufacturer. Without this high impedance source, the 6R12 and 8.5R8 coupling systems produce a different output spectrum (this will be discussed in more detail below). Earmold plumbing systems which can be driven successfully by a low impedance source are currently under development (Killion, 1978b).

The 6R12 sound input system is a five-section system incorporating about 27mm of #13 tubing and 18mm of earmold bore of which the lateral 8mm has an I.D. = 3.0mm and the medial 10mm has I.D. = 4.0mm. The #13 tubing is slipped about 5mm over the earhook of the hearing aid such that the actual length of #13 tubing in the system is 22mm. In addition, two 680 ohm mesh screen damping elements are located in the # 13 tubing, 20mm and 35mm from the tip of the earmold, respectively.

Prototype systems may be constructed from lengths of plastic tubing which have the appropriate internal and external diameters. Figure 13 shows the output of one such prototype 6R12 system (solid line) compared with the output of a typical three-section system (dotted line) with each system coupled to a Zwislocki coupler and driven by a receiver with the same electrical input. The relative smoothness and high frequency emphasis of the 6R12 system is obvious. The purpose of presenting the data in Figure 13 is to demonstrate the output control which is available to the hearing aid fitter through modifications of the acoustic aspects of the coupling system. Thus, the data were obtained without the capacitor across the receiver since this modification is not available to the hearing aid fitter. The omission of the capacitor results in slightly less high frequency output: the rise in level from 1 kHz to the high frequency cut-off is 10.5 dB rather than 12 dB. The high frequency cut-off obtained with this 6R12 system was 5.4 kHz rather than 6.0 kHz. The reason for this discrepancy is not obvious but might be related to small, unintentional changes in the designated dimensions. Nevertheless, it is clear that the 6R12 coupling system can provide a relatively smooth, rising frequency response at the average eardrum. Many hearing aid fitters would feel that this is more desirable than the highly peaked low frequency emphasis output obtained with the typical coupling system. It is also important to note that little sacrifice in output level is necessary to obtain this more desirable spectrum since the overall output level of the two systems is very nearly the same. In practical terms, this results in efficient battery consumption when the 6R12 system is used.

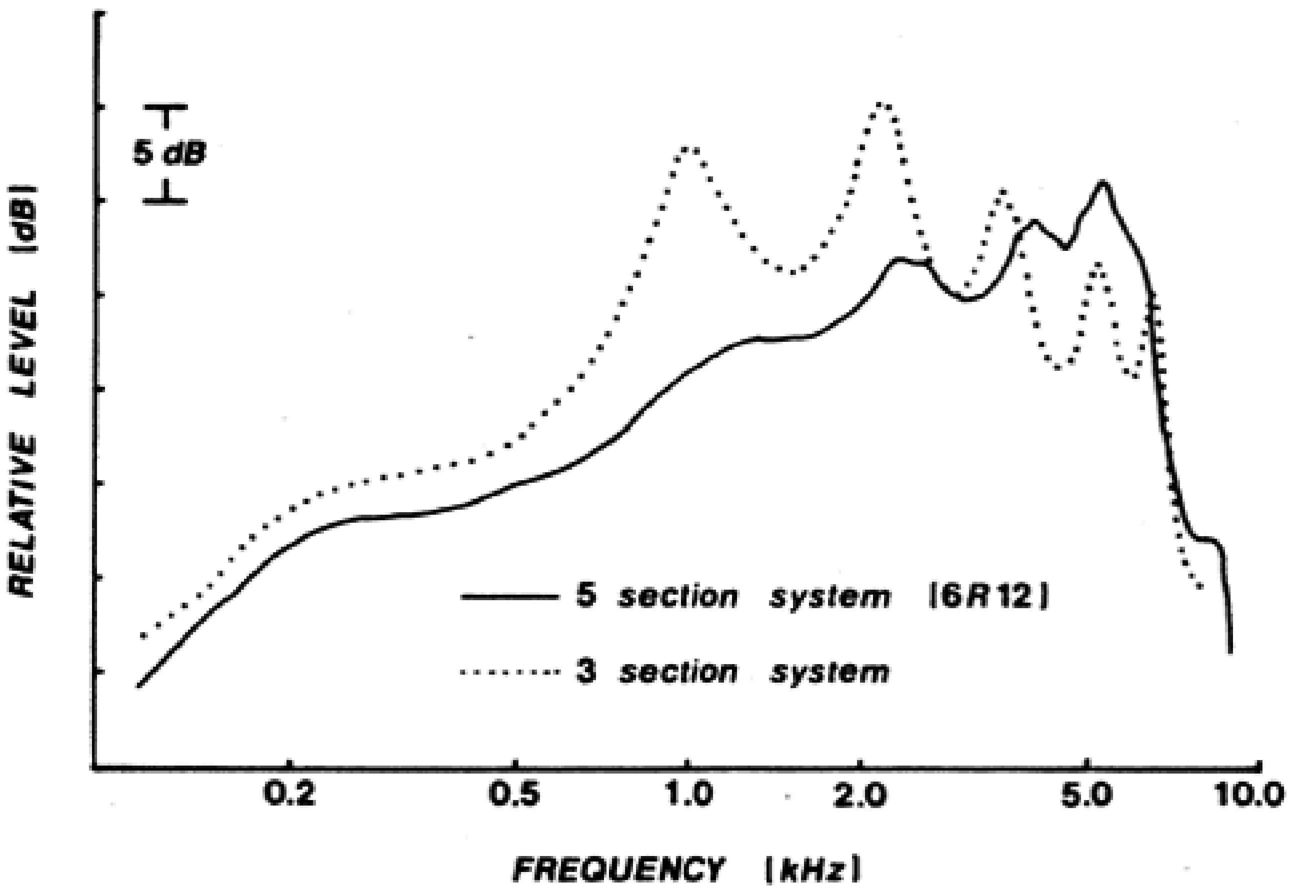

Fig. 13 Comparison of output obtained from prototype five section coupling system a "6R12 earmold" (Killion, 1977) and a typical three section system.

As noted earlier, it is necessary for the hearing aid receiver in the 6R12 system to be driven by an essentially constant current electrical source if the desired output is to be obtained. Since the electro-mechanical coupling of the receiver is beyond the control of the hearing aid fitter, it is of interest to assess the change in output spectrum to be expected if the electrical source impedance is low (constant voltage) rather than high (constant current). Figure 14 shows the output spectra obtained using a 6R12 system with essentially constant current drive (solid line) and with essentially constant voltage drive (dotted line). These curves have been matched arbitrarily at

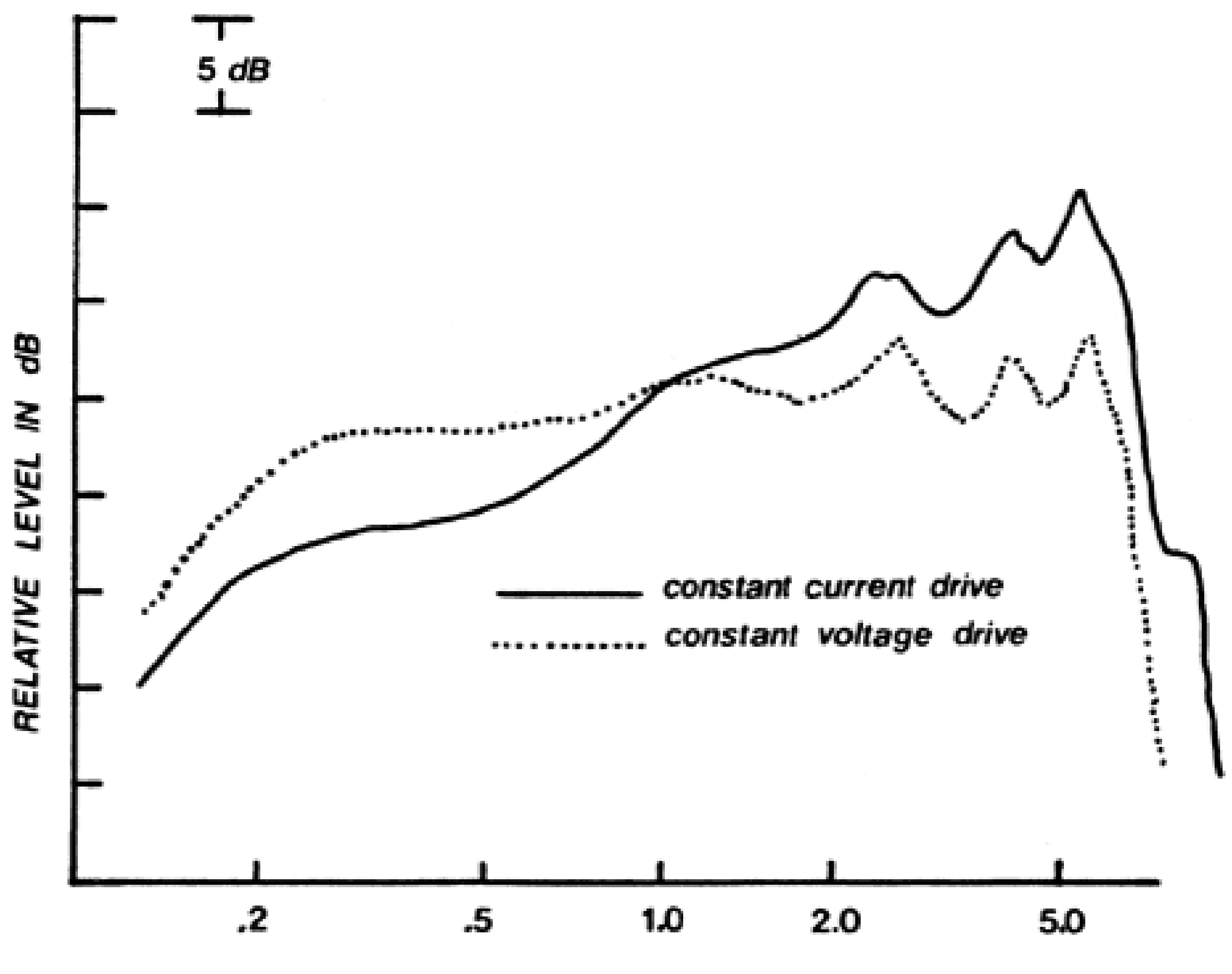

Fig. 14 Comparison of 6R12 earmold and subminiature receiver output with essentially constant current drive (solid) and essentially constant voltage drive (dotted). These curves have been matched at 1 kHz.

1000 Hz. Clearly, the high frequency emphasis is not obtained when the receiver is driven by a low impedance. Nevertheless, the output observed (dotted curve) is relatively smooth and broad-band and may still be more desirable than the output obtained from the typical coupling system.

Solutions have been suggested (Killion, 1978a) for some of the problems which may occur in implementing a 6R12 coupling system.

If only a shell-style earmold is available, the earmold bore may not be long enough to incorporate the 3mm and 4mm portions of the system (about 22mm of earmold bore is needed). In this case, sections of plastic tubing of the appropriate dimensions may be used lateral to the earmold. Also, if the dimensions of the ear canal are oval rather than round and the final section of 4mm diameter cannot be accommodated, Killion (1978a) has noted that the same result can be obtained utilizing a section of approximately the same cross-sectional area (for example, a 3 x 5mm oval).

The 8.5R8 coupling system, as the designation implies, extends the output to almost 9 kHz with an accompanying high frequency boost of about 8.0 dB above 1 kHz. This is a six-section coupling system in which the final section has a 5.0mm diameter. A large ear canal is required for the implementation of this system.

THE ACOUSTIC SEAL

In the foregoing discussion, the assumption was made that the earmold in the coupling system described provided a good acoustic seal (i.e., that there was no significant leakage of acoustic energy from the ear canal around or through the earmold to the outside air). When the low-cut tone hook is used, potential exists for the escape of acoustic energy to the outside air but this leakage does not involve the earmold. In many hearing aid-ear canal coupling systems, there is significant acoustic leakage; either unintentionally or intentionally created. The effect of this acoustic leakage on the spectrum and level of the signal received at the eardrum is often quite important and warrants close scrutiny. Effects of intentional and unintentional acoustic leakage will be discussed separately.

Intentional Acoustic Leaks: Vented and Open Earmolds

Intentional acoustic leaks are created by boring an additional hole (known as a vent) through the earmold. Earmold vents may be wide or narrow, long or short, unobstructed or damped. In the extreme case, the vent may be so large that nothing remains of the canal portion of the earmold except the minimum amount necessary to retain the sound input tubing. This variety of vented earmold is known as an "open" earmold. The issues involved in open molds are slightly different and are discussed separately.

Measurement Procedures

Several studies have shown that measurements of the effects of earmold vents using 2cm^3 couplers are not good estimates of those same effects observed in real ear canals (Studebaker and Zachman, 1970; Cooper and O'Malley, 1975; Studebaker, Cox and Wark, 1978). Conversely, it has been shown that when an excellent acoustic seal is achieved by the earmold (i.e., there is no leakage around the earmold), measurements of the effects of earmold vents in real ear canals and in a well sealed Zwislocki coupler gives essentially the same results (Studebaker and Cox, 1977). The data reported here revealing the effects of earmold vents were obtained using a Zwislocki coupler.

Acoustic Effects of Vented Earmolds

Vented earmolds have been incorporated into hearing aid-ear canal coupling systems for at least 30 years (Berger, 1974). For the most part, the use of a vent has been recommended with the purpose of achieving a high-pass filter effect (Grossman and Malloy, 1944) thereby attenuating undesirable low frequency energy; however, the precise acoustic effect of any particular earmold vent in a real ear is not easy to predict.

The effects of earmold vents obtained when the earmold is mounted on a hard-walled cylindrical cavity such as 2cm^3 cavity have been measured by numerous investigators (Dalsgaard *et al,* 1966; Studebaker and Zachman, 1970; Cooper *et al,* 1975; Lybarger, 1975; Sung *et al,* 1975). A number of investigators have reported measurements made in real ear canals (McDonald and Studebaker, 1970; Studebaker and Zachman, 1970; Weatherton and Goetzinger, 1971; Lybarger, 1975; Studebaker and Cox, 1977; Studebaker *et al,* 1978). From these and similar studies, an overall picture of the acoustic effects of earmold vents has gradually emerged.

In describing the acoustic effects of earmold vents, several variables must be considered. First, the configuration of the vent is of considerable importance. A "parallel" vent is one in which the vent bore opens directly into the ear canal cavity, whereas a "side branch" vent is one in which the vent bore opens into the main bore of the earmold, some distance lateral to the ear canal cavity. These two configurations are shown schematically in Figure 15. Second, the length and diameter of the vent are important and, in a side branch configuration, the length and diameter of the main bore medial to the vent opening are also important.

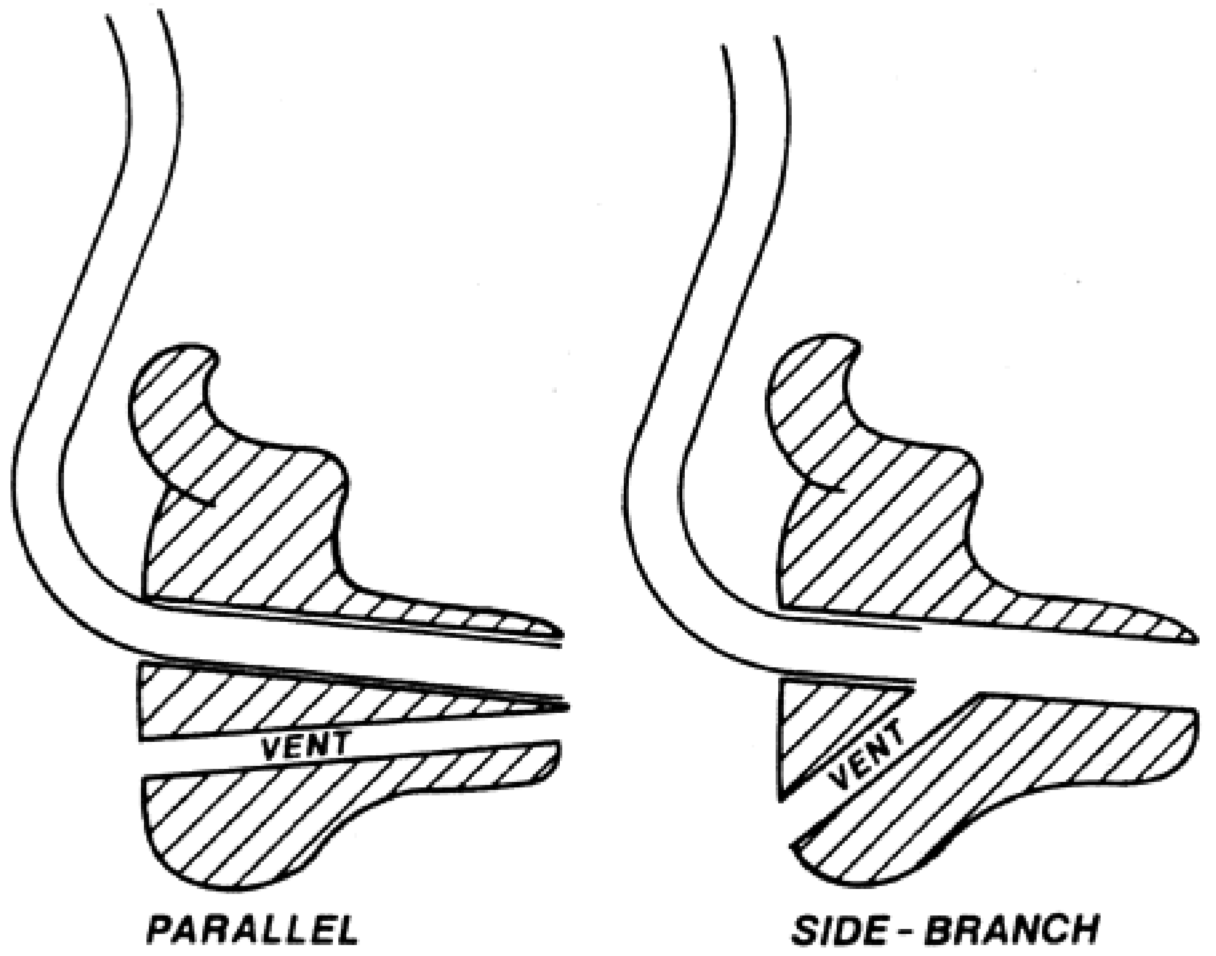

Fig. 15 Schematic illustration of parallel and side branch vent configurations.

In general, the acoustical effects of earmold vents may be described in terms of two loosely defined frequency regions: a low frequency/resonance region, and a high frequency region. These regions are illustrated in Figure 16 for both a side branch and a parallel vent. These data and those in Figures 16, 19 and 20 reflect the output into a Zwislocki coupler of a subminiature receiver working into a typical coupling system incorporating a vent. The data in Figures 16, 19 and 20 are plotted to show the spectrum of a signal in the ear canal (or "ear-like" coupler) when a vented earmold was used relative to the spectrum of the same signal in the ear canal when an unvented (but otherwise identical) earmold was used. A data point on the zero line indicates that the ear canal level at that frequency was identical with both earmolds. A negative data point indicates that the sound level was lower with the vented earmold, whereas a positive data point indicates that the sound level was higher with the vented earmold.

As Figure 16 indicates, the presence of a vent in the earmold typically reduces the level of low frequency energy in the ear canal. This "low frequency cut" decreases rapidly at a rate of 14-20 dB per octave as the curve slopes upward towards a peak which may or may not actually rise above the zero dB reference line. Both curves in Figure 16 reach the peak at approximately 500 Hz. The cut-off point between the high frequency region and the low frequency resonance region is defined here, somewhat arbitrarily, as one-half an octave above the peak frequency.

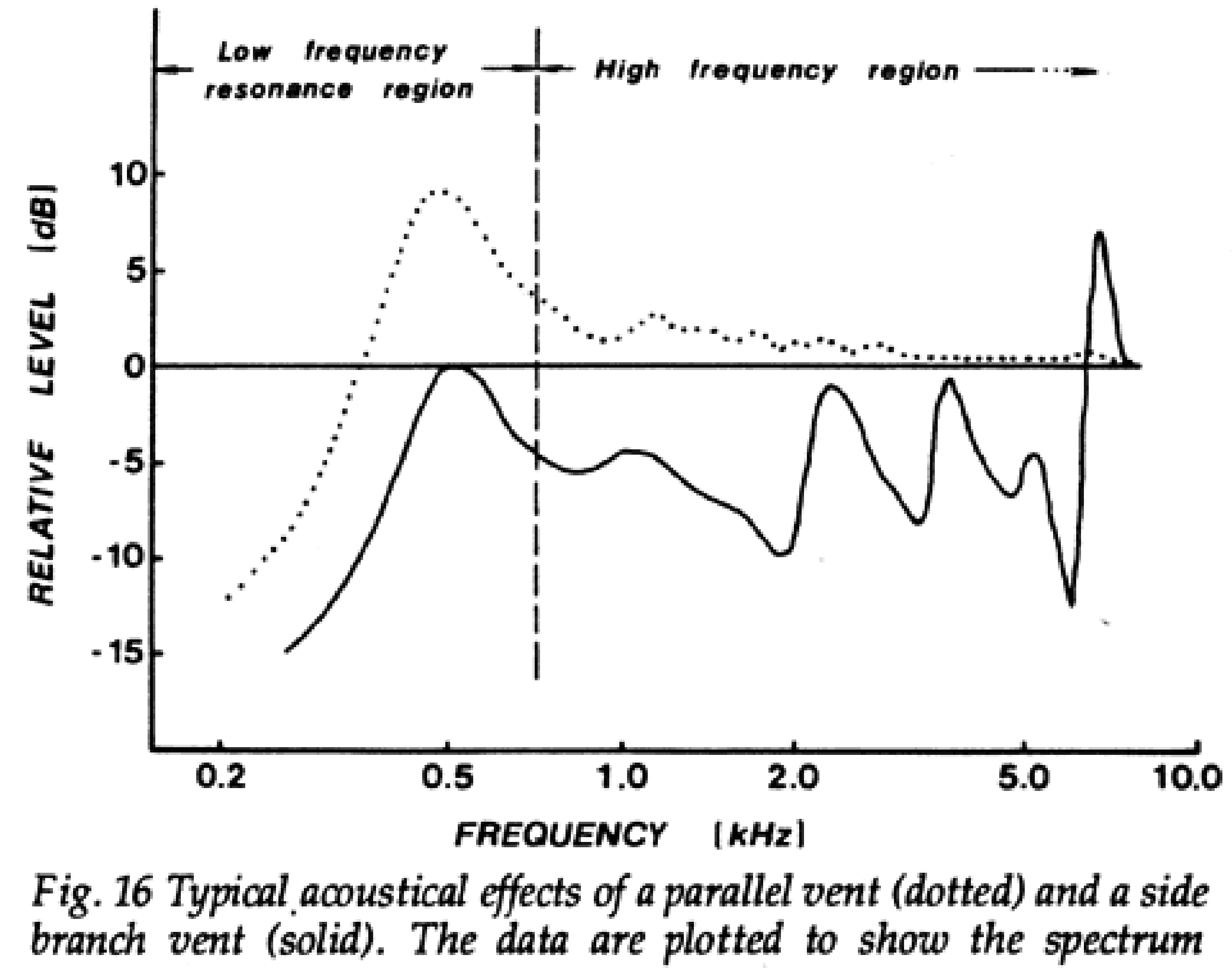

Fig. 16 Typical acoustical effects of a parallel vent (dotted) and a side branch vent (solid). The data are plotted to show the spectrum measured in the simulated ear canal with the vented earmold relative to the corresponding spectrum measured with an unvented earmold.

The Low Frequency Resonance Region

Most of the studies of acoustic effects of earmold venting reported to date have focused on the effects observed in the low frequency/resonance region. In this region both side branch and parallel vent configurations have similar general effects: a vented earmold results in a decrease in the low frequency energy reaching the eardrum relative to the level present when an unvented (standard) earmold is used. Immediately adjacent to this low frequency drop in level, a resonance region is seen in which the levels at the eardrum may be greater when the vented mold is used than with an identical, but unvented, mold. This pattern may be observed in the data shown in Figure 16 although the magnitude of the effects is clearly different for the two vents. The resonant frequency for both vents was approximately 500 Hz. The ear canal level at resonance, however, was actually 9 dB greater for the parallel vented earmold than for the corresponding unvented mold, whereas the ear canal level measured with the side branch vented earmold never exceeded that observed with the corresponding unvented mold. In addition, the extent of the low frequency transmission loss was greater for the side branch vent than for the parallel vent (13.0 dB versus 5.5 dB at 300 Hz). These data are typical but the absolute values are specific to the particular vents portrayed. Other examples of side branch and parallel vents will not necessarily yield the same absolute data values.

Studebaker and Zachman (1970) presented data in support of the hypothesis that these effects were attributable to the combined action of a Helmholtz resonator and a side branch acoustic filter. They postulated that a Helmholtz resonance is produced between the compliance of the air in the ear canal cavity and the mass of the air in the vent bore (for a parallel vent) or in the vent bore plus the main bore medial to the vent (for a side branch configuration). Subsequent investigations by Studebaker and Cox (1977) have also substantiated this hypothesis. This resonance is referred to hereafter as the "vent-associated" resonance. The approximate frequency of the vent-associated resonance may be calculated using the formula:

$$f=5500 \sqrt{\frac{\pi a^2}{lV}} \text{ (Hz)}$$

where: a = radius of vent (cm)
l = effective length of vent (cm)
V = equivalent of volume at the resonant frequency of ear canal/eardrum enclosed by earmold (cm^3)

A side branch acoustic filter is formed when an alternative pathway for acoustic energy branches off a continuing pipe. The general theory of side branches was developed by Kinsler and Frey (1962). Certain aspects of the theory are quite useful in interpreting the effects of venting in earmolds. It is necessary, however, to draw a distinction between a "side branch vent" and a "side branch acoustic filter". As Figure 17 shows, both side branch and parallel vent configurations can be thought of as forming side branch acoustic filters.

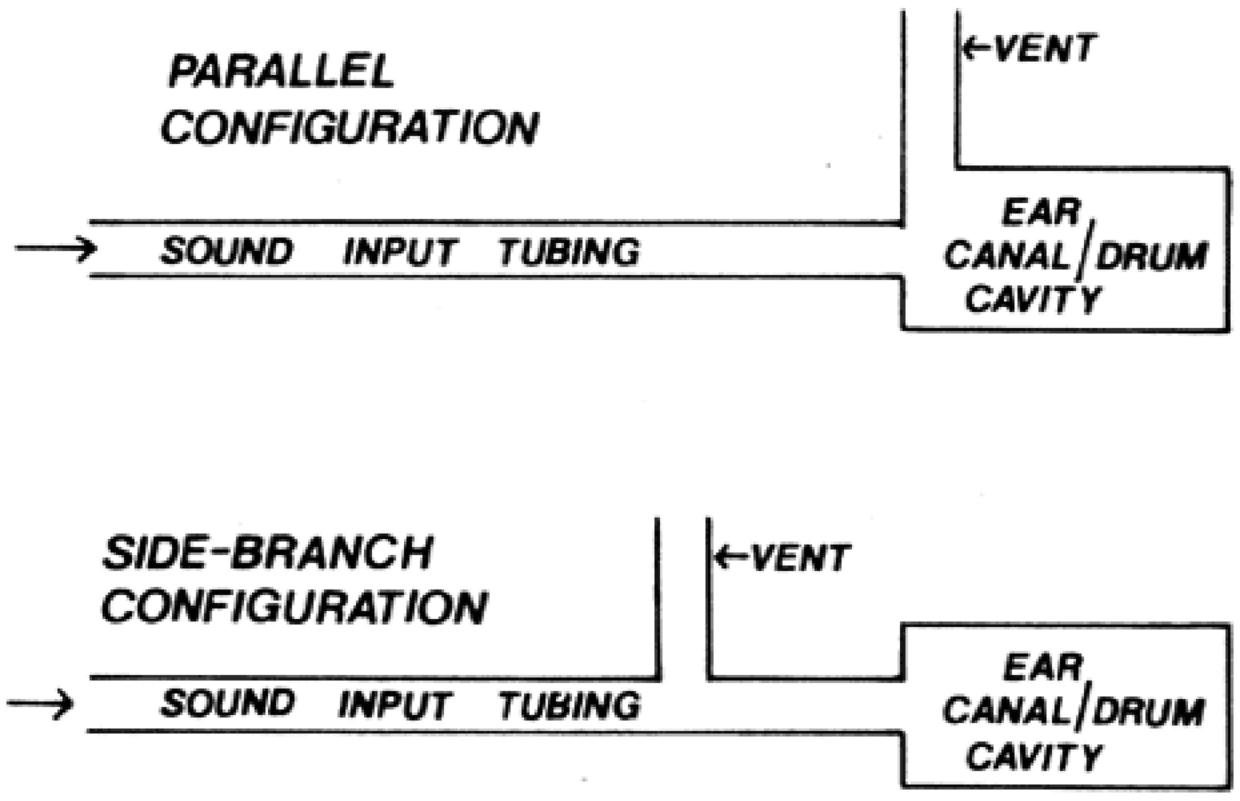

Fig. 17 Conceptualization of both types of vent configurations as side branch acoustic filters.

The presence of a side branch on a continuing pipe such as an earmold main bore produces an impedance discontinuity at the junction. At this discontinuity, some proportion of the incident sound energy is transmitted past the side branch and on down the main pipe; some proportion is transmitted into the side branch and the remainder is reflected back towards the source.

As long as the length of the vent is short relative to a wavelength — a condition which holds for almost any vent at frequencies below 1000 Hz — the transmission coefficient (the proportion of the incident energy which is transmitted past the vent and on down the main pipe) may be calculated fairly conveniently.* The theoretical results indicate that the proportion of the incident energy which is transmitted past the side branch is very small at low frequencies and increases steadily to almost 100% at high frequencies (Kinsler and Frey, 1962). Studebaker and Zachman (1970) and MacDonald and Studebaker (1970) compared calculated transmission coefficients with measured low frequency drop in level for several different earmold vents of side branch configuration. At very low frequencies, the measured and calculated transmission losses coincided very closely. These data support the hypothesis that at low frequencies the vent may be thought of as a side branch acoustic filter. As the resonance region is approached, the vent-associated resonance is superimposed upon the low frequency transmission loss, causing this loss to be less than the calculated magnitude.

The absolute magnitude of the low frequency transmission loss is determined by the impedance of the vent bore (which is largely an inertance) for both vent configurations. Vents with lower inertance (i.e., shorter, wider bores) produce a greater low frequency transmission loss. This has been shown in real ears and/or couplers by numerous investigators (MacDonald and Studebaker, 1970; Studebaker and Zachman, 1970; Weatherton and Goetzinger, 1971; Lybarger, 1978a,b). For a parallel vent the location of the vent-associated resonance is also determined by the inertance of the vent bore. In a side branch configuration, however, the inertance which enters into the production of the vent-associated resonance is comprised of the inertance of the vent bore plus that of the earmold main bore medial to the vent. Hence, in a side branch vent, the inertance which results in the low frequency cut is different from the inertance which enters into the production of the vent-associated resonance, whereas in a parallel vent these two inertances are identical. As a consequence, and as demonstrated in Figure 16, when a side branch and a parallel vent have the same vent-associated resonant frequency, the low frequency transmission loss will tend to be greater for the side branch configuration. This effect was noted by Cooper *et al* (1975).

The High Frequency Region

The effects of earmold vents in the high frequency region have been the subject of relatively little investigative effort. Cooper *et al* (1975), Studebaker and Cox (1977) and Lybarger (1978b) have reported that side branch and parallel vent configurations have quite different effects in the frequency region above the vent associated resonance. When a parallel vented earmold is used, no significant decrease in level is observed relative to the unvented earmold levels in the region above the vent-associated resonance. On the other hand, when a side branch vented earmold is used, the high frequency levels in the ear canal are observed to be less than the analogous levels measured with an unvented earmold. These effects are seen for the two vents shown in Figure 16. Studebaker and Cox (1977) hypothesized that the high frequency effects observed when side branch vents are used are due to the combined effects of two separate factors: (1) the changing input impedance of the vent and the continuing main bore, and (2) the reflected wave produced by the impedance discontinuity at the junction of the vent and the main bore.

Recall that at the junction of the side branch and the main bore of the earmold a portion of the incident energy is reflected and the remainder is transmitted either into the branch or along the continuing bore. The proportion of the energy which is reflected depends upon the combined impedance presented at the junction by the vent

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**The assumption is made that the main pipe is terminated without reflection. This assumption is obviously not met in the typical coupling system since the main pipe is terminated in the ear canal cavity and impedance discontinuities exist at the tubing-ear canal junction and at the eardrum. Perhaps this assumption is not critical in the case where two systems which differ only in the presence or absence of the side branch are being compared.*

bore and the continuing main bore (Kinsler and Frey, 1962). By analogy with electrical circuits, the transmitted energy may be thought of as distributed between the side branch and the main bore according to the reciprocal of their impedance ratio (Ford, 1970). The air in the vent bore behaves primarily as an acoustic inertance and, therefore, its impedance increases as frequency increases. The air in the continuing main bore also behaves as an inertance; however, the total impedance of the continuing main bore is comprised of a series combination of this inertance and the impedance of the ear canal/eardrum which terminates it. Calculations reveal that the impedance of this combination increases at a faster rate with frequency rise than does the impedance of the vent bore. As a consequence of these rising input impedances, less and less of the incident energy is transmitted down the continuing main bore and into the ear canal as frequency increases. More and more energy is either reflected back towards the source from the junction joint or is transmitted into the vent.

Figure 18 illustrates the output of a typical coupling system incorporating a side branch vented earmold (dotted line) and the output of the same coupling system with an unvented earmold (solid line). The wavelength resonances (R2, R3, R5) appear at slightly higher frequencies when a side branch vented earmold is used than with an identical but unvented mold. This seems logical since one expects to see in the vented condition a strong reflected wave originating at the junction of the vent and main bore, rather than at the earmold/ear canal interface. We could expect the effective length of the system to be reduced resulting in higher frequency wavelength resonances. The reduction in effective length, however, is usually not as great as the length of the main bore of the earmold medial to the vent. In the vent portrayed in Figure 18, this portion of the earmold was about 13mm in length, whereas the reduction in effective length which may be calculated by comparing the solid and dotted lines in the figure is in the range of 3-8mm. Resonance peaks which are sensitive to the total inertance of the sound input tubing (R1 and R4) may also migrate upwards in frequency when a side branch vent is introduced into the coupling system. This is probably due to a slight decrease in the total inertance of the sound input tubing which results from the introduction of a parallel inertance (the vent).

The same data seen in Figure 18 were shown with vented plotted relative to unvented molds similar to the side branch vent example in Figure 16. If one compares Figures 18 and 16, it becomes clear that the pronounced peaks in the side branch vent curve in Figure 16 (solid line) at 2300 Hz, 3700 Hz and 6700 Hz are the result of upward migration of peaks designated as R2, R3 and R5 in the vented condition. In addition, the slight perturbations in the curve at 1050 Hz and 5200 Hz are the result of very small upward shifts in R1 and R4.

In practical terms, this slight upward shifting of resonance peaks is of relatively little importance. Hence, the pronounced pattern of peaks and dips which is seen in the high frequency region for the side branch vent in Figure 16 is probably not of much consequence in the fitting of hearing aids.

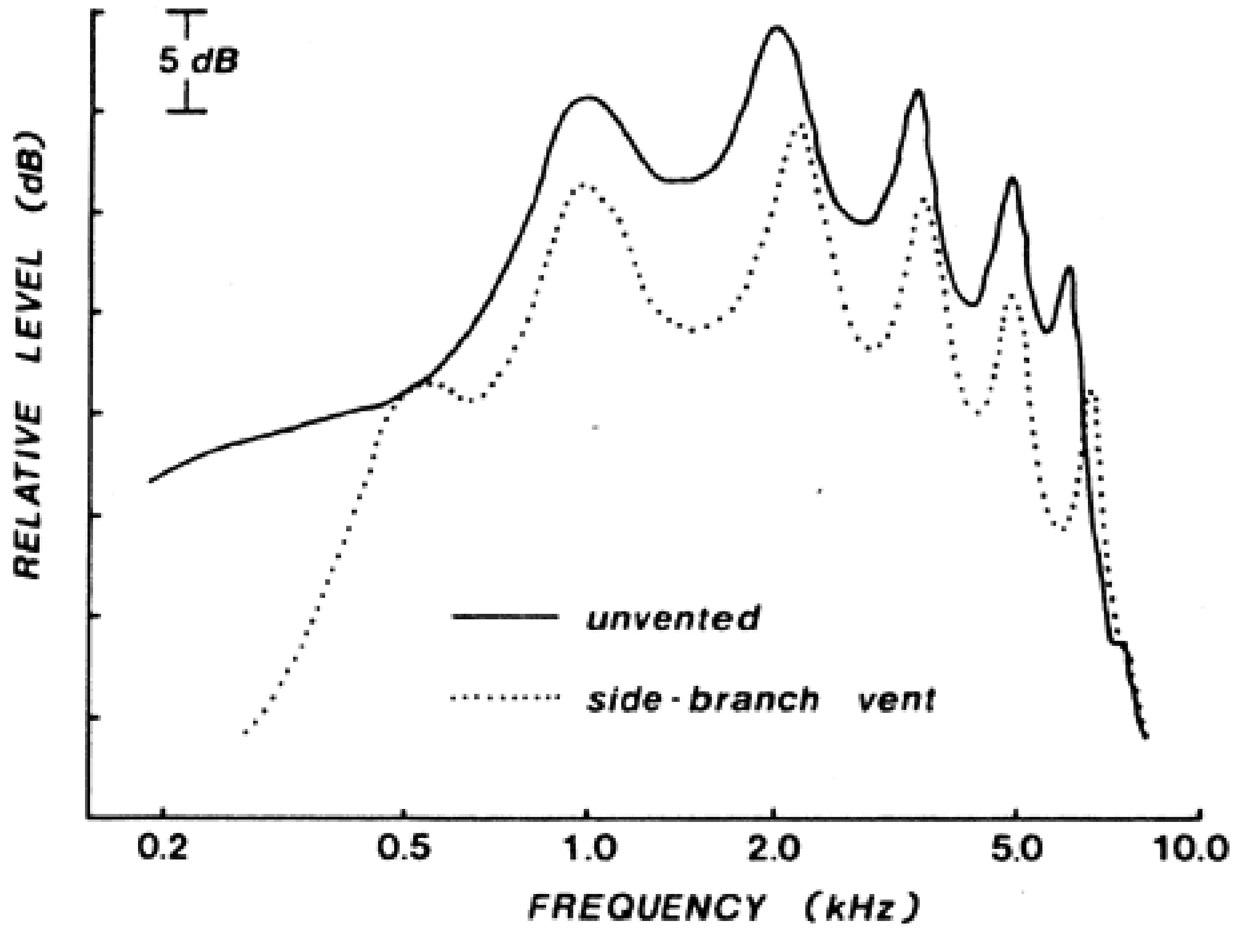

Fig. 18 Output into a simulated ear canal of a typical coupling system incorporating a side branch vent (dotted) and the output of the same coupling system with an unvented earmold (solid).

In contrast, the relative decrease in high frequency sound level in the ear canal, which is observed for the side branch vent in Figure 16, is an outcome which is almost never desired in the fitting of a hearing aid.

If a side branch vent is employed, the consequence of a high frequency drop in level, together with the vent-associated resonance, can be an effective emphasis of low frequencies rather than the anticipated high frequency emphasis.

The magnitude of the high frequency transmission loss due to a side branch vent is largely controlled by the length and diameter of the portion of the main bore which is medial to the junction of the vent and the main bore. The shorter and wider this portion of the system, the less high frequency transmission loss observed. Studebaker and Cox (1977) recommended that side branch vents be employed only when the physical size of the ear canal was too small to permit the drilling of a parallel vent which would be large enough to produce the desired amount of low frequency transmission loss. If the canal portion of the earmold is sufficiently large to accommodate only a small diameter parallel vent, it is possible to improve the low frequency filtering effect of such a vent by progressively widening the vent bore towards the lateral surface of the earmold. Figure 19 shows the result of such a modification. The solid line shows the effect of a parallel vent 13mm long and 1.3mm in diameter. The ear canal level at 200 Hz is only 3.5 dB less with the vented mold than with the unvented mold. The dotted line depicts the effect when the lateral 5-6mm of this vent was widened to a diameter of 2.5mm. This maneuver resulted in a vent which produced a 12 dB drop in level at 200 Hz relative to an unvented condition. The vent-associated resonance appeared at a slightly higher frequency as a result of the decreased inertance of the wider portion of the vent. Note that the desirable high frequency characteristics of a parallel configuration were maintained.

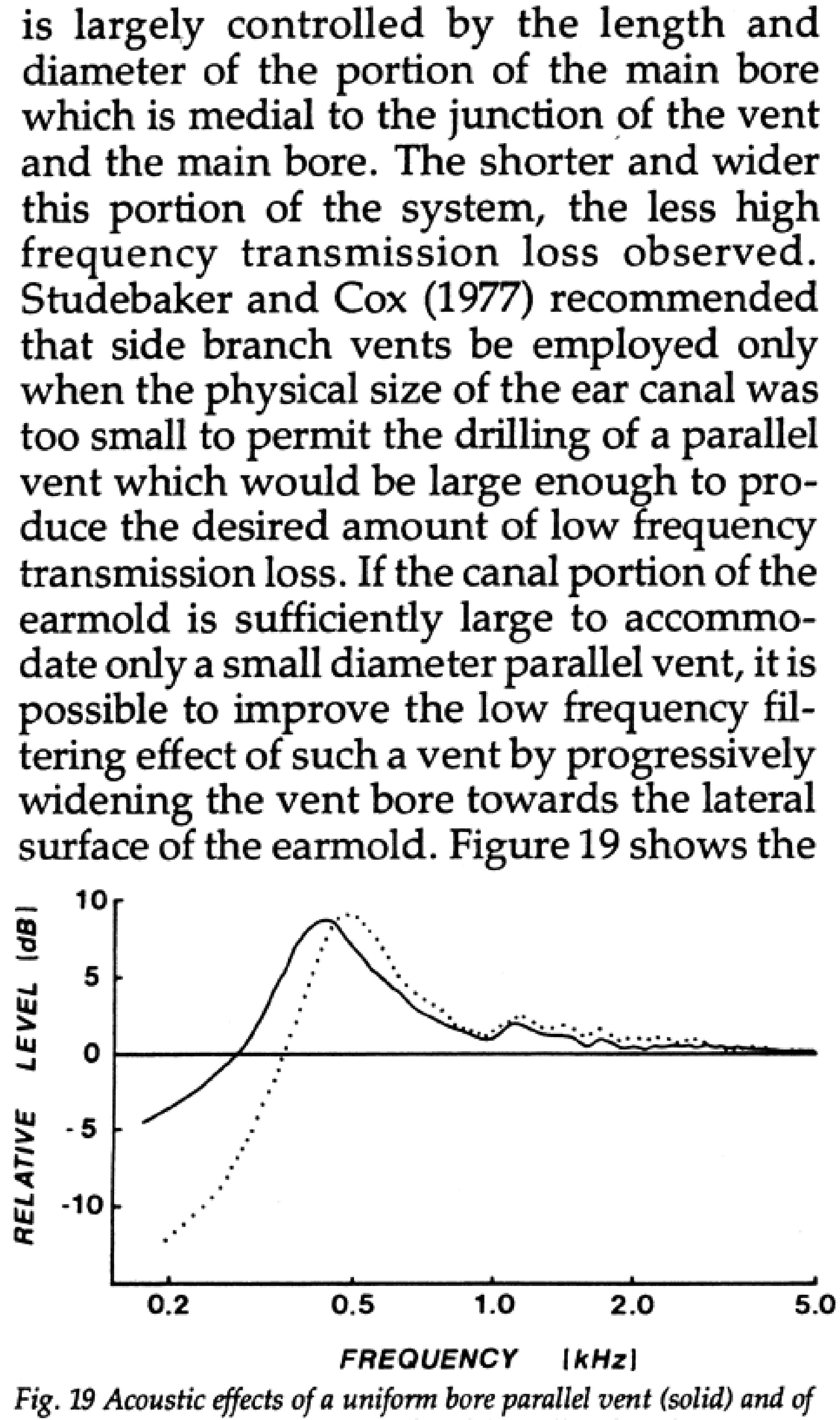

Fig. 19 Acoustic effects of a uniform bore parallel vent (solid) and of the same vent with the bore widened laterally (dotted). Data are plotted to show the spectrum measured in the simulated ear canal with each vented earmold relative to the corresponding spectrum measured with an unvented earmold.

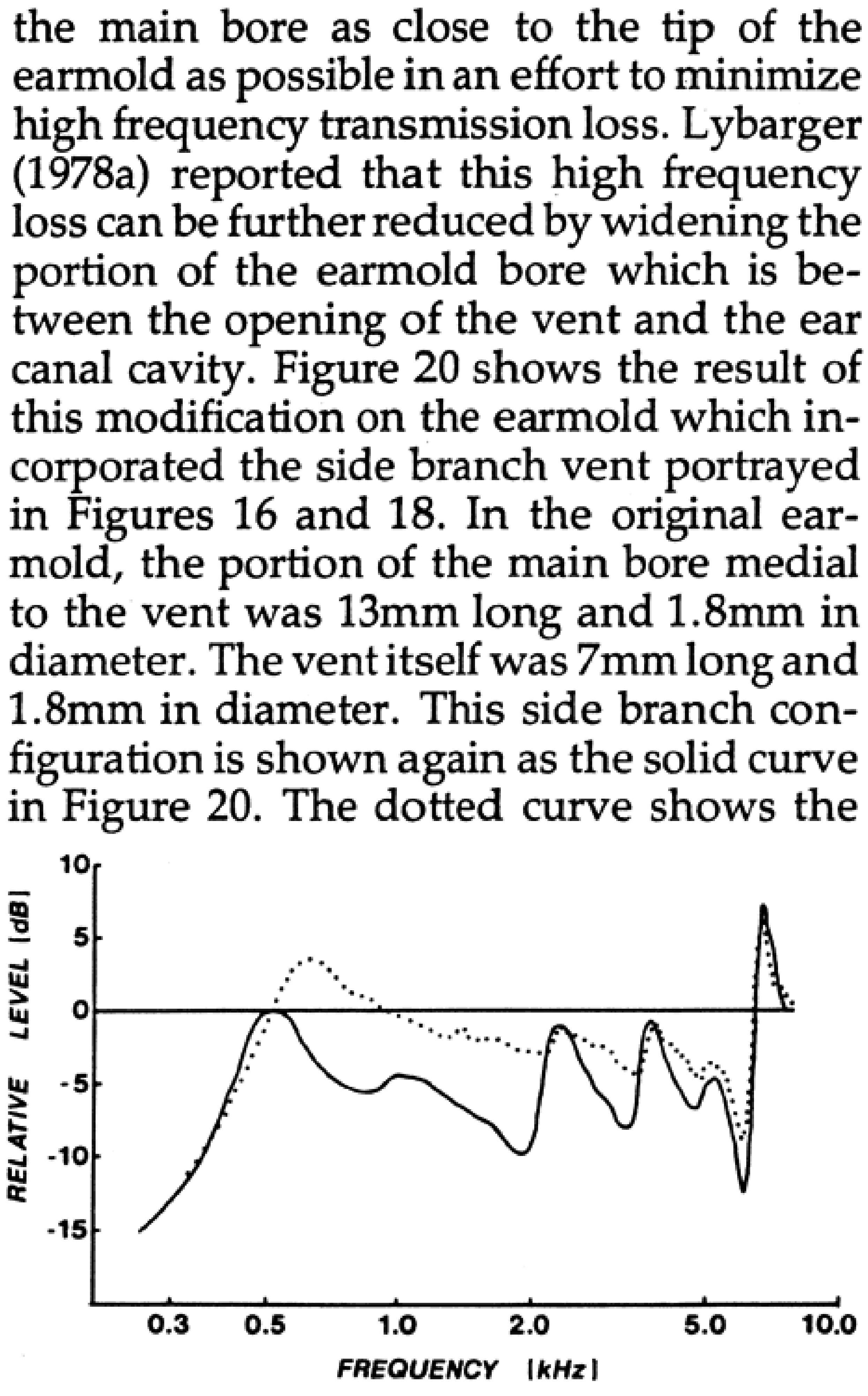

Fig. 20 Acoustic effects of a side branch vent when the earmold main bore medial to the vent was 1.8mm in diameter (solid) and when this portion of the main bore was 3.2mm in diameter (dotted). Data are plotted to show the spectrum measured in the simulated ear canal with each vented earmold relative to the corresponding spectrum measured with an unvented earmold.

If use of a side branch vent is unavoidable, the vent should be drilled to intersect the main bore as close to the tip of the earmold as possible in an effort to minimize high frequency transmission loss. Lybarger (1978a) reported that this high frequency loss can be further reduced by widening the portion of the earmold bore which is between the opening of the vent and the ear canal cavity. Figure 20 shows the result of this modification on the earmold which incorporated the side branch vent portrayed in Figures 16 and 18. In the original earmold, the portion of the main bore medial to the vent was 13mm long and 1.8mm in diameter. The vent itself was 7mm long and 1.8mm in diameter. This side branch configuration is shown again as the solid curve in Figure 20. The dotted curve shows the effects of the same vent when the main bore portion of the earmold was widened to a diameter of 3.2mm. The decreased impedance of this portion of the main bore resulted in significantly less high frequency transmission loss in the vented condition. The vent-associated resonance appeared at a higher frequency as a result of the decreased inertance of the wider main bore section.

Damping in Vents

The effects of placing acoustic resistance material, such as lambswool, in the vent bore have been described by Studebaker (1974) and Lybarger (1978a). Both investigators noted that the amplitude of the vent-associated resonance is reduced considerably by even small amounts of acoustic damping material placed in the vent bore. As the resistive component of the side branch impedance is increased by the damping material, however, the transmission of low frequency energy down the continuing main bore improves, resulting in less low frequency transmission loss than with an undamped vent. There is, therefore, an inescapable trade-off between the amount of low frequency transmission loss and the height of the vent-associated resonance. When moderate to heavy damping is placed in the vent bore, the height of the resonance and the low frequency transmission loss are both reduced to zero and the vent is essentially eliminated from the system.

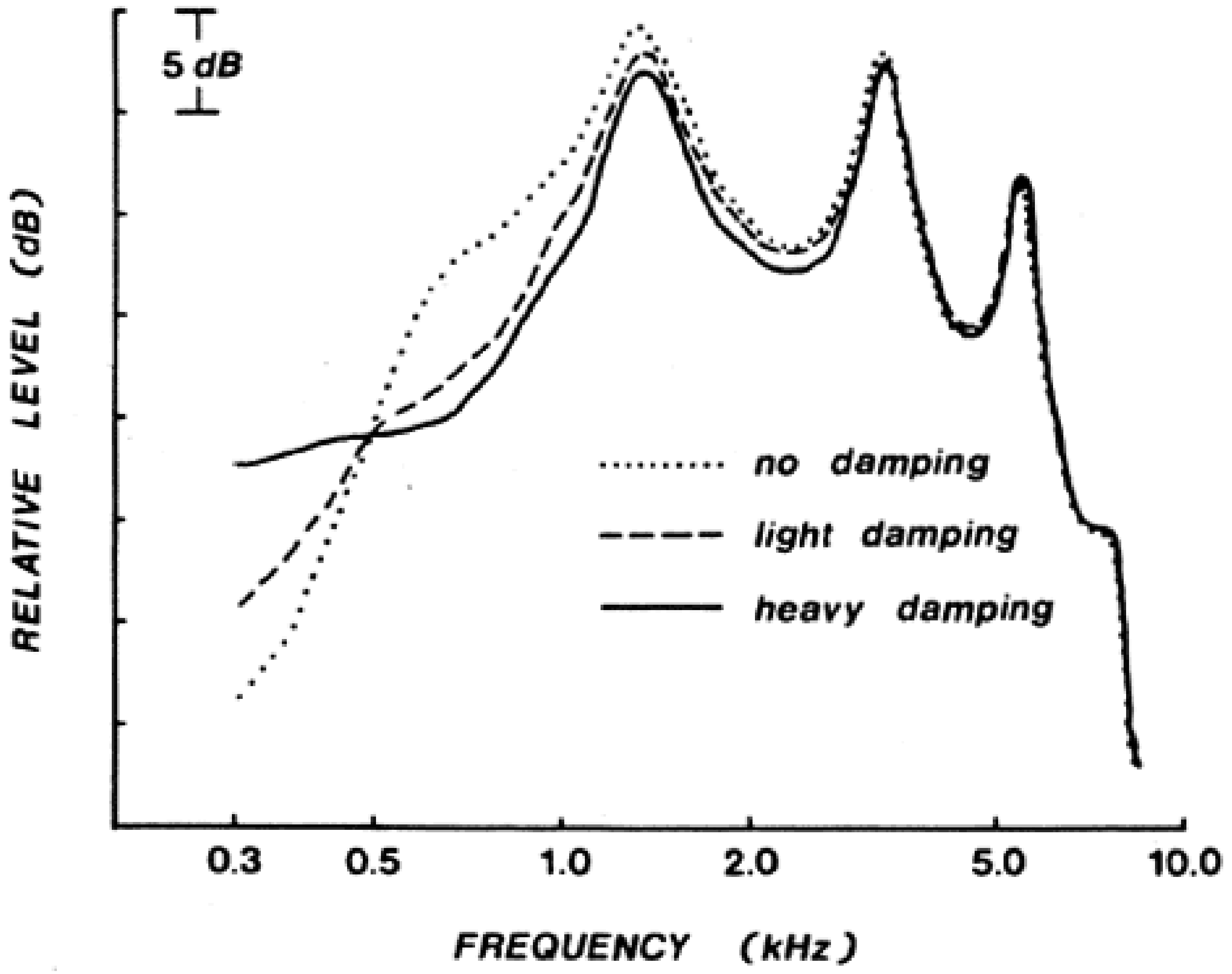

Fig. 21 Output of a parallel vented coupling system incorporating different amounts of damping in the vent.

Figure 21 presents an example of these effects. The dotted line represents the frequency response obtained in a Zwislocki coupler from a subminiature receiver coupled to a 30mm length of tubing when an undamped parallel vent was present in the system. The vent-associated resonance is seen as a "hump" in the curve at approximately 650 Hz. The dashed line shows the result obtained when a small amount of damping material was placed in the vent bore: the height of the vent-associated resonance has been reduced by 6 dB and the low frequency transmission loss at 300 Hz has also been reduced by about 4.5 dB. The solid line reveals results obtained when a larger amount of damping material was placed in the vent; this output is essentially the same as the one which could be obtained if no vent were present in the system — both the low frequency transmission loss and the vent-associated resonance have been eliminated.

The reader will recall that when an acoustic resistance element is placed in the sound input tubing, the location of the element is of considerable importance in determining the amount of reduction achieved in the height of peaks R1 through R5. By contrast, when an acoustic resistance element is placed in the vent bore, the location of this element is not a factor in determining the amount of reduction achieved in the height of the vent-associated resonance. The same damping effect is observed for a given amount of acoustic resistance whether the material is placed medially, laterally or in the middle of the vent length. This occurs because particle flow rate is relatively uniform throughout the vent bore since all dimensions of the vent/ear canal resonator are small relative to a wavelength at the resonant frequency.

Adjustable Venting Systems

In recent years several adjustable venting systems have come into widespread use. These systems provide the hearing aid fitter with a means of varying the dimensions of the vent bore, presumably altering its acoustic effect, until the "optimal" vent is found. Probably the most popular adjustable systems are those which include a set of inserts, each of which is a push-fit into a precisely bored hole in the lateral face of the earmold. A length of vent bore extends from the insert to the medial surface of the earmold. Two systems will be discussed here: the select-a-vent (S.A.V.) system and the positive-venting-valve (P.V.V.) system (Haigh, 1973). Each system includes six inserts, one of which is simply a plug. The remaining five inserts each incorporate an opening of a different diameter. The two types of inserts are illustrated in Figure 22.

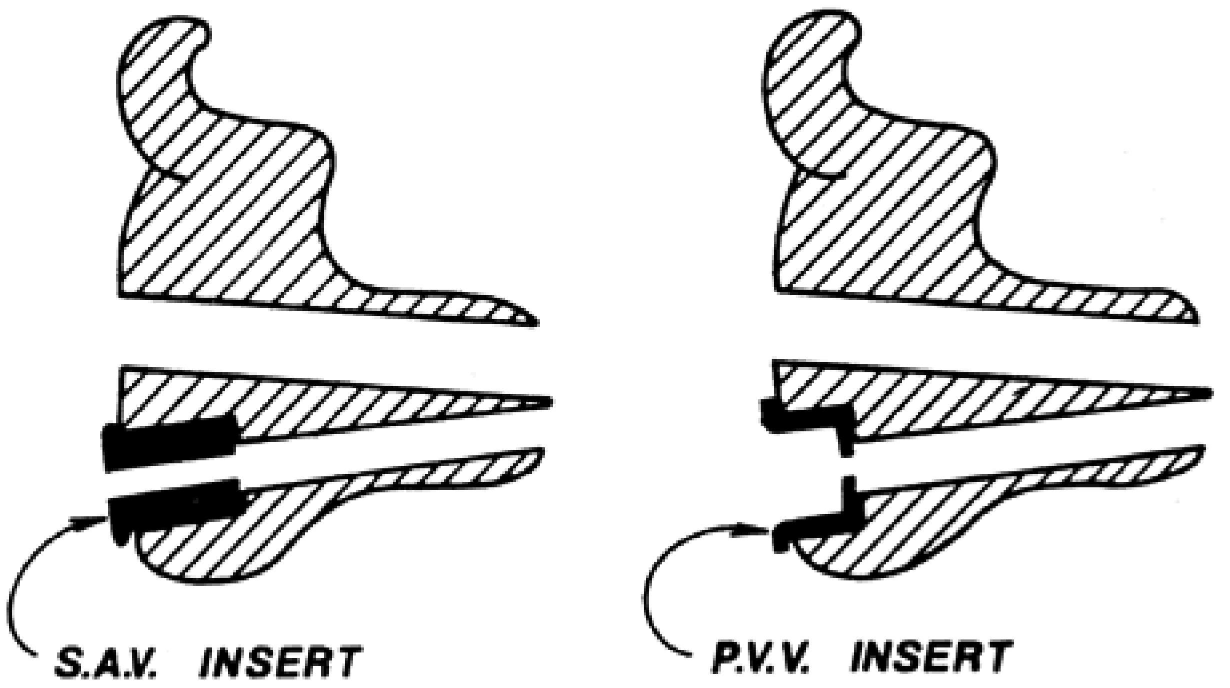

Fig. 22 Schematic illustration of the vent inserts in the S.A.V. and P.V.V. adjustable venting systems.

The P.V.V. insert is thimble-shaped, 2.5mm deep and 4.0mm in outer diameter. The inserts incorporate centered holes which have diameters of 0.51mm, 0.79mm, 1.57mm, 2.39mm or 3.17mm. The thickness of the floor of the insert (and therefore the measured length of each hole) is approximately 0.5mm. The S.A.V. insert is a solid cylinder 4.7mm long and 3.6mm in outer diameter with a hole which extends its full length. Inserts with holes which have diameters of 0.79mm, 1.19mm, 1.57mm, 1.98mm and 2.36mm are provided. Lybarger (1978a,b) has reported data obtained using a set of S.A.V. inserts which differed slightly in their hole diameters from those used here. The measured length of each hole is 4.7mm.

The acoustic effects of vents incorporating adjustable venting systems are, in principle, exactly the same as those discussed above for uniform bore vents. The data presented in Figures 23, 24 and 25 were obtained using a parallel vent configuration incorporating the adjustable venting system, as illustrated in Figure 22. It is, of course, also possible to incorporate these venting systems into a side branch vent configuration. Use of a side branch configuration, however, will result in a high frequency transmission loss as noted above.

In assessing the effects of adjustable venting systems, it is necessary to evaluate a number of factors which do not arise in considerations of traditional uniform bore vents. Several of these factors are discussed below.

Effect of the Vent Bore

As has already been discussed, the magnitude of the low frequency transmission loss which occurs when a vent is incorporated into the coupling system is determined by the impedance of the vent. In the case of an adjustable vent this impedance is comprised of the impedance of the vent bore beyond the insert as well as the impedance of the insert itself. Hence, if the impedance of the insert is to be the dominating factor, impedance of the vent bore beyond the insert must be kept as small as possible. To accomplish this, the vent bore should be as short and wide as possible (Lybarger 1978a).

Figure 23 illustrates the importance of the dimensions of the vent bore beyond the insert on the acoustic effect of the adjustable vent. Here, the data are plotted to show the levels in the Zwislocki coupler when the vented earmold was used relative to the analogous levels observed when an unvented earmold was used. In Figures 23, 24, and 25, the unvented reference condition was an earmold in which no vent bore was present (i.e., the vented earmold with the vent bore plugged laterally was not used as the reference condition).

The solid line in Figure 23 shows the effect of a parallel vent incorporating a P.V.V. insert (1.57mm diameter) with a vent bore beyond the insert 15mm in length and 1.3mm in diameter. The dotted line illustrates the effect of the vent incorporating the same P.V.V. insert when the 15mm vent bore beyond the insert was enlarged to a diameter of 2.4mm. Observe that although the same P.V.V. insert was used in both vents, the acoustic effect of these two vents was clearly very different in terms of both the low frequency transmission loss at a given frequency and the location of the vent-associated resonance. The same effects can be demonstrated with the S.A.V. inserts. In general, a longer, narrower vent bore beyond the insert will result in a lower frequency location for the vent-associated resonances with all inserts. In addition, the differences observed in the effects obtained with different inserts will be greater with a short, wide vent bore than with a long, narrow one.

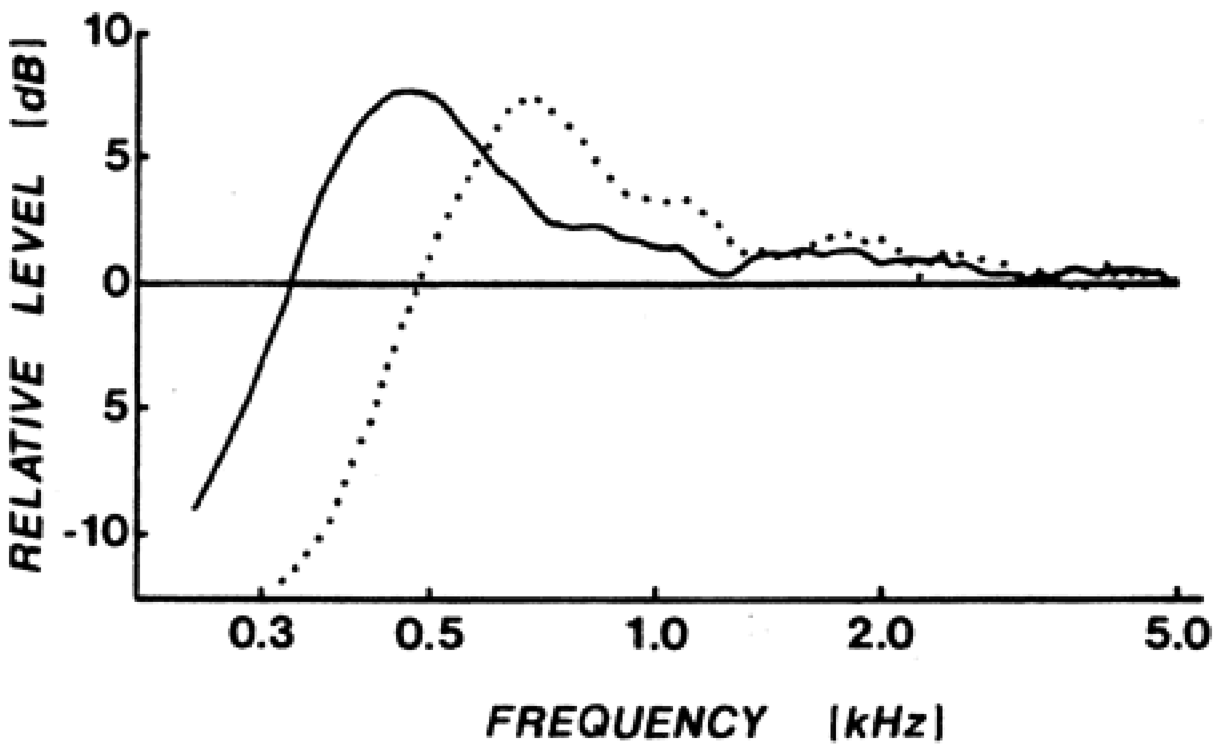

Fig. 23 Acoustic effect of P.V.V. insert #3 in conjunction with a vent bore beyond the insert 1.3mm in diameter (solid) and with a vent bore beyond the insert 2.4mm in diameter (dotted). Data are plotted to show the spectrum measured in the simulated ear canal with each vented earmold relative to the corresponding spectrum measured with an unvented earmold.

Effect of the Insert

Figure 24 depicts the acoustic effects of a parallel vent incorporating each of the P.V.V. inserts. The vent bore beyond the insert was 15mm in length and 2.4mm in diameter. Two findings are immediately apparent: first, the five inserts did not result functionally in five different vents. The five inserts actually produced only two different vents since the two smaller diameter inserts produced effects which are functionally indistinguishable from each other as did the three larger diameter inserts. Lybarger (1978a) reported data obtained using P.V.V. inserts with a vent bore beyond the insert 4.6mm in length and 3.0mm in diameter. With this short, wide vent bore, the two smaller diameter inserts produced results which were different from each other but the three larger diameter inserts still gave essentially indistinguishable results. Second, the range of effects obtainable from the smallest to the largest diameter insert is not very great; the frequency of the vent-associated resonance changed from about 540 Hz with the two smaller diameter inserts to about 680 Hz with the three larger diameter inserts. The low frequency transmission loss for a given frequency is about 7-8 dB greater for the large diameter inserts than for the small diameter inserts. A comparison of Figures 23 and 24 reveals that the effect of changing the diameter of the vent bore beyond the insert is potentially much greater than the effect of changing the hole size in the insert itself.

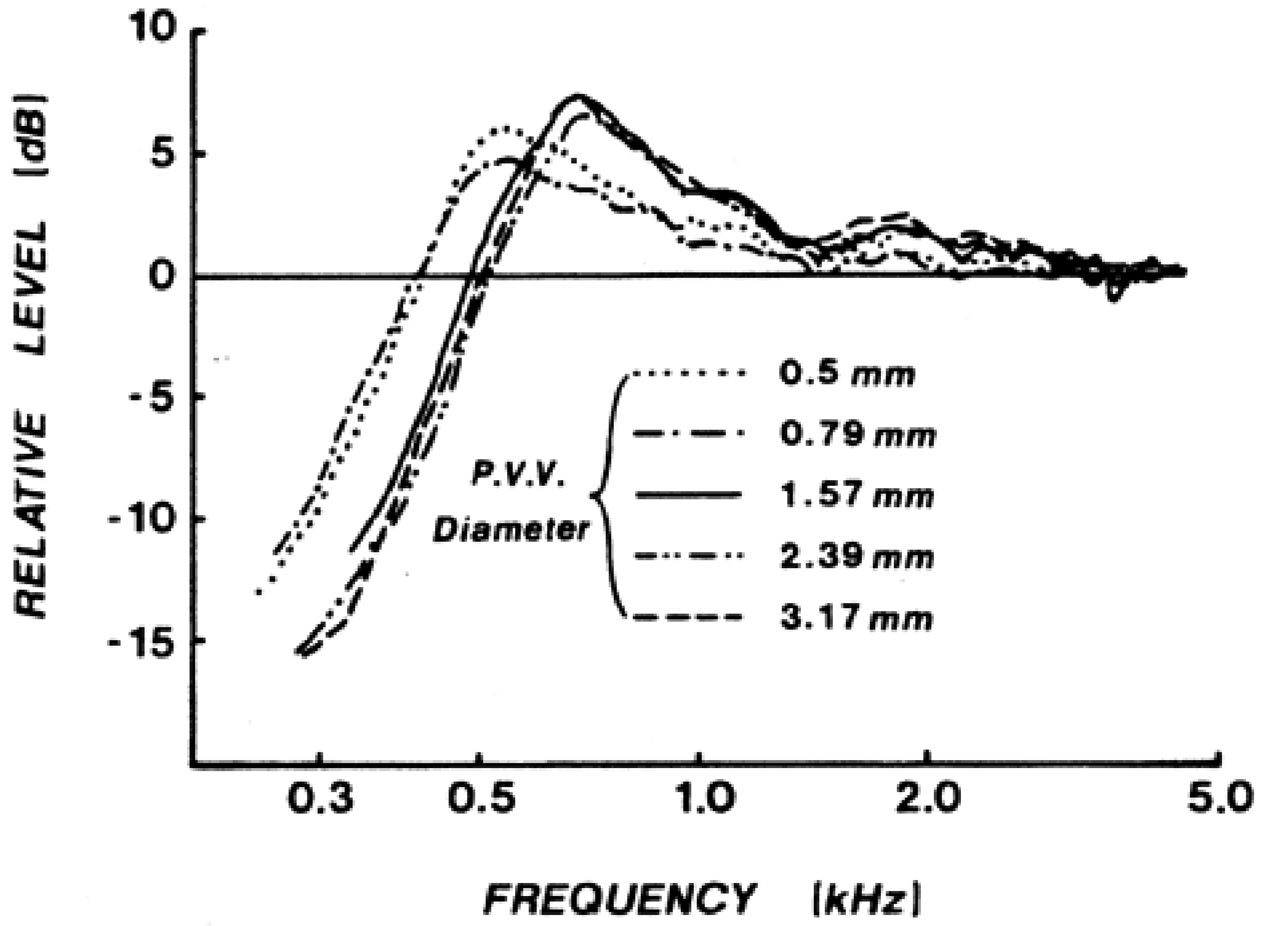

Fig. 24 Acoustic effects of a parallel vent incorporating each of the P.V.V. inserts. Data are plotted to show the spectrum measured in the simulated ear canal with each insert relative to the corresponding spectrum measured with an unvented earmold.

The set of curves in the upper portion of Figure 25 compares the acoustic effects of a parallel vent incorporating each of the S.A.V. inserts. The vent bore beyond the insert was 13mm in length and 2.5mm in diameter. The five inserts produced a fairly evenly spaced set of distinct curves. The range of the effects across inserts was again restricted. The frequency of the vent-associated resonance changed from 480 Hz with the smallest diameter insert to 650 Hz with the largest diameter insert; the low frequency transmission loss at a given frequency was about 10-11 dB greater for the largest diameter insert than for the smallest diameter insert.

This set of curves has been extended upward in frequency to reveal the effect in the ear canal of the quarter wave resonance which developed in the vent bore when S.A.V. inserts were used with a wide vent bore. (This resonance was much smaller or absent when the vent bore was 1.9mm in diameter.) The 6.5 dB notch observed at 6500 Hz for the dotted curve appears to be due to the resonant behavior of the vent bore beyond the insert. This bore, terminated by the insert, seems to be a quarter wave resonator which enters its first resonant mode at 5800 Hz or above (the effective length of the bore appears to become shorter as the hole in the insert becomes wider). The reader will recall that the input impedance of the quarter wave resonator is minimum when it is in a resonant state. At the resonant frequency, therefore, the vent bore absorbs some of the energy which would otherwise be present in the ear canal resulting in an antiresonant notch in the spectrum measured in the ear canal relative to the analogous spectrum measured with an unvented earmold. As long as hearing aids do not supply significant functional gains above about 4 kHz, an antiresonance at 6 kHz or above is of no practical significance. If extended high frequency amplification is considered, however, as in Pascoe, (1975), such an antiresonance may well be undesirable.

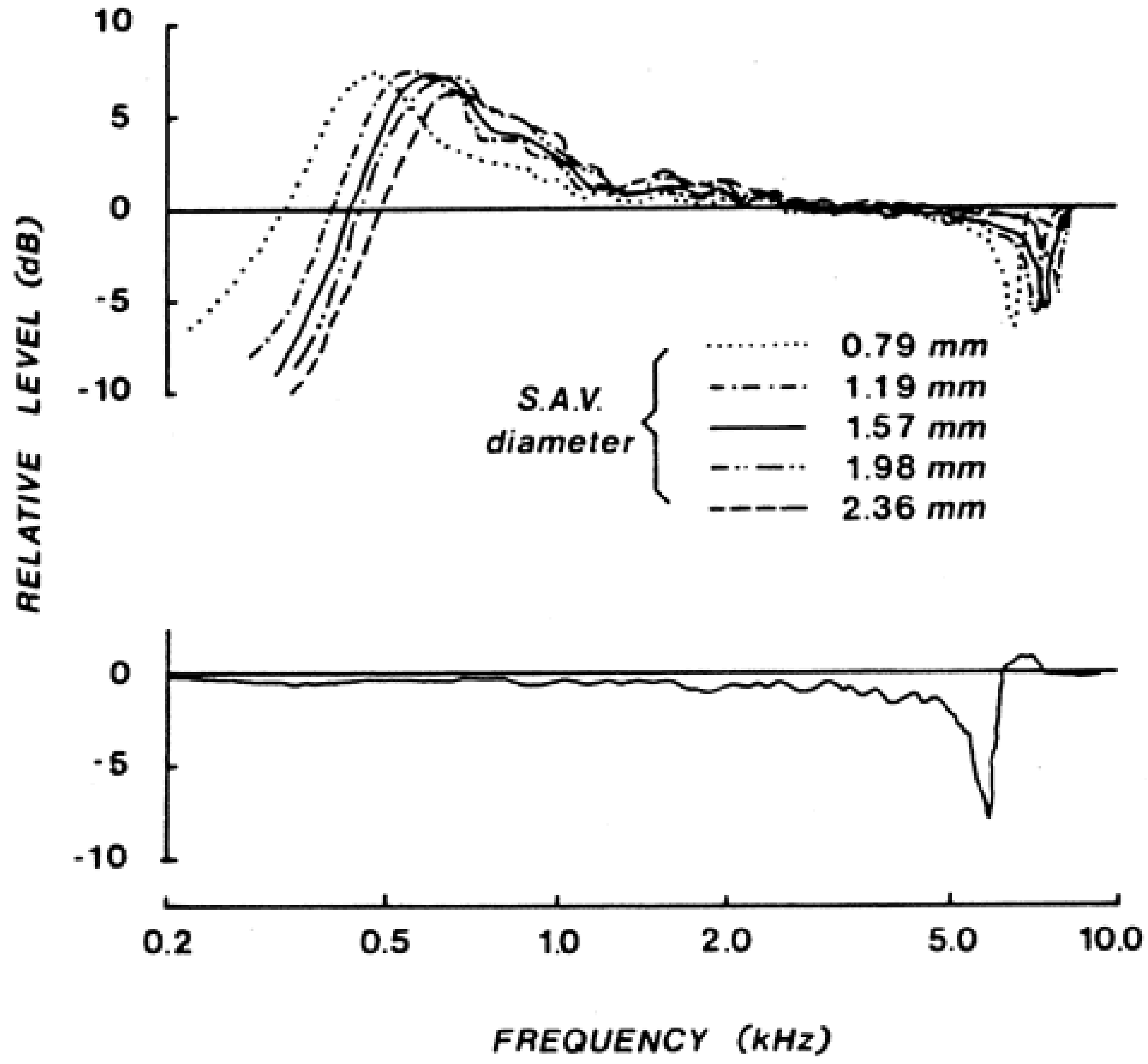

Fig. 25 Acoustic effects of a parallel vent incorporating each of the S.A.V. inserts. The set of curves in the upper portion show the spectrum measured in the simulated ear canal with each vent insert relative to the corresponding spectrum measured with an unvented earmold. The curve in the lower portion shows the spectrum measured when the vent bore was occluded laterally with the "plug" insert relative to the spectrum measured with an unvented earmold.

Effect of Plugging the Vent

The lower curve in Figure 25 shows the effect of closing the 13.0 x 2.5mm vent bore laterally using the S.A.V. plug insert. The data show the spectrum in the Zwislocki coupler measured with an earmold with a laterally plugged vent relative to the analogous spectrum measured with a traditional unvented earmold. As illustrated, the presence of the plugged vent results in a signal level in the ear canal which is about 0.5 dB lower than that observed with the traditional earmold. This occurs because the volume of air in the vent bore increases slightly the total equivalent volume of the ear canal/eardrum cavity, thereby decreasing the overall level developed in the cavity for a given input signal. In addition, the quarter wave resonance of the vent bore, which occurs at 5800 Hz, results in an antiresonant notch in the ear canal of 8.0 dB at that frequency. These data are typical of results found with laterally plugged vent bores.

Predicting the Acoustic Effect of Venting

Adjustable venting systems are attractive to the hearing aid fitter because their apparent flexibility allows the selection of an optimal venting arrangement for an individual on *a posteriori* basis. (The reader should recognize from a consideration of Figures 24 and 25 that the actual flexibility offered by adjustable venting systems is usually limited to a range of frequencies perhaps 200 Hz wide.) This flexibility is an attractive feature for current venting practice since it is often difficult or impossible to select vent parameters (such as: length, diameter, configuration, damping) *a priori* which will, if properly executed by the earmold laboratory, give the desired acoustic result.

Attempts have been made to improve the precision with which vent parameters can be appropriately selected and specified by the hearing aid fitter. Lybarger (1978b) has tabulated the acoustic effects of numerous vent parameters as a function of frequency from 200 Hz to 1600 Hz. His data include effects of vent length from 6.3mm to 22.0mm and diameter from 1.0mm to 3.0mm for uniform bore parallel vents. A range of length and diameters is also specified for uniform bore side branch vents. In addition, he provides data on the effects of P.V.V. and S.A.V. inserts in parallel vent configurations in which the vent bore beyond the insert is varied in length and diameter. (The S.A.V. inserts used by Lybarger incorporated holes of slightly different dimensions from those used to obtain the data in Figure 25.) Reference to these tables should make it possible either to predict with reasonable accuracy the acoustic effect of a vent which is in hand, or to specify with some precision the values desired on various vent parameters in a yet-to-be fabricated earmold.

Another approach to the prediction of venting effects has been presented by Studebaker and Cox (1977). They constructed a simple, lumped parameter electrical model of the hearing aid-ear canal coupling system incorporating either a side branch or parallel vent. The effect of any vent of known dimension could be predicted with considerable accuracy using this model by: (1) calculating the values of the various inertances and compliances in the system, (2) transforming these into analogous electrical quantities, substituting these quantities into the model, and (3) measuring the effect on the voltage developed in the simulated ear canal. Such a model could conceivably be developed for clinical use.

Egolf *et al* (1978) have successfully modeled the hearing aid-ear canal coupling system via computer. This approach also may hold considerable promise for clinical use as computer technology becomes more widely available.

Acoustic Effects of Open Earmolds

As mentioned previously, an earmold vent may be made so large that only a very small portion of the earmold canal remains (just enough to retain the sound input tubing in the ear canal). This variety of vented mold is called an "open" mold. On occasion, even the small remnant of earmold is omitted and the sound input tubing is allowed to lie freely in the ear canal. The resulting arrangement is called a "no-mold" fitting. The acoustic difference between a no-mold fitting and an otherwise identical open mold arrangement is minor except perhaps in the case of a very small ear canal in which even the small bulk of the canal portion of the open mold may effectively occlude the canal.

Open earmolds and no-mold fittings behave acoustically as if they are earmolds with maximally large parallel vents. Figure 26 shows the acoustic effect of one example of a no-mold fitting. These data were obtained using a subminiature hearing aid receiver and a typical coupling system incorporating 45mm of #13 tubing. These items were placed on the right ear of a KEMAR manikin in the position they would occupy in an over-the-ear hearing aid. The ear canal/eardrum of the KEMAR was simulated by a Zwislocki coupler. First, the section of #13 tubing was bent and extended into the "ear canal" approximately 10mm (no earmold was used). The receiver was driven electrically with a broad band, flat spectrum noise and the sound level developed at the eardrum position was measured by the coupler microphone. Second, a standard (unvented) earmold with a canal portion extending 10mm into the ear canal was added to the coupling system. The receiver was again driven with the same electrical signal and the sound level developed at the eardrum position was measured. In Figure 26, the results obtained in the no-mold condition are plotted relative to the results obtained in the standard mold condition. The data reveal a pattern which is characteristic of parallel vents but in which the low frequency transmission loss is

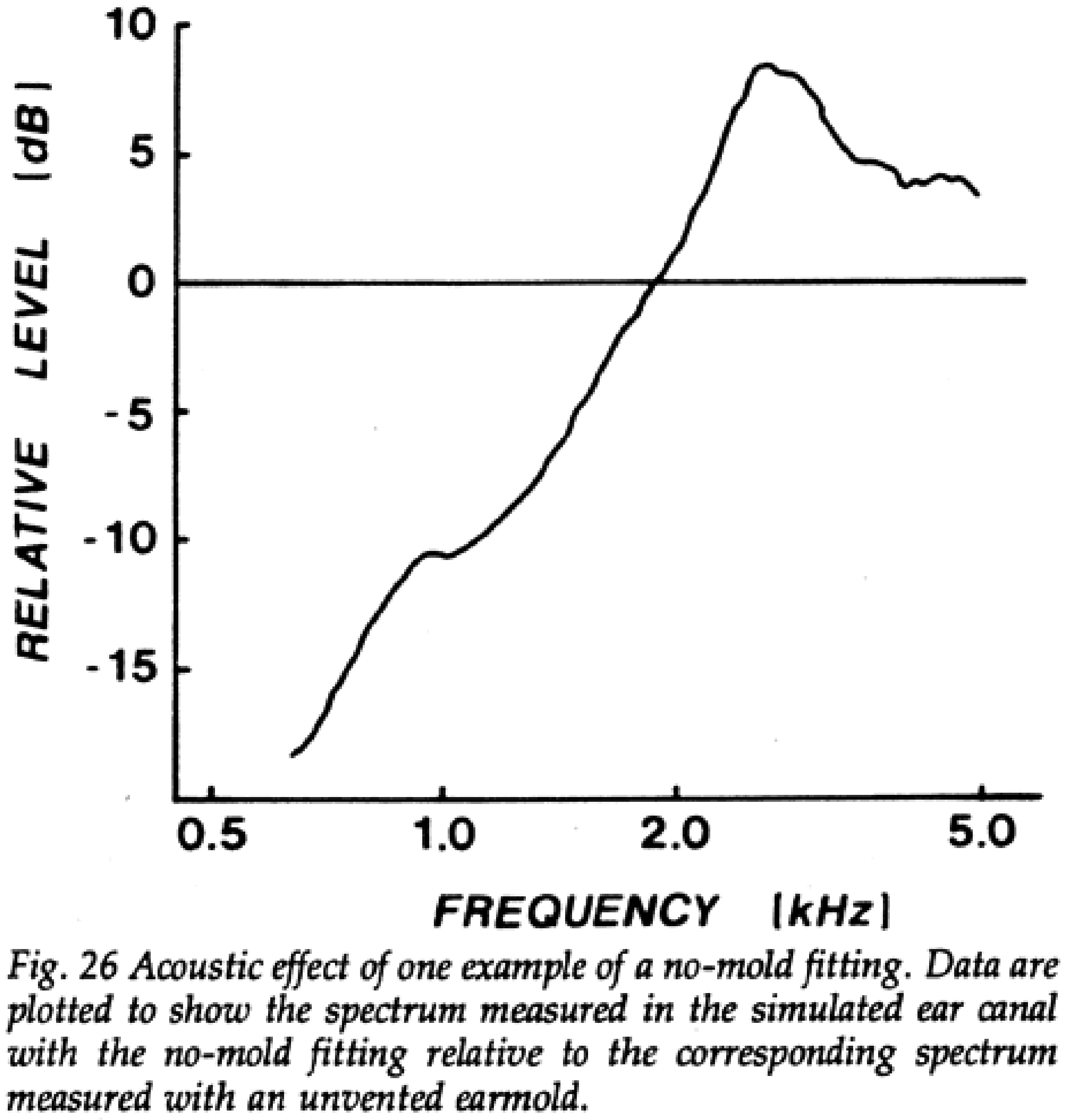

Fig. 26 Acoustic effect of one example of a no-mold fitting. Data are plotted to show the spectrum measured in the simulated ear canal with the no-mold fitting relative to the corresponding spectrum measured with an unvented earmold.

greater and the vent-associated resonance occurs at a higher frequency than that seen with more typical vented earmolds. The low frequency transmission loss in this example is 10.5 dB at 1 kHz and the vent-associated resonance occurs at 2.6 kHz. Comparison of Figure 26 with Figures 19, 24 and 25 clearly reveals that the no-mold fitting results in a much greater attenuation of low frequency sound level than that seen with these conventional parallel vents.

Figure 27 compares the ear canal spectra in the no-mold and standard mold conditions which were used to derive the curve in Figure 26. This figure reveals even more clearly the dramatic high frequency emphasis imparted to the signal in the ear canal by a no-mold fitting. Note that the typical resonant peaks (R1 through R5) remain visible in the no-mold response. Their location is unchanged with the exception of R5. The R5 peak behaves as if the effective length of the sound input tubing is slightly greater in the no-mold fitting at high frequencies. Also note that the vent-associated resonance, although present (as shown in Figure 26), is not readily identifiable in the no-mold data curve.

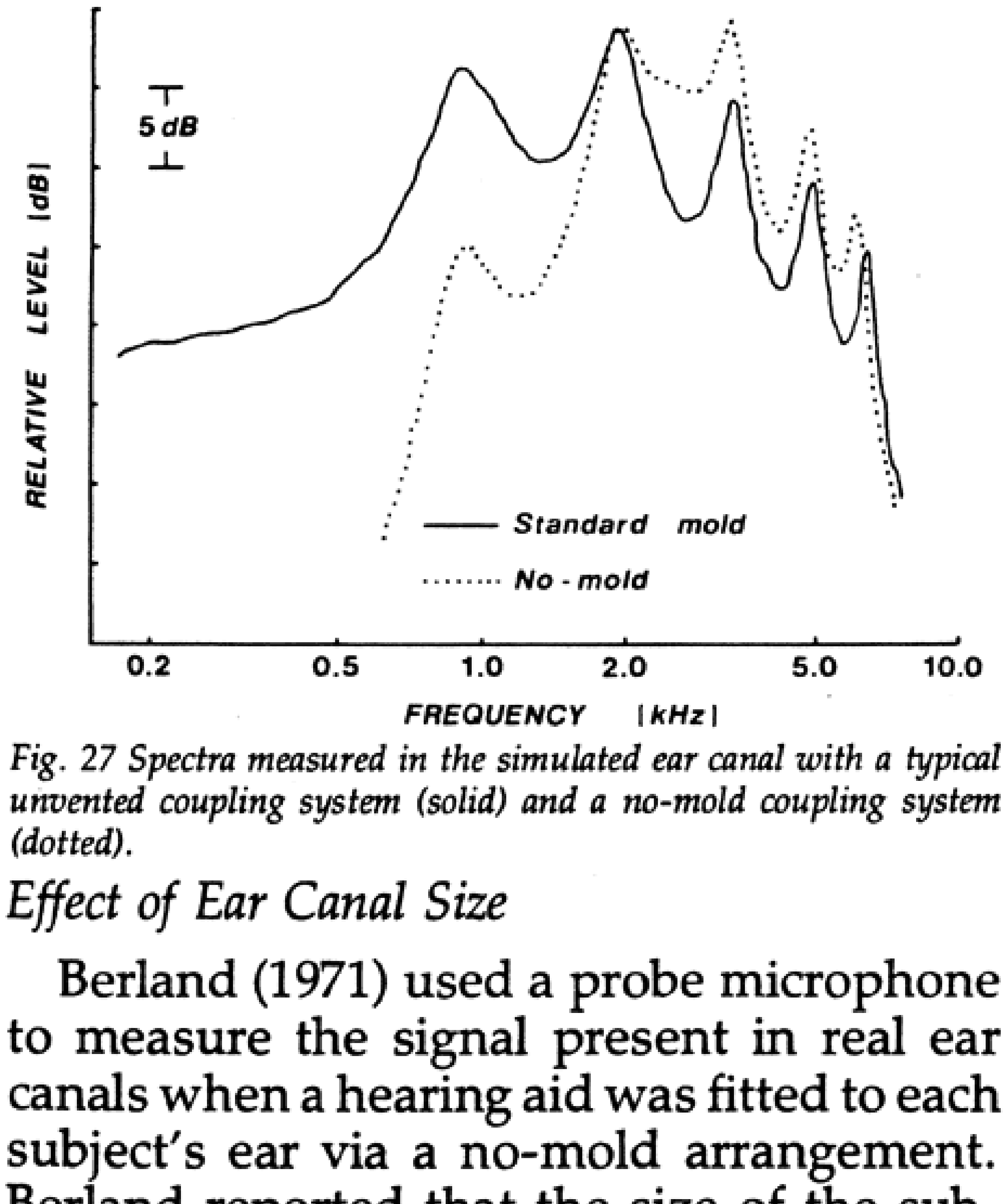

Fig. 27 Spectra measured in the simulated ear canal with a typical unvented coupling system (solid) and a no-mold coupling system (dotted).

Effect of Ear Canal Size

Berland (1971) used a probe microphone to measure the signal present in real ear canals when a hearing aid was fitted to each subject's ear via a no-mold arrangement. Berland reported that the size of the subject's ear canal had an important influence on the obtained results. Subjects with narrow ear canals (typical dimension: 9 x 5mm) did not experience as much low frequency transmission loss with a no-mold fitting as did subjects with normal or wide ear canals. (The KEMAR's ear canal is round with a diameter of 7.5mm.) Berland also reported, however, that the gain available before feedback with a no-mold fitting tended to be greater for individuals with narrow ear canals. His data indicate that 25-30 dB of functional gain in the 2-5 kHz range was often measured in narrow ear canals before acoustic feedback was observed. In comparison, the achievable functional gain in the 2-5 kHz range was usually 15-20 dB n normal and wide ear canals.

Effect of Insertion Depth

The depth to which the sound input tubing is inserted into the ear canal has an effect upon the spectrum observed at the eardrum. Deeper penetration into the ear canal necessitates a longer sound input tubing with resultant lower frequency resonant peaks as shown earlier in Figure 4. In addition, deeper penetration into the ear canal probably increases the length of the "vent" portion of the ear canal and decreases the "volume" portion, thus reducing the low frequency transmission loss and perhaps changing the frequency of the vent-associated resonance. Figure 28 demonstrates the result of changing the insertion depth of a no-mold fitting on the KEMAR manikin. These data were obtained as described for the no-mold condition in Figure 26. The solid line shows the spectrum measured at the eardrum position with the sound input tubing (standard #13 tubing) inserted approximately 14mm into the ear canal. The total length of the coupling system was 64mm. The dotted line represents the spectrum measured at the eardrum position with the sound input tubing extending only about 3mm into the ear canal. Thus, the total length of the coupling system was 11mm shorter (53mm). Comparison of the two lines indicates that the low frequency transmission loss was greater for the 3mm insertion depth than for the 14mm insertion depth. Additionally, all of the system resonances occured at higher frequencies for the system with the shorter total length (the dotted line). Again, the vent-associated resonance is not readily identifiable in these data although it can be shown to be present.

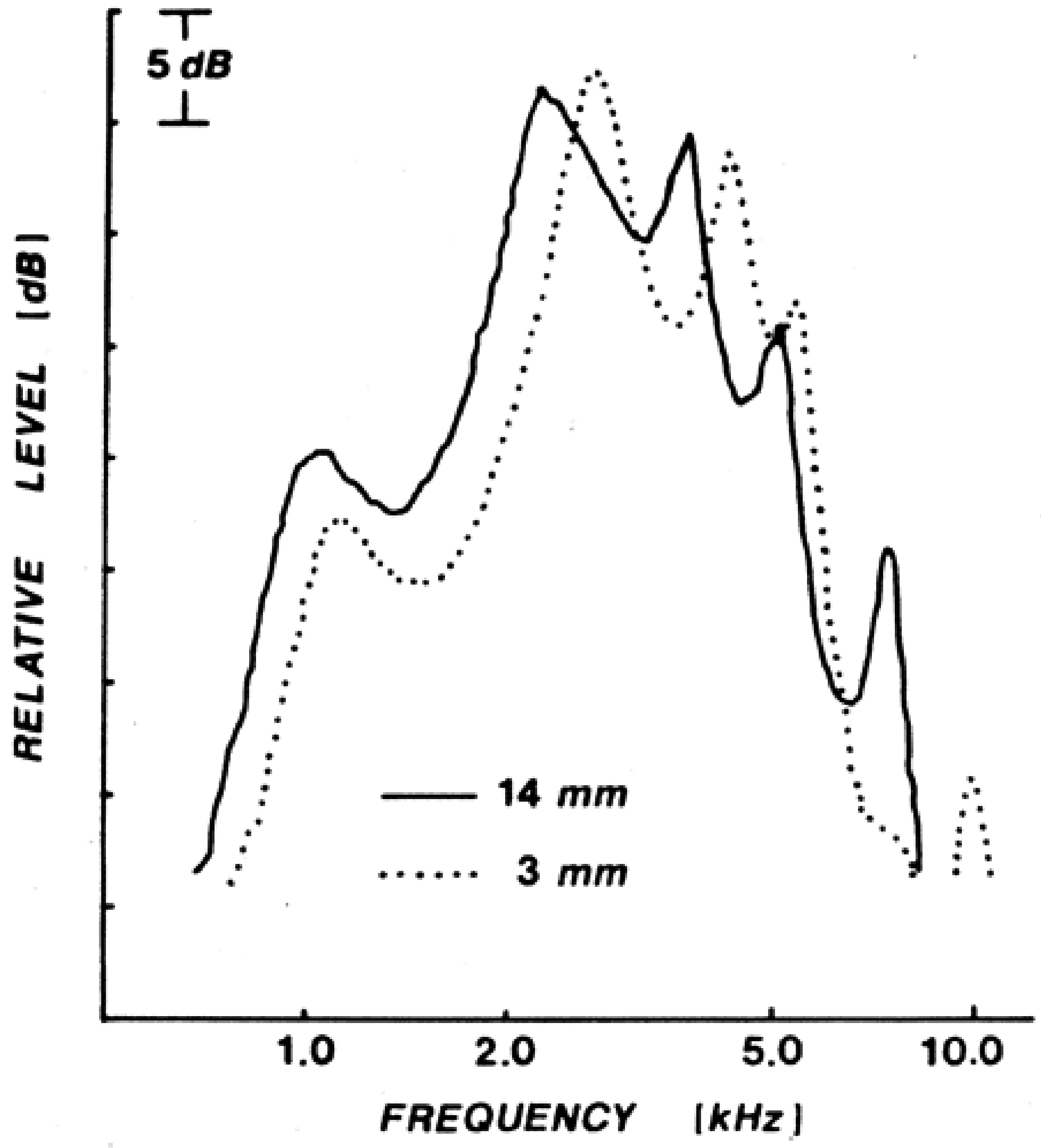

Fig. 28 Spectra measured in the simulated ear canal with two no-mold coupling systems which differ in their total length and in the depth of insertion of the tubing into the open ear canal.

The net result of decreasing insertion depth is a general movement of the spectrum in the ear canal towards the higher frequencies. The results shown in Figure 28 are somewhat at variance with those reported by Courtois and Berland (1972) in which they varied insertion depth by pulling the tube 5mm out of the ear canal (i.e., they did not decrease the length of the coupling system to achieve reduction in insertion depth). These investigators reported some decrease in high frequency levels with reduced insertion depth which was not observed in Figure 28 or in other similar data. As Courtois and Berland (1972) point out, however, reduction in insertion depth is not a satisfactory means of increasing the low frequency transmission loss. A shallow tube placement will probably result in a reduction in available gain because of increased acoustic feedback. In addition, such a tube will be easily dislodged from the ear canal.

Effect of Tubing Diameter

The internal diameter of the tubing which is attached to the earhook of the hearing aid has an effect on the signal in the ear canal when a no-mold fitting is used (Courtois and Berland, 1972; Lybarger, 1978a,b). As discussed earlier, decreasing the diameter of a section of tubing increases its inertance and its acoustic impedance. This change results in a lower output level into the ear canal than with the wider tube. In addition, resonances which are sensitive to the total inertance of the sound input tubing (R1 and R4) will appear at a lower frequency for the narrower tubing. These effects were described previously in connection with Figure 3. The effects in a no-mold fitting are shown in Figure 29. The solid line depicts the spectrum measured at the KEMAR's eardrum position when a no-mold fitting incorporating #13 tubing (I.D. = 1.9mm) was used. The dotted line represents the analagous specturm measured with a no-mold fitting incorporating #16 tubing (I.D. = 1.3mm). The total length of the sound input tubing was 64mm in each condition and insertion depth was about 14mm into the KEMAR's ear canal. The data indicate, as expected, that the signal level at the eardrum position was lower for the narrower tubing. In addition, both

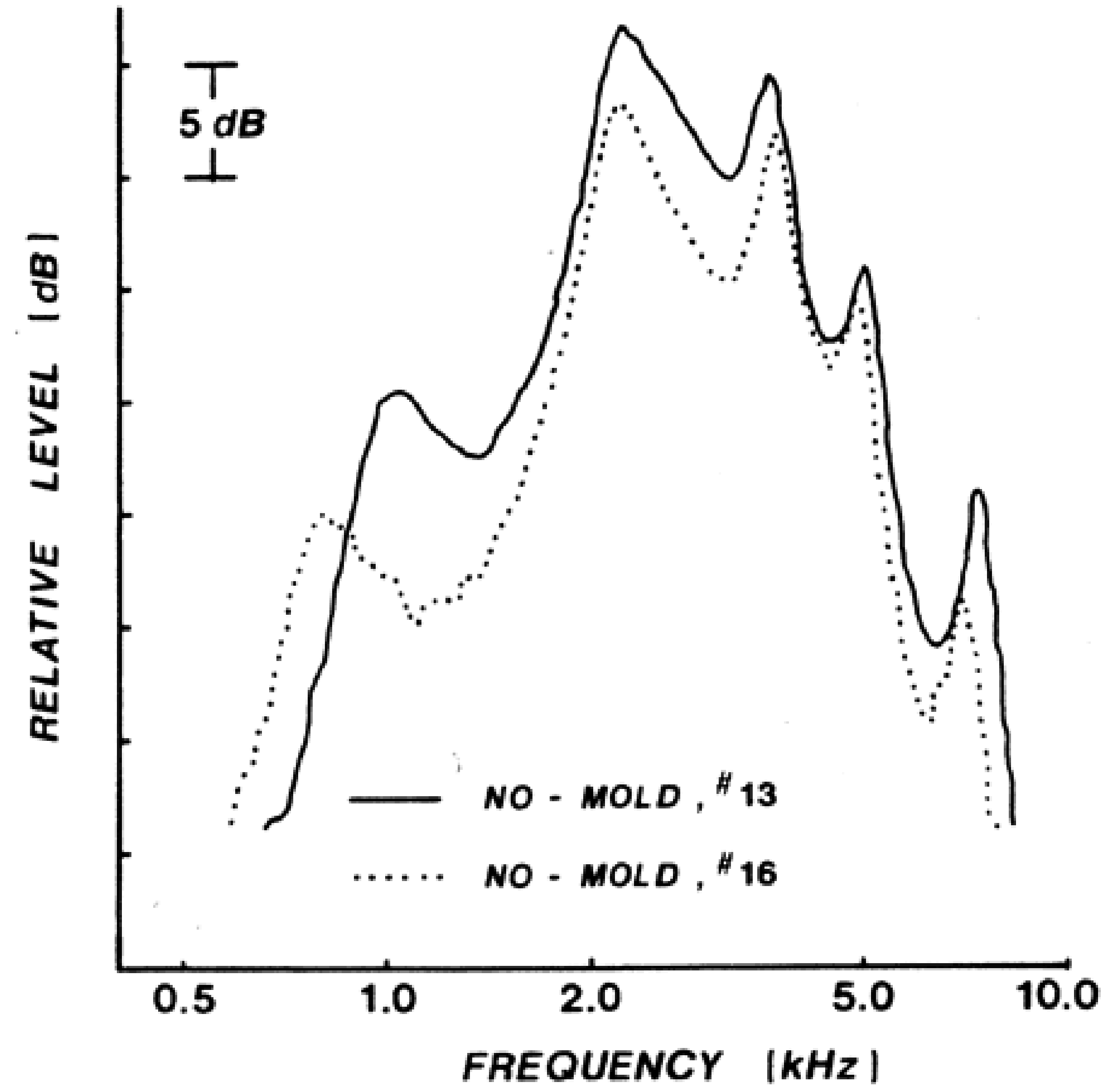

Fig. 29 Spectra measured in the simulated ear canal with two no-mold coupling systems which differ in the diameter of the sound input tubing.

R1 and R4 occur at a lower frequency in the system incorporating the narrower tubing (R5 has also shifted downward in its location). This movement indicates that the effective length of the narrower tubing was 2-3mm greater than that of the wide tubing in this high frequency region. This effect is possibly related to the loss of the acoustic transformer action provided by the wider diameter tubing.

Courtois and Berland (1972) reported that use of a smaller diameter tubing in a no-mold fitting frequently results in better acceptance of the hearing aid by the hearing impaired individual. Perhaps the explanation for this behavior lies in the movement of R1 towards lower frequencies when a narrower tubing is used. As Figure 29 illustrates, the shifting of R1 for narrow tubing, relative to R1 for the wide tubing, results in a decrease in level of about 10 dB at 1100 Hz. (However, there may be an increase in level at lower frequencies.)

Effect of Direct Signal

When an open mold or no-mold fitting is used, the relatively unobstructed ear canal entrance offers an opportunity for the signal to pass directly into the ear canal much as it would in an unaided ear. As a result, the signal present in the ear canal at any instant is a composite of this directly received signal and the amplified version of the same signal which has been routed through the hearing aid. The portion of the signal which enters the ear canal directly is amplified by the normal resonances of the ear canal and concha. In general these resonances supply 10-15 dB of gain in the 2-5 kHz range (Shaw, 1975). In addition, low frequency energy which would normally be blocked by an earmold gains access to the eardrum in the open mold or no-mold fittings. As a result, when a hearing aid is coupled to the ear canal using a no-mold fitting, the signal measured at the eardrum position consists of three components: (1) a low frequency, directly received component; (2) an amplified component in approximately the 800-4000 Hz range, and (3) a high frequency directly received component in approximately the 4-6 kHz range which appears to be comprised mainly of concha resonances. Figure 30 presents an example of the signal measured at the KEMAR's eardrum position when a hearing aid was fitted to the KEMAR's ear with a standard mold (dotted line) and a no-mold fitting (solid line). The level of the input signal at the hearing aid microphone was approximately 65 dB SPL in both conditions and the peak gain provided by the hearing aid (in the no-mold condition) was about 16.0 dB. Comparison of the standard mold and no-mold results reveals that the eardrum level in the no-mold condition was greater than that in the standard mold condition at very low frequencies (about 200-600 Hz) and at very high frequencies (about 4-6 kHz). These two regions of energy are both received directly via the open ear canal. Within the pass-band of the hearing aid (about 700-4000 Hz) the eardrum level in the no-mold condition is lower in the 700-1800 Hz range and higher in the 1800-4000 Hz range than with the standard mold. The pattern of these data is typical of no-mold/open mold fittings although the details differ with different hearing aids and ear anatomy. The net effect is to provide a boost in the middle-high frequency region while retaining both very high and low frequency information in an unaltered state. The major limitation on the use of open mold/no-mold fittings is the occurence of acoustic feedback at relatively low gain levels.

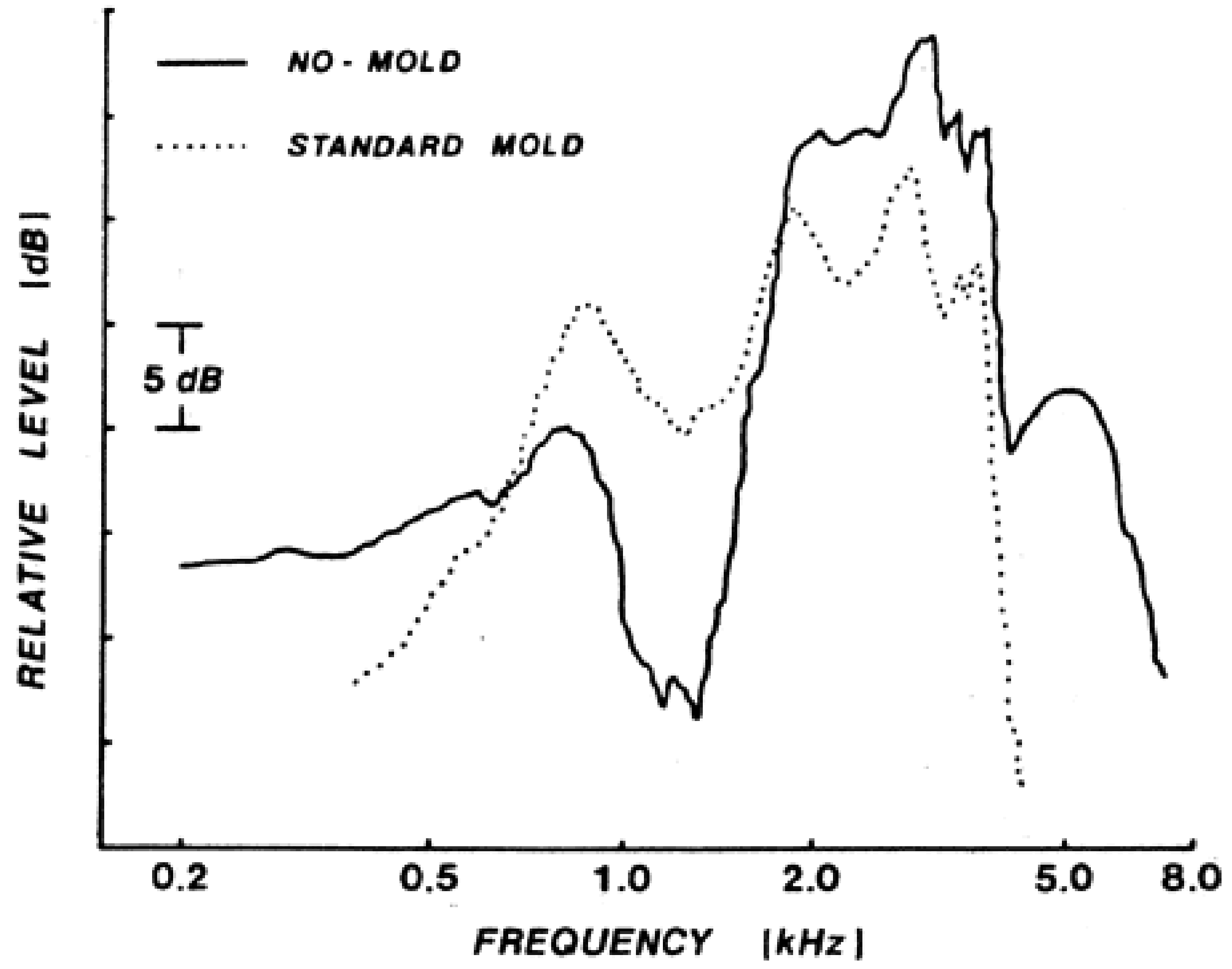

Fig. 30 Spectra measured at the KEMAR's eardrum position with a hearing aid coupled to the ear canal using a standard, unvented earmold (dotted) and using a no-mold fitting (solid).

Cancellation Effects

Within the pass-band of the hearing aid, when a no-mold fitting is used, amplified and unamplified (directly received) versions of the same signal are present in the ear canal simultaneously. These signals combine according to their relative level and phase relationships. Since the processing of the signal by the hearing aid almost always results in some phase shift, the possibility exists of cancellation between the directly received and amplified signals. Such cancellation does occur and is a more prominent effect when the hearing aid gain is at a low setting, thus causing the amplified signal to be not too different in level from that of the directly received signal. The result of this cancellation effect is demonstrated in Figure 31 (Cox and Studebaker, 1978). In this figure the dashed line shows the signal at the KEMAR's eardrum position with the open mold fitted hearing aid turned off (the directly received signal). The dotted line demonstrates the signal at the eardrum position when the output of the hearing aid has been tape recorded and played back through a hearing aid receiver thus providing no opportunity for unamplified signal to enter the ear canal. The dotted line shows, therefore, the signal which would be present at the eardrum position in this open mold fitting if there was no directly received sound energy. The solid line represents the signal at the eardrum position with the hearing aid turned on. The solid line depicts, therefore, the combination of the signals represented by the dotted and dashed lines and, hence, represents the signal as it actually occurs in an open mold fitting. Note that there are several frequency regions (approximately 800, 2000 and 3600 Hz) in which the level of the two signals combined (the solid line) is actually less than the level of the signal provided by the hearing aid alone (the dotted line). This effect is presumably due to cancellation between the amplified and directly-received signals. The exact location and extent of this cancellation effect in open mold fittings varies with different hearing aids. It is a curious phenomenon but is probably of little or no practical significance in most hearing aid fittings.

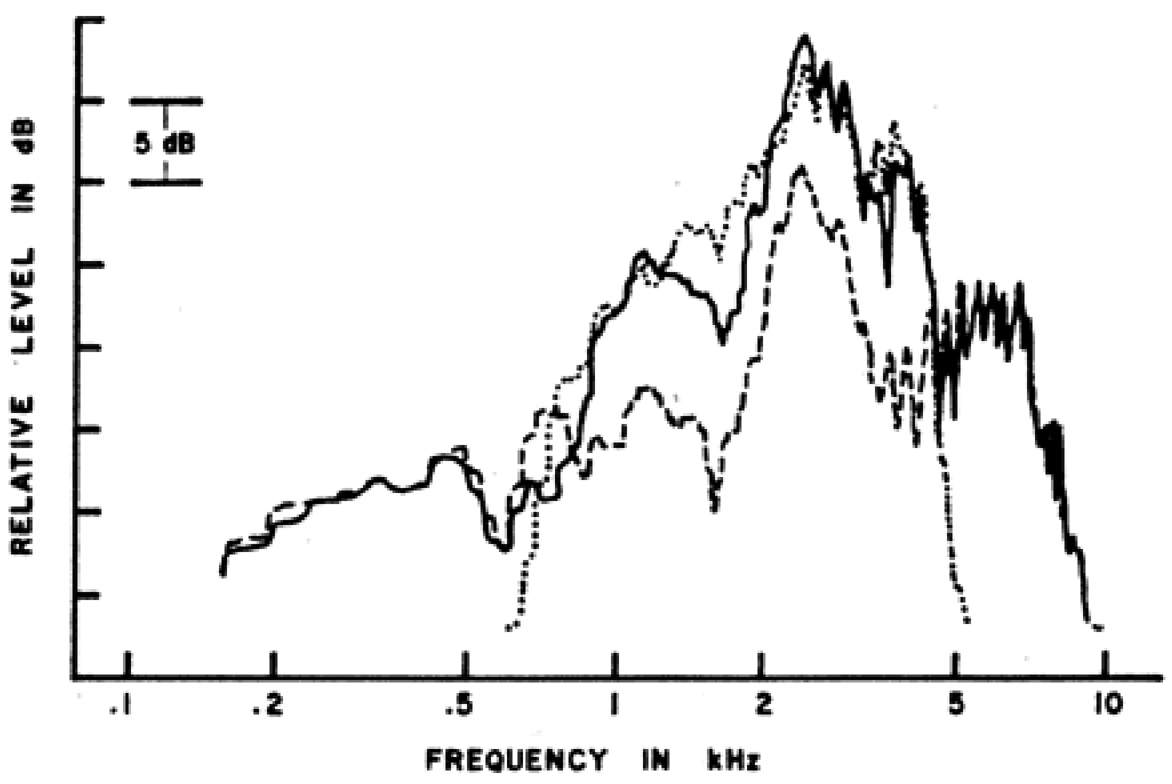

Fig. 31 Spectra measured at the KEMAR's eardrum position with an open mold fitted hearing aid. The directly received signal is shown by the dashed line; the amplified signal is shown by the dotted line; and the combined amplified and directly received signal is shown by the solid line.

Unintentional Acoustic Leaks

All of the previous discussion has been predicated on the assumption that no unintentional acoustic leaks existed around or through the earmold. Yet, unintentional acoustic leaks do frequently exist around the periphery of custom fabricated earmolds. A small leak may even be desirable to prevent excessive air pressure within the ear canal. Experience has shown that some measurable amount of acoustic leakage occurs with almost all earmolds, although the magnitude of the leak varies considerably across individuals and earmolds.

Limited information is available concerning the magnitude and variability of acoustic leaks associated with custom earmolds. The acoustic impedance of the leak existing around a standard earmold was measured and averaged across four subjects by Aspinall and Morton (1957). Lybarger (1978a) constructed a simulated earmold incorporating a leak with the specified impedance and measured the effect of that leak on the signal spectrum at the Zwislocki coupler microphone. The effect of the leak was similar to that expected of a long, small diameter, parallel vent: the low frequency transmission loss was about 1.5 dB at 200 Hz and the "vent-associated resonance" reached a maximum level of about 1.0 dB greater than that of the "unvented" (i.e., no leakage) condition at about 500 Hz. Hence, the presence of this "average" leak had no significant effect (from a practical point of view) on the spectrum measured in the ear canal when a standard earmold was used.

On the other hand, when a vented earmold is used, the effect of a small unintentional leak can be quite significant. This is demonstrated in Figure 32 (Cox and Studebaker, 1978). This figure contains two sets of curves: the upper set shows spectra measured in a real ear canal (using a probe microphone) with a coupling system consisting of a subminiature hearing aid receiver, a short length of tubing and a standard earmold; the lower set of curves presents analogous spectra measured with the same earmold now incorporating a parallel vent. In each set, the dotted line shows the spectrum measured with the earmold worn normally (no particular efforts were made to prevent acoustic leakage), and the solid line shows the spectrum measured after considerable efforts had been made to prevent acoustic leaks.

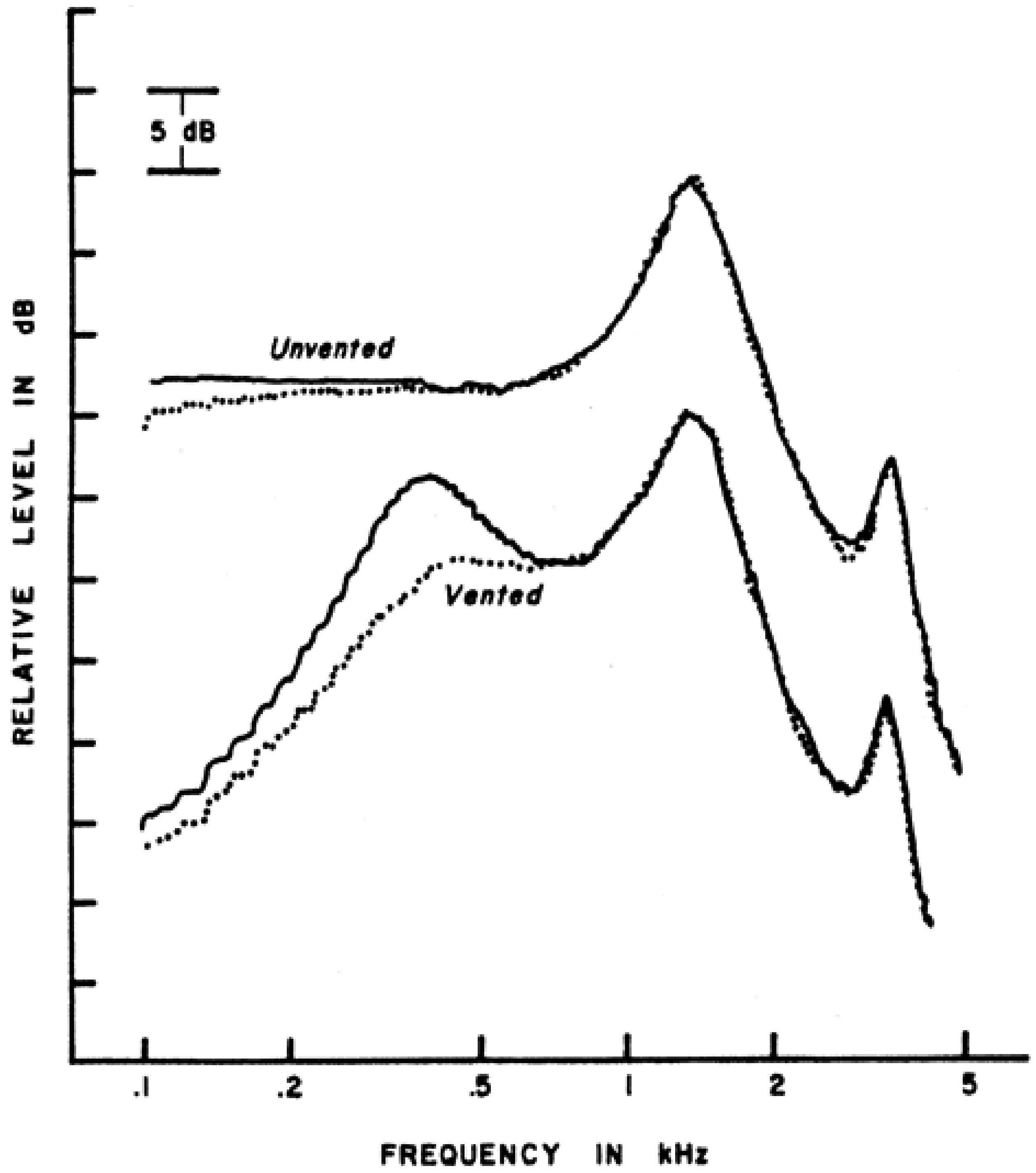

Fig. 32 Spectra measured in a real ear canal with an earmold incorporating a "typical" leak (dotted) and with a maximally sealed earmold (solid). The upper curves show the data for an unvented earmold. The lower curves show the data for a parallel-vented earmold.

Comparison of the two upper curves indicates that the acoustic leakage displayed by the standard earmold was similar in effect to that described earlier for an "average" leak — amounting to a 1 dB reduction in level at 200 Hz. In contrast, comparison of the two lower curves reveals a relatively large effect below about 1 kHz which is attributable to the presence of the acoustic leak: the height of the vent-associated resonance at 400 Hz is reduced 6 dB by the presence of a leak which, by itself, has no effect at 400 Hz.

Work with electrical models of hearing aid-ear canal coupling systems has indicated that the earmold acoustic leak consists of an inertance in series with a large resistance. The presence of this large resistance results in a vent-associated resonance of greatly decreased amplitude and somewhat increased frequency.

Since many vented earmolds also allow some unintentional acoustic leakage around their periphery, it seems likely that the Helmholtz resonance which would normally be produced by the combination of the vent bore and the equivalent volume of the ear canal/eardrum (the vent-associated resonance) will be greatly decreased in these ear canals due to the effect of the unintentional leak. The magnitude of the vent-associated resonance appearing in the ear canal is inversely proportional to the magnitude of the unintentional acoustic leakage around the earmold.

Several investigations relative to the acoustic effects of vented or open earmolds in real ears have shown the vent-associated resonance to be absent from the real ear data, but present in the coupler data (Studebaker and Zachman, 1970; Preves, 1977; Studebaker, Cox and Wark, 1978). Other studies have revealed a measurable vent-associated resonance in real ear canals (McDonald and Studebaker, 190; Studebaker and Cox, 1977). Cox and Studebaker (1977) have shown that when the unintentional acoustic leakage from vented earmolds is eliminated, the vent-associated resonance and the low frequency transmission loss measured in real ear canals is very similar to that seen in an ear simulator coupler such as the Zwislocki coupler.

Occasionally the use of an earmold vent has been recommended to provide enhancement of low frequency output (Lybarger 1967, and 1978a; Goldberg, 1977). This recommendation is intended to take advantage of the vent-associated resonance since it often results in a relative increase in level in the resonance region over the unvented response. As Figure 32 reveals, the height of this resonance is reduced by the presence of any unintentional leakage around the earmold. As a result, enhancement of low frequency levels will occur in a vented earmold fitting only if the earmold allows no significant acoustic leakage around its periphery.

Acoustic Feedback

When acoustic leakage occurs around or through an earmold, some proportion of the hearing aid's output is radiated back into the outside air adjacent to the earmold. Some of this radiated signal reaches the microphone of the hearing aid, thus completing a feedback loop from output to input. When the proportion of the hearing aid's output being fed back to the hearing aid's microphone is equal to the gain of the hearing aid at that frequency, and is in phase with the input, an audible squeal (oscillation) known as "feedback" will occur. The appearance of audible oscillation due to acoustic feedback imposes an absolute limit on the gain available with any given hearing aid/earmold combination.

Effect on Frequency Response

Even when the conditions necessary to produce audible "feedback" do not exist, a fraction of the hearing aid's output is often fed back to the hearing aid microphone after transversing one or more acoustic leakage pathways. This "sub-audible" acoustic feedback combines with the signal which is being presented to the hearing aid from an external source resulting in a change in the spectrum of the signal being presented to the hearing aid. This change in the input spectrum is reflected in a change in the frequency response of the hearing aid's output into the ear canal. The manner in which sub-audible acoustic feedback changes the input to the hearing aid is illustrated in Figure 33 (Cox, 1978). This figure illustrates the spectrum of the signal being presented to the microphone of the hearing aid when no feedback was present (dotted line) and when sub-audible feedback was present (solid line). In each condition, the same external signal was being presented to the hearing aid from a nearby loudspeaker. The data show that when acoustic feedback from the hearing aid was present, the spectrum of the signal being presented to the hearing aid's microphone became much less flat, with several sizable peaks and dips developing as a result of the combination of external signal and fed-back signal.

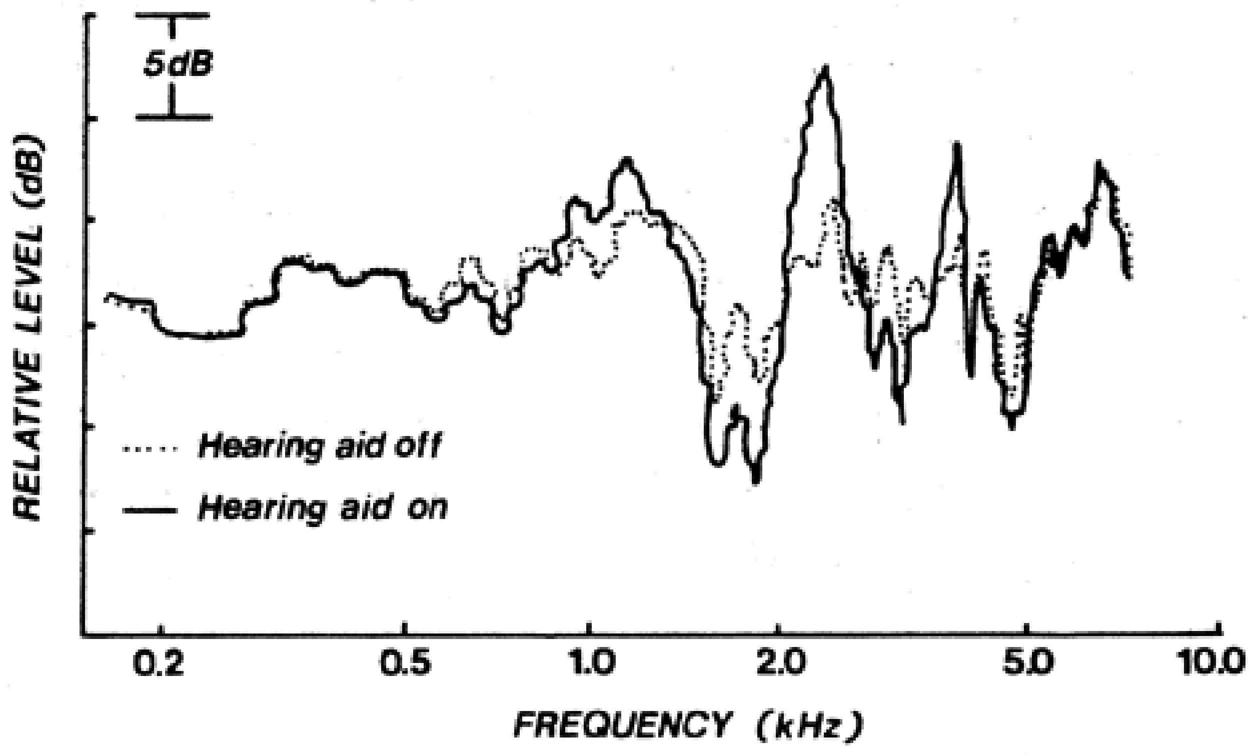

Fig. 33 Spectrum of a signal at the microphone of a hearing aid when no feedback was present (dotted) and when a relatively high level of sub-audible feedback was present (solid).

The introduction of a vent into an earmold (or use of an open/no-mold fitting) serves to increase the level of acoustic feedback by providing a low impedance feedback pathway. As a result, a potential side-effect of using a vented or open earmold is an increased irregularity (greater peak to dip ratio) in the hearing aid's output spectrum due to the effects of sub-audible acoustic feedback. The effects of acoustic feedback are superimposed on the effects of the vent. Figure 34 presents an example of the combined effects of sub-audible acoustic feedback and a side branch vent on the frequency response of a hearing aid measured at the eardrum position of a KEMAR manikin. The dotted line is the frequency response of the hearing aid when coupled to the KEMAR's ear canal using an unvented earmold. The solid line shows the frequency response of the same hearing aid at the same gain setting when coupled to the KEMAR's ear canal using a side branch vented earmold. The gain setting of the hearing aid was only a few decibels below the level required to produce audible feedback in the vented condition. The reader will recall that a side branch vent (in the absence of acoustic feedback) produces a low frequency transmission loss, a possible vent-associated resonance, and a high frequency transmission loss of variable extent. In the example shown in Figure 34, a small vent-associated resonance is seen at approximately 520 Hz. The low frequency transmission loss associated with the vent is quite irrelevant in this case since the hearing aid itself provides little amplification for the low frequencies which would normally be reduced as a result of the presence of the vent. The high frequency transmission loss relative to the unvented mold result is apparent, beginning at 600 Hz. In addition to these effects, peaks can be seen in the vented mold response at 2200 Hz and 3600 Hz. These peaks are attributable to the effects of sub-audible acoustic feedback. It is characteristic of side branch vents to result in high frequency "feedback peaks" (above approximately 2 kHz), whereas parallel earmold vents (and open/no-molds) typically produce the greatest sub-audible feedback effects in the mid-frequency range (approximately 1-3 kHz). In Figure 34, the side branch vent resulted in substantially reduced gain and increased response irregularity instead of producing the anticipated low frequency transmission loss. This is clearly an undesirable outcome. It should be noted that the peaks and dips in the frequency response which are produced by acoustic feedback are maximum when the gain of the hearing aid is set, as it was for these data, at a level just below that needed to produce audible acoustic feedback. If the hearing aid (closed loop) gain is set at a level 10 dB or more below that level which produces audible feedback, these peaks and dips are small (less than a few dB) or absent.

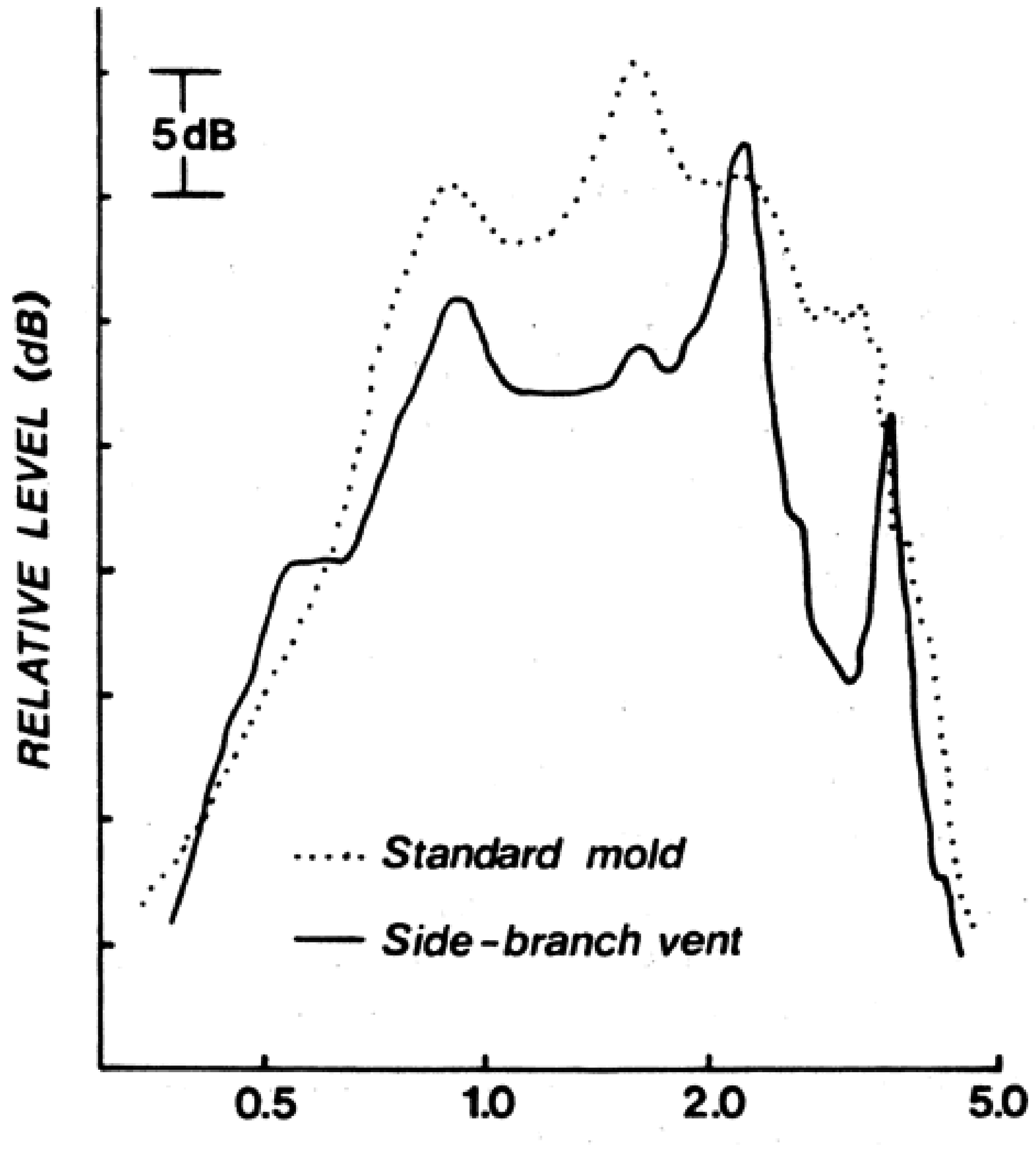

Fig. 34 Frequency response of a hearing aid with a coupling system incorporating a standard, unvented earmold (dotted) and with a coupling system incorporating a side branch vented earmold combined with sub-audible acoustic feedback (solid).

Effect on Available Gain

Audible acoustic feedback is the limiting factor in determining the gain which can be used in many hearing aid fittings, particularly those involving vented, open or no-mold coupling systems. It has been suggested that the threshold for audible feedback in a hearing aid/earmold combination might be affected by the location of the hearing aid's microphone (Grover and Martin, 1974), or by the configuration of the earmold vent (Johansen, 1975; Studebaker and Cox, 1977). The possible effects of these factors were investigated by Cox (1978) using one parallel and one side branch vent, matched in terms of the low frequency transmission losses they produced (the high frequency effects of the two vents were characteristic of the two configurations). Four hearing aids were used, two with front-facing microphones and two with rear (downward-facing) microphones. For each hearing aid/earmold combination the maximum overall (closed loop) gain obtainable before audible feedback occurred was measured by subtracting the overall SPL at the input to the hearing aid from the overall SPL measured at the KEMAR's eardrum position. (This method of measuring gain produces results which may be quite different from standard, three-frequency averaging methods.) The results, shown in Figure 35, indicate that location of the hearing aid's microphone had a negligible effect on available maximum gain, whereas vent configuration seemed to exercise a considerable effect, with the parallel vent allowing 15 dB more overall gain than the side branch vent. These results are consistent with those reported by Grover and Martin (1974) and Johansen (1975).

	microphone front	rear	
parallel vent	49.5 47.5	46.0 48.0	$\bar{X}=47.7$
side-branch vent	31.0 34.0	31.0 34.5	$\bar{X}=32.6$
	$\bar{X}=40.5$	$\bar{X}=39.9$	

Fig. 35 Overall closed-loop gain (dB) for two hearing aid microphone positions and two vent configurations.

FINAL COMMENTS

As indicated in the introduction, this discussion has focused on the acoustic aspects of the hearing aid-ear canal coupling system which are accessible to the hearing aid fitter and may be potentially manipulated to achieve the optimal output. Although general agreement has yet to be reached concerning the frequency-gain characteristic which is optimal in a hearing aid fitting, there is consensus that high frequency information is necessary for good speech intelligibility and that low frequency energy, while it provides a pleasing psychoacoustic quality, should not be too great if maximum speech intelligibility is to be achieved.

A sizable body of knowledge has accumulated about the acoustic behavior of hearing aid-ear canal coupling systems. It seems apparent that the typical, three section coupling system may not be the best one to use in many cases since it tends to de-emphasize the high frequency content of the signal. It is hoped that the reader will be able to utilize the information presented here to modify the system's output in the desired direction.

APPENDIX

The presence of the small side-branch orifice in the earhook introduces an impedance discontinuity at that location which probably divides the 75mm coupling system into two effective lengths of approximately 10mm and 65mm. The impedance discontinuity probably appears as a low impedance termination to each section of tubing. Calculations indicate that the presence of the side branch results in a reduction in the inertance of the tubing system by a factor of .54. These considerations would lead to the following predictions: (1) resonant peaks which are sensitive to tubing inertance should migrate upward by approximately 35%; (2) half wave resonances of the longer section of tubing should appear at the output and the quarter wave resonances characteristic of the typical system output should disappear. The data shown in Figure 5 only partially support this interpretation.

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