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ON SOUND TRANSMISSION: AUDIOLOGICAL
IMPLICATIONS.

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THE EFFECTS OF TYMPANIC MEMBRANE PERFORATIONS ON SOUND TRANSMISSION: AUDIOLOGICAL IMPLICATIONS

by

BARBARA KRUGER

A dissertation submitted to the Graduate
Faculty in Speech and Hearing Sciences in
partial fulfillment of the requirements
for the degree of Doctor of Philosophy,
The City University of New York

1975

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ABSTRACT

A small tympanic membrane (TM) perforation produces a low frequency response-loss in terms of sound pressure changes in front of the TM re: a 10μV round window cochlear microphonic (RW CM) that varies inversely with frequency at a rate of 12 dB/octave with a surgically shortened ear canal (EAM, feline). Its frequency pattern is determined by changes in the (calculated) net sound pressure acting on the TM. Response-losses were also determined at the outer opening and at the TM of four artificial EAMs of various lengths, volumes and leakiness. In the low frequency region, a leaky EAM produced a flat response-loss. In the mid-frequency region, the flatness of response-losses was attributed to 1.) the length of the EAM and 2.) the location at which the response-loss was determined. EAM volume was not related to the configuration of the loss. Response-losses, under all conditions, were always identical in shape and magnitude for the open and closed systems. Clinically, hearing losses due to TM perforations are essentially frequency independent especially in the low frequencies. The relation between voltage changes and response-losses with different EAMs suggest that the differences between audiometric results and CM response-losses -- at least in the mid- and high frequencies -- may be due to the use of precalibrated SPLs in clinical audiometry.

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CHAPTER I. STATEMENT OF THE PROBLEM

The effects of tympanic membrane perforations on sound transmission have been studied for more than the last century both in humans and in experimental animals. In human listeners, a perforation usually produced a hearing loss; its frequency and intensity characteristics have been determined either with tuning forks (an open sound delivery system), i.e., before the introduction of electronic audiometers, or audiometrically (earphones - a closed sound delivery system). In experimental animals (usually cats), the response loss produced by a perforation has been determined either by the change in sound pressure necessary to elicit a criterion cochlear microphonic potential, or by the change in sound pressure necessary to produce a criterion ossicular displacement.

There is no consensus on the auditory effects of tympanic membrane (TM) perforations of either traumatic or experimentally induced origin. Reports vary greatly. There may be: 1.) little or no effect on hearing (Cooper, 1800; Bingham, 1907) or little or no response loss (Crowe and Hughson, 1932; Wagemann, 1953); 2.) a small frequency independent amount of loss over the entire auditory range (humans: Toynbee, 1860; Treitel, 1903; Pohlman, 1941; Shambaugh, 1967; rabbits: Lorente de No' and Harris, 1932; Lorente de No', 1933) 3.) a low frequency loss which is independent of frequency in that region (humans: Minton, 1925; Bordley and

Hardy, 1937; Kobrak, 1959; Anthony and Harrison, 1972; cats: Bordley and Hardy, 1937; Wever, 1950; Payne and Githler, 1951 Goto and Hibino, 1954; Kanabu, 1954; and 4.) a low frequency loss which varies inversely with frequency (humans: Bekesy, 1936, 1939, and 1960; Kobrak, 1959 p. 163 for one individual; cats: McArdle and Tonndorf, 1968). The effect of a perforation varies with size and location. Animal experiments have shown that the largest percentage of the transmission loss is due to the removal of the first 10% of the TM or even less, and that the amount of loss increases approximately 5 dB per 10% of TM area as more TM is removed (Lorente de No' and Harris, 1932; Wever, 1950; Wagemann, 1953; Goto and Hibino, 1954; Wever and Lawrence, 1954). Generally, it has been found that, until the entire TM has been extirpated, postero-superior lesions produce more loss than antero-superior lesions, which in turn produce more loss than inferior lesions (Lorente de No' and Harris, 1932; Wever, 1950; Payne and Githler, 1951; Goto and Hibino, 1954; Wever and Lawrence, 1954; McArdle and Tonndorf, 1968). Bordley and Hardy (1937) found that the largest loss was caused by a lesion in pars flaccida and the next largest loss by a posterior TM lesion. Crowe and Hughson (1932) were the only investigators who found no difference in the amount of loss induced by anterior or posterior TM lesions.

The most recent and best controlled study in cats on the nature of the loss induced by a small (1 mm^2) perforation (McArdle and Tonndorf, 1968) showed a low frequency response loss which varied inversely with frequency at the rate of 10.2 dB/octave under conditions of either open or closed sound systems. The degree of loss did vary with the location of the lesion, but the shape of the function did not. The earlier studies of Payne and Githler (1951) and of Goto and Hibino (1954) had indicated that a TM perforation produces a flat low frequency response loss, i.e, independent of frequency below 1000 Hz. However, McArdle and Tonndorf (1968) showed that this flat loss was due to the presence of an open bulla in the surgical preparation of the cats used by Payne and Githler (1951) and Goto and Hibino (1954). With the bulla closed, McArdle and Tonndorf (1968) found a low frequency response loss which varied inversely with frequency. They determined that the response loss was due to an alteration of the differential pressure acting upon the TM by partial cancelation of the incident pressure, mainly in the low frequency region, because a small hole in the TM acts as a low pass filter. (This notion had been previously suggested: by Bekesy (1936, 1939, and 1960) - additional path through the perforation; by Wever (1950) and Wever and Lawrence (1954) - back pressure; and by Kobrak (1959) - loss of baffle effect.)

In contrast to these animal findings, studies of hearing loss in humans with TM perforations showed essentially flat, low frequency losses (Bordley and Hardy, 1937; Anthony and Harrison, 1972) or flat losses across all frequencies (Shambaugh, 1967). The data reported include many variations in hearing loss configuration which seem to be somewhat related to the size and location of the perforation (size: Toynbee, 1860; Kobrak, 1959; Shambaugh, 1967; Anthony and Harrison, 1972; location: Shambaugh, 1967. However, it would be noted that, in humans, perforations cannot be experimentally controlled in size and location. Those suitable for study are usually traumatic in origin and are likely to be accompanied by other complicating factors (bleeding, and/or disarticulation of the ossicular chain). On humans, only two sets of data exist that show low frequency losses which vary inversely with frequency: the first stems from "calibrated" tuning fork testing of human patients with TM perforations (Bezold and Siebenmann, 1908; Ostmann, 1909; cf. also Feldman, 1970); the second was assessed by measuring TM displacement on human cadavers with experimentally induced perforations (Bekesy, 1936).

The existing data on humans appear to conflict in that the open and closed system findings differ from each other: open - low frequency loss increasing with inverse frequency as measured via tuning forks (patients) or manubrial displacements (cadavers); closed - flat low frequency loss. However, there was no essential difference between open and closed sound system data in cats; low frequency losses increased with inverse frequency in both cases (McArdle and Tonndorf, 1968).

There are two hypothetical explanations for this conflict worthy of testing. For a number of reasons (see Chapter II), it appeared best to perform the necessary experiments on cats, and to employ the registration of cochlear microphonic responses (CM) at the round window (RW) as the method for assessing the changes in middle ear transmission due to a TM perforation.

I. An audiometer is calibrated by placing its earphone on a specially designed coupler[1] and adjusting the signal voltage across the earphone until a standard acoustic output level (specified by ANSI S3.6-1969) is obtained. The coupler respresents the acoustic properties of a human ear canal and TM. Therefore, when the earphone is placed on a patient's ear, it is assumed that a given voltage across the earphone, as regulated by an attenuator, represents a definite sound pressure in the ear canal in reference to the calibration value.

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[1] The National Bureau of Standards 9-A coupler, specified by ANSI S3.7-1973 standards, is a short, wide cylindrical. hard-walled, slightly leaky 6 cc cavity.

The relation between voltage across the earphone and SPL in the ear canal is correct only as long as the impedance the earphone looks into is reasonably similar to that of the coupler, i.e., when one deals with patients with sensorineural disorders, but normal middle ears. If, however, the middle ear impedance is altered (e.g., by a TM perforation), the above relation is no longer necessarily valid. This follows from consideration of electrical analog networks. If, for instance, the impedance the earphone looks into would decrease on account of a perforation, there would be a drop in SPL, which is the equivalent of an I·R drop in an electrical system. In that case, the voltage across the earphone would indicate a higher SPL than what really existed. Such an altered relation between voltage and SPL could conceivably affect the configuration of the audiogram.

With an open system, however, one would not expect alterations of middle ear impedance to affect the transducer output because the system is loosely coupled and the transducer works essentially into the impedance of air.

Therefore, it appeared appropriate to study the relation between voltage values across the transducer and the sound pressure necessary to produce a criterion round window cochlear microphonic (RW CM) that expresses the transmission loss due to a TM perforation. It was planned to take these measurements in the same animal for both open and closed sound systems.

II. An alternate explanation might be that the flat configuration of the low frequency loss caused by a perforation when measured audiometrically in a closed system may have to do with the presence of an ear canal. The various measurements taken via microphones or RW electrodes in experiments on cats had required the surgical removal of the pinna and all but a 1.0 cm length of the cartilaginous portion of the external auditory meatus (EAM). The measurements of manubrial displacements (Bekesy, 1936) in human cadavers were likewise made after removal of the pinna and the EAM, in an open system.

The only testing condition which, in human listeners, produced a low frequency hearing loss that varied inversely with frequency was that using calibrated tuning forks, i.e., in an open system. The presence of a canal would be less significant in an open system than in a closed system for the reasons just discussed. Therefore, it appeared appropriate to study the relation between the characteristics of length, volume, and leakiness of an artificial ear canal and the nature of the RW CM response loss in cats with small TM perforations.

In summary, there were two propositions open to testing. The goal of Experiment I was to study the relation between the electrical voltage values across the transducer and the sound pressure (amplitude and phase) in front of the TM necessary to produce a criterion RW CM: a.) before and after TM perforations and b.) in open and closed sound systems. It was further planned to measure, under all these conditions, the sound pressure immediately behind the TM - i.e., in addition to that in front of it. The two sound pressure values would permit the calculation of the effective pressure acting on the TM. The latter value and its change with frequency could then be related to the magnitude of the response loss and its change with frequency produced by the perforation. The goal of Experiment II was to study the relation between the physical characteristics of length, volume, and leakiness of an artificial EAM and the nature of the RW CM response loss induced by the TM perforation. The response losses would be determined for two positions of the microphones: 1.) at the entrance to the artificial EAM; and 2.) at the TM.

CHAPTER II. REVIEW OF THE LITERATURE

The mechanism for sound transmission in a normal ear must be considered as the reference condition in order to explore the effects TM perforations have on sound transmission.[1] The interposition of the outer and middle ears between the open air, in which sound is propagated, and the fluid filled sensory organ (cochlea), which processes that sound, facilitates sound transmission into the cochlea. The outer and middle ears serve as impedance matching transformers compensating for the transmission loss that would occur without them. A transmission loss of 30 dB occurs on an open air/water boundary (Wever, Lawrence and Smith, 1948; Lawrence, 1950): only 0.1% of the incident sound energy will enter the water, while 99.9% will be reflected.

The Outer Ear

The outer ear consists of the ear canal (EAM) and the pinna. There is a pressure transformation due to the combined effects of the diffraction around the head and pinna, and the EAM resonance; the ratio between the sound pressure at the TM and the sound pressure in a free field is near 0 dB

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[1] With respect to such purely mechanical problems, the outer and middle ears of mammals, including man, are very similar to each other. Therefore, the use of cats in these experiments and the comparison between data from experiments with cats or humans is quite appropriate. Furthermore, in addition to the fact that there is a large body of literature on cats, the cat middle ear is wide and largely accessible to surgical manipulation.

in the low frequencies (< 1 kHz), it increases to a maximum of 10-20 dB around 3-4 kHz, and then decreases (Wiener and Ross, 1946; Bekesy, 1960; Wiener, Pfeiffer and Backus, 1966; Tonndorf and Khanna, 1967; Bauer, Rosenheck and Abbagnaro, 1967; Djupesland and Zwislocki, 1972; Price, 1972, 1974a; Shaw, 1969, 1974). The sound pressure transfer function (from the outer ear to the TM) varies somewhat with the azimuth up to 8 kHz. This ratio is largest for perpendicular incidence. The elevation of the sound source is significant at $f > 5$ kHz; the pinna contributes to the increase in pressure in the 2-6 kHz region (Flynn, 1965; Markey and Moshier, 1971; Shaw, 1974). Diffraction of sound due to the head and pinna contributes to the increase in pressure in the high frequency region, since, as frequency (*f*) increases, the wavelength (λ) decreases until around 1600 Hz it approaches the size of the head. This head shadow effect introduces interaural intensity differences mainly in the high frequency region; they are cues for localization. Diffraction, however, accounts for only a small part of the transfer function in one ear.

The increase in pressure at the TM is due primarily to the EAM resonance. Since the EAM can be considered a tube with rigid termination (the TM), the theory of resonant tubes predicts that its resonant frequency should occur at the 1/4 λ; its wavelength is four times the length of the EAM. There is also an anti-resonant frequency at $1/2\lambda$ (Wiener and Ross, 1946; Olson, 1947; Djupesland and Zwislocki, 1972). The resonant frequency for the outer ear varies according to the location to which the sound pressure at the TM is referred: entrance, 3.5 kHz; tragus, 3.2 kHz; 1 cm external to the tragus, 3 kHz (Djupesland and Zwislocki, 1972). Wiener and Ross (1946) probably made one of their measurements at, or just lateral to, the tragus since their maximum enhancement occurred at 3 kHz. For the cat (Weiner, Pfeiffler and Backus, 1966), the pressure ratio reaches its maximum at 4 kHz which agrees well with Kirikae's (1960) calculation of 4100 Hz as the cat's EAM resonance.

Both electrical networks and physical models of the EAM have been designed to simulate the sound pressure transfer function for predictive value and for the purpose of testing earphones (Bauer, Rosenheck and Abbagnaro, 1967; Teranishi and Shaw, 1968; Shaw and Teranishi, 1968; Gardner and Hawley, 1971, 1972); the standard NBS 9-A coupler (ANSI S3. 71973) might also be considered a model of the outer ear. Sinyor and Laszlo (1971, 1972) have shown that the EAM can be represented by a tube that is open at one end and has the appropriate dimensions.

The unoccluded outer ear behaves differently form the occluded outer ear -- the ear with an earphone on. With an earphone occluding the canal, 6-10 dB more sound pressure is needed in order to produce the same loudness sensation that is generated by a sound source in open air, e.g., a loud speaker. Minimum audible pressures (MAP) require higher SPLs than do minimum audible fields (MAF) (Sivian and White, 1933; Stevens and Davis, 1938; Munson and Wiener, 1952). This as yet unexplained difference has been attributed to physiological noise, static pressure changes in the outer and middle ear, receiver fit, middle ear muscles, and/or the fact that the loudness change is a CNS effect.

The ear canal itself is responsible for some low frequency leakage due to the compliance of the tissues of the cartilaginous ear canal (Sivian and White, 1933; Olson, 1947; Tonndorf, et. al., 1966; ANSI S3.7-1973). Tonndorf, et. al., (1966) found that the bone conduction occlusion effect was optimal when the occlusion was made directly at the end of the osseous part of the canal; it became less when the occlusion was made within the cartilaginous part of the canal. Furthermore, in an occluded EAM, some of the low frequency leakage is obviously caused by the quality of the fit between a supra-aural earphone cushion and the pinna (Sivian and White, 1933; Munson and Wiener, 1952; Erber, 1968; Villchur, 1970; Zwislocki, 1970, 1971; ANSI S3.7-1973. Some of the variability in threshold determination is due to such physical variables as 1.) cushion/pinna seal, 2.) earphone application force, 3.) ear canal volume, and 4.) earphone cushion type, which affect the acoustic stimuli (Erber, 1968). In fact, because of the problems in reproducibility of seal, force and position, Villchur (1970) designed a vented circumaural phone in order to better predict the way the ear canal behaves when occluded by an earphone.

Certainly the single, most-important characteristic of an earphone (as used in audiometry, at least,) is "the accuracy with which the sound stimulus it presents to the subject can be predicted from the electrical input" (Villchur, 1970, p. 1387). The sound pressures generated in an acoustic coupler, or in an artificial ear, when a specific earphone is activated by a certain voltage, should be equivalent to the sound pressures generated by the same earphone in a real EAM; that is to say, a coupler should present the same acoustic impedance (load) to the earphone as does the average ear (Morton and Jones, 1956; Larson, 1973). There are, however, some discrepancies between the sound pressures generated in an artificial ear and in a real ear which exist predominantly at $f > 1$ kHz (McDonald and Studebaker, 1970; Villchur, 1970; and Larson, 1973). These discrepancies are due both to normal intersubject variation in the impedance that each subject's ear presents to the earphone (Benson and Eldredge, 1965) and to the fact that the artificial ears currently employed do not adequately represent the acoustic impedance of the ear. In this regard, the Zwislocki ear-like coupler (1970, 1971) represents a better approximation than the standard NBS 9-A acoustic coupler (ANSI S3.7-1973). It must be noted that both of these couplers have a capillary tube incorporated in their design which provides a "leak" permitting the equalization of static air pressures that build up in the coupler (or in the EAM) while the earphone is on the coupler (Corliss and Cook, 1948; Zwislocki, 1970, 1971; ANSI S3.7-1973; Larson, 1973).

The Middle Ear

Transformer Mechanism

The impedance matching achieved by the middle ear transformer is the result of three combined effects: 1.) the tympanic membrane/oval window area ratio, 2.) the ossicular lever ratio and 3.) the TM lever ratio. Together, they provide a mechanical transformation which appears to compensate almost completely for the impedance mis-match between the environment and the cochlear fluid. The ossicular lever ratio (the ratio of the forces acting on the lower tip of the malleus (umbo) to those acting on the stapes) is approximately 2.2 for cats (Wever and Lawrence, 1954; Tonndorf and Khanna, 1967) and 1.3 for man (Dahmann, 1930; Bekesy, 1941, 1960; Fischler, Frei, Spira and Rubinstein, 1967). It had been thought that the TM is hinged superiorly, around the ossicular axis of rotation, and that it vibrates as a rigid stiff plate with equal amplitude curves that run perpendicular to the malleus (Bekesy, 1941). A lower fold, just below the malleus, was thought to facilitate this mode of displacement. Since the lower fold seemed to be decoupled from the rest of the TM, it was thought that it did not participate in sound transmission through the middle ear. Therefore, the effective area of the TM was considered to be between 2/3 and 3/4 of the whole TM area. In other words, the effective area ratio of the TM was 24 for the cat and 17.5 for man as compared to the total ratio of 36.5 for the cat and 26 for man Wever, Lawrence and Smith, 1948; Bekesy, 1949, 1960; Lawrence, 1950; Kirikae, 1960). However, not only has it been shown that no lower fold exists, but also it has been demonstrated that the vibrational pattern of the TM has equal amplitude lines that run parallel to the malleus, a pattern that remains unchanged up to 2 kHz. The TM becomes essentially decoupled from the malleus at $f \geq$ 3-4 kHz (Tonndorf and Khanna, 1970, 1971, 1972; Khanna and Tonndorf, 1972; Tonndorf, Khanna and Greenfield, 1972). Below 1 kHz, the whole TM acts as the sound receiver. There is a range of transition between 1 kHz and 4 kHz, and, above 4 kHz, the TM acts as a baffle, while the manubrium is the sole receiver. The TM vibrates according to the <u>curved membrane</u> or <u>catenary</u> principle. This mode of action was first suggested by Helmholtz (1868, 1873), but his experimental results were in error due to a mathematical slip finally detected by Hartman (1971). The radial and circular fibers of the TM are nonelastic, i.e., collagen (Lim, 1970), a finding which is compatible with Helmholtz's vibrational principle (Tonndorf and Khanna, 1972). The curvature of the TM assumes the role of a lever; the less the curvature, the larger the transformer ratio. There is a reciprocal relation between the contributions of the curved membrane mechanism and of the ossicular lever ratio. All parts of the TM contribute equally to the transformation process. In that case, however, the ossicular lever ratio is smaller than that measured from the tip of the malleus to the stapes. For the cat, the "effective" ossicular lever ratio was calculated as only 1.2, instead of 2.2, and for man it may even be smaller than one. However, the effective area of the TM is that of the entire TM; the area ratio is thus 36.5 for cats and 26 for man. For the cat, the TM transformer ratio is approximately 2.0. Therefore, the combined ratio of the middle ear transformer is 87.6 for cats (38.9 dB) and 69 for man (36.8 dB) (Khanna and Tonndorf, 1972).

The pressure transformation ratio of the middle ear is described by the ratio of stapes displacement to the sound pressure at the TM. This ratio is constant up to 2-3 kHz, above which it drops off with the square of frequency (Bekesy, 1941, 1960; Perlman, 1949; Wever and Lawrence, 1950; Lawrence, 1962; Møller, 1963, 1964a; Guinan and Peake 1967; and Khanna and Tonndorf, 1969). Based on this information, Bekesy (1960) stated that the low frequency limitation of the threshold curve has apparently no basis in middle ear function. However, Khanna and Tonndorf (1969) demonstrated that the calculated power transformation of the middle ear attenuates inversely with frequency below 2-3 kHz and is approximately constant above that frequency, to decrease once more at higher frequencies. This finding indicates that the low frequency attenuation of the auditory threshold might well be a function of the impedance matching properties of the middle ear. Again, middle ear models (Onchi, 1949, 1961; Møller, 1961b, 1963; Zwislocki, 1962; Peake and Guinan, 1965) have been designed in order to better understand middle ear function and to formalize its detailed functions.

The middle ear transformer mechanism is essentially linear up to very high SPLs. Stapes displacement is linear below 130 dB SPL (Bekesy, 1949; Wever and Lawrence, 1950, Pong and Maracaccio, 1963; Guinan and Peake 1967). Price (1974), using the CM as an indicator, showed that the nonlinearlity, for free field stimuli, begins between 110 and 120 dB SPL in the mid-frequency region, a finding which is consistent with the results of others due to the enhancement effect of the EAM resonances in that region. Rubinstein, Feldman, Fischler, Frei and Spira (1966) showed that the nonlinearity of stapes displacement begins at 104 dB SPL, when the middle ear system was unloaded; i.e., when there was no cochlear fluid. At SPLs above 130 dB SPL, subharmonics, equal to 1/2f, may be heard. This latter phenomenon has been attributed to the change in the displacement pattern of the stapes as described by Bekesy (1941) and/or the differences in amplitude between inward and outward TM displacements. Therefore, it is important that, in order to avoid non-linear effects, experiments be performed at SPLs that fall within the linear range of the middle ear mechanism.

The tympanic cavity is air filled. The normal middle ear, then, contains an air cushion (Stevens and Davis, 1938) which is lost when there is a perforation in the TM or in animals, so equipped, when the bulla is opened.

The middle ear transformer is changed by the impedance of the middle ear (Fowler, 1920; Wever, Bray, and Lawrence, 1942; Wever, Lawrence and Smith, 1948; Guinan and Peake, 1967; Tonndorf and Khanna, 1967, 1968; Funnell, 1974). Tonndorf and Khanna (1968) demonstrated, in cats, that when the bulla is closed the middle ear transformer works just below the optimal matching region of the power transfer curve. (The power transfer between two systems is best when the impedances of the two systems are equal.) When the bulla is open, however, the spring action of the air cushion is reduced (decreased compliance) and the opening also introduces a shunt (increased inductance). Consequently, the reactance is less with the bulla open. This lowers the input impedance of the middle ear and shifts the transformation into the overmatched region of the power curve. With the bulla open, there is an improvement in transmission of 6 to 10 dB for the low frequency region (Guinan and Peake, 1967; McArdle and Tonndorf, 1968). Also, the resonant frequency of the middle ear is lowered from 2300 to 1600 Hz (Møller, 1963).

Normally, of course, the bulla is closed and the middle ear pressure is equalized by the action of the Eustachian tube. However, in an anesthetized (and tracheotomized) animal, this pressure equalization process is inactivated. Therefore, with a closed bulla, a negative middle ear pressure builds up. The accumulation of negative middle ear pressure (due to the absorption of the air in the middle ear by the middle ear mucosa) causes an increased tension of the TM (stiffness) and interlocking of the auditory ossicles (damping) both of which reduce sound transmission through the middle ear. As an outward sign of it, the CM output is reduced (see later). A decrease in this cochlear potential must be compensated by an increase in SPL. The largest increase in SPL (8.5-20 dB) is required in the low and mid-frequencies (Mundie, 1963). The increase in stiffness, due to negative middle ear pressure, causes an increase in the resonant frequency (Møller, 1963). Then, a vent or capillary tube, acting as a low pass pressure release, is necessary to equalize static middle ear pressures in anesthetized or tracheotomized experimental animals in order to prevent the middle ear transmission from being attenuated. Such a vent has been employed in this laboratory for quite some time (Tonndorf and Khanna, 1968).

The Muscles

The two middle ear muscles -- the stapedius and the tensor tympani muscles -- work antagonistically; the former pulls the stapes into the middle ear cavity while the latter pulls the TM inward (Moller, 1964b, 1972). However, both of these actions serve to interlock the ossicular chain. (For a review of relevant anatomy see Blevins, 1964). The stapedius responds at lower intensity levels <u>and</u> with shorter latencies than does the tensor tympani (Loeb, 1964). Although <u>both</u> muscles respond to acoustic stimuli, the tensor tympani's response is less (Weiss, Mundie, Cushin and Shinabarger, 1962; Møller, 1965, 1972). The effect of the muscle reflex contraction is seen in the reduction of the EMG response and in an attenuation of middle ear transmission, i.e., size of the CM output. There are also changes in the psychophysical measures of absolute threshold, loudness and TTS (Lawrence, 1961; Lawrence, Wolsk and Schmidt, 1962; Wever, 1962; Holst, Ingelstedt and Örtegren, 1963; Loeb, 1964; Møller, 1972). The reduction in EMG is a more sensitive measure than is CM attenuation, but often not by more than 10 dB sound pressure; there is a good correlation between the two of them (Simmons, 1962). The muscle reflex is not precisely related to cochlear sensitivity (Simmons, 1964). There is bilateral interaction between these two sets of muscles. At low to moderate intensities, the binaural response is stronger than the monaural response, but there is no difference in response strength at high intensities (Møller, 1964b, 1972; Simmons, 1965). Research efforts have so far failed to prove whether the middle ear muscles function as limiters (contract with the same strength to stimuli at and above a specific SPL) or as differential attenuators (produce a different degree of contraction for faint stimuli than for intense stimuli) or in some combination of these two mechanisms (Jepsen, 1951; Loeb, 1964; Price, 1967, 1969; Møller, 1961b, 1972). The middle ear muscle reflex is abolished by deep (Nembutal) anesthesia (Simmons, 1959; Perlman, 1960; Carmel and Starr, 1963; Baust and Berlucchi, 1964). Simmons (1959) showed that the major difference between an awake and an anesthetized cat's CM response was due to the action of the middle ear muscles. The effect of the reflex was strongest for the low frequency signals (see also Stevens and Davis, 1938).

The CM and its Relation to Hearing

The cochlear microphonic is a local, graded AC potential, generated by the hair cells as a result of the deflection of their sensory hairs which is produced by the shearing movement between the tectorial membrane and the organ of Corti (Tasaki, Davis and Legouix, 1952; Tasaki, Davis and Eldredge, 1954; Davis, 1968; Karlan, Tonndorf and Khanna, 1972; Dallos, 1973). This electrical potential has 1.) no threshold, 2.) no latency, 3.) no refractory period and 4.) there is no evidence of adaptation or fatigue. Instead of a threshold, there is simply a limiting noise level (Stevens and Davis, 1938; Davis, 1957; Dallow, 1972, 1973). The CM represents the cumulative response of a large number of hair cells and can be recorded from many locations: either from within the cochlear (differential electrodes) or from as near to the inner ear as the round window (gross electrodes) to as far away as the ear lobe (Cullen, Ellis, Berlin, and Lousteau, 1972; Dallos, 1973). The further away the pick-up electrode, the more averaging is needed to resolve the response. A gross RW electrode records the CM primarily from the very high frequency region of the basilar membrane -- somewhat less than the first turn. Simmons and Beatty (1962) showed that the input/output function of the RW CM does not reflect cochlear changes that occur more apically than a very few mm from the RW. Within its linear range, the CM output is proportional to the intensity of the acoustic stimulus acting on the ear (TM), especially in the low frequencies. The input/output function is a linear power function at low and moderate intensities; i.e., at outputs below 200 μV (Wever and Bray, 1938; Engelbretson and Eldredge, 1968; Dallos, 1973). This relation breaks down at high intensity levels. At these high levels, harmonic and odd and/or even subharmonic distortions (at least in the guinea pig) may become apparent (Dallos, 1966; Dallos and Linnell, 1966a,b). After cochlear injury, the shape of the input/output function may become truncated (reduced saturation point) and/or shifted to a higher input intensity (Tonndorf and Brogan, 1952).

The CM is proportional to the first time derivative of stapes displacement, i.e., stapes velocity, and since the basilar membrane displacement is proportional to stapes velocity, the CM is also proportional to basilar membrane displacement. Furthermore, both the RW CM and the vibratory velocity of the cochlear fluids are proportional to the vibratory velocity of the malleus. Also, since the reciprocal of the vibratory velocity of the malleus, for a constant SPL at the TM, is proportional to the acoustic impedance, the CM is proportional to the inverse of acoustic impedance or to admittance (Wever, Rahm and Strother, 1959; Bekesy, 1960; Mundie, 1963; Møller, 1965; Guinan and Peake, 1967; Tonndorf and Khanna, 1967; Dallos and Durant, 1972; Dallos, 1972, 1973). Therefore, since the CM is essentially a measure of sound pressure transmission through the middle ear, (gross RW electrode) recordings of the CM can be used to study transmission properties of the middle ear (Dallos, 1957; Simmons and Beatty, 1962;

Guinan and Peake, 1967; Dallos, 1973).

Although the CM output varies proportionally with the acoustic input level, there is no simple correlation between CM electrical sensitivity and behavioral auditory sensitivity. The auditory sensitivity of cats has been determined and was contrasted with that of humans by Elliot, Stein and Harrison (1960) and by Miller, Watson, and Covell (1963). The cat has an auditory frequency range which is three times wider than that of man. Its absolute threshold levels are better, while its frequency discrimination ability is poorer. The sensitivity of cat and man is only nearly identical at the low frequency end, i.e., 62.5-500 Hz. Above 500 Hz, cats have superior sensitivity, especially above 4 kHz. The cat's auditory sensitivity extends to 60 kHz, but man's only extends to 20 kHz. Therefore, considering its discrimination ability over its larger frequency range, the cat's discriminable steps are probably equivalent to those of man.

Whether or not the CM is an index of auditory capacity has been questioned since the "Wever-Bray effect" was first discovered. Such a relation is suggested by the fact that some animals (Dalmation dogs, Walzing guinea pigs, Dancing mice, and Albino cats) who are deaf because of an absence of cochlear hair cells have no CM potentials (which, as recalled, are generated by the hair cells). Price (1971) compared the CM and behavioral thresholds. He corrected the CM responses for the open bulla and added the appropriate sound pressure transformation for the head and EAM. Under such conditions, he found that the CM overlapped the behavioral threshold from 0.1 to 20 kHz when the CM curve was shifted vertically by 34 dB to a lower level of output (0.02µV RW CM). For his average cat, the CM sensitivity measured with the bulla closed reproduced the behavioral auditory threshold from 0.1 to 20 kHz. This finding tends to support the proposition that the CM is an essential link in the auditory process and not merely an epiphenomenon. However, there was no evidence of a causal relation between the CM and hearing.

Other investigators (Wever, 1959; Lawrence, 1961; Simmons and Beatty, 1962) showed poor correlations between the CM and auditory sensitivity. This might be due to the fact that they had not considered the open vs. closed bulla effect and the EAM resonance. However, these authors found that auditory sensitivity in cats improved at a rate proportional to frequency squared between 0.1 and 1 kHz, while the rate at which electrical sensitivity improved between 0.2 and 2 kHz was less steep Above 1 kHz, the auditory sensitivity improved more gradually than frequency squared, reaching its maximum at 8 kHz, while the CM sensitivity was fairly constant from 2 to 45 kHz. Its region of maximum sensitivity was between 2 and 7 kHz. In addition, the electrical responses extended far beyond the auditory responses toward the high frequencies, i.e., to 100 kHz. Although these studies showed a fairly poor correspondance between CM and auditory sensitivity, they do not preclude a direct relation between them.

Regardless of whether or not there is a causal relation between CM and auditory sensitivity, the RW CM is a good indicator of middle ear output, and any changes in the outer or middle ear are reflected in a change in CM output. Furthermore, any changes caused by a middle ear lesion should be proportional to the hearing loss as assessed by cortical action. This, after all, is the basis of all topological diagnosis of hearing loss.

Tympanic Membrane Perforations

As discussed above (see Chapter I), a TM perforation reportedly produces 1.) little or no effect on hearing (Cooper, 1800; Bingham, 1907) or little or no response loss (Crowe and Hughson, 1932; Wagemann, 1953); 2.) a small frequency independent loss across the entire frequency range (humans: Toynbee, 1860; Treitel, 1903; Pohlman, 1941; Shambaugh, 1967; rabbits: Lorente de Nó and Harris, 1933; Lorente de Nó, 1933); 3.) a flat low frequency loss (humans: Minton. 1925; Bordley and Hardy, 1937; Kobrak, 1959; Shambaugh, 1967; Anthony and Harrison, 1972; cats: Bordley and Hardy, 1937; Wever, 1950; Payne and Githler, 1951; Goto and Hibino, 1954; Kanabu, 1954; Wever and Lawrence, 1954) and 4.) a low frequency loss which varies inversely with frequency (humans: Ostmann, 1909; Bekesy, 1936, 1939, 1960; Kobrak, 1959; cats: McArdle and Tonndorf, 1968).

In the 1800s and early 1900s, before the advent and general usage of electronic audiometers, the identification and classification of hearing losses due to a TM perforation (or any other cause) were made with the aid of 'calibrated' tuning fork tests (Bezold and Siebenmann, 1908; Ostmann, 1908; see also Feldman, 1970). Although today, tuning fork testing is only ancillary to the audiometric evaluation of hearing loss (Johnson, 1970; Sheehy, 1971, 1972), then, the use of tuning forks was a carefully practiced art. The force applied to the forks was always kept uniform. In fact, a device called the Standard Acuity Meter, designed by Ostmann, was placed between the prongs, giving them a certain initial displacement when suddenly withdrawn. This device guaranteed high repeatability. This testing condition employed an open sound delivery system since the test ear was unoccluded.

At about the turn of the century, tuning fork test results were graphically represented on "auditory charts" or "hearing curves". On such charts, the <u>duration</u> of perception was recorded, for each frequency, as a vertical column. Each column represented the sensitivity for that frequency as the percentage of the normal duration a given tone was heard. One hundred percent was equal to normal duration, or normal hearing. Less than 100%, at any particular frequency, indicated a hearing loss. The pattern or configuration of these columns for a number of frequencies described different forms of hearing losses. The pattern associated with a TM perforation showed a hearing loss which became worse (shorter and shorter durations) at lower and lower frequencies, without an apparent limit. It does appear, then, that the hearing loss due to a TM perforation varies inversely with frequency, in an open system.

Some of the very early writings on the effect of a TM perforation probably gave little or no evidence of hearing losses because of the lack of refined testing techniques. Often the descriptions of methods used were omitted or inadequate. For example, Cooper (1800) reported that a patient, with a destroyed TM and discharging left ear (with the ossicles found in the discharge) and a right ear that had a 1/4" perforation, heard what was said to him "in the usual tone of conversation" (p. 627). He also indicated that this patient's hearing was better with his left ear than with his right ear, but neglected to say how he determined that. Toynbee (1860) stated that a TM perforation, without other complications, did not produce a degree of deafness that was 'uncomfortable'. He suggested that the reduction of hearing sensitivity was due to sound vibrations acting on the RW. Bingham (1907) reported a case in which the TM was totally absent and there were adhesions and necrosis of the ossicles bilaterally; hearing was less than normal, but in his opinion, the patient was not hard of hearing. On the contrary, he felt that the patient possessed a very "efficient auditory acuity" (p. 243). Testing procedures and results were not specified but the use of a Seashore audiometer and a whispered speech test (percentage accuracy/normal distance) was mentioned.

Crowe and Hughson (1932) and Wagemann (1953) each reported that little or no response loss could be attributed to a TM perforation. Crowe and Hughson stated, at a meeting of the American Otological Society, that puncturing the TM (anteriorly or posteriorly) of a cat "has little effect on sound" (p. 127). Their technique was to record CM potentials from an electrode on the auditory nerve in response to sound generated by an oscillator and speaker, and directed to the ear through a 12' garden hose. Wagemann (1953), in a later study, found no effect from a slit made in the TM and only a flat 10 dB loss when the entire TM had been removed. However, Wagemann, who was recording CM responses from the bony shell of the cochlea, made no mention of 1.) his measurement criteria, nor of 2.) the use of probe microphones. Furthermore, his description of the TM lesion did not include its size, its location or the method for making the lesion.

Certainly, these two studies that showed little or no effect on 'hearing' when a TM perforation was present were of questionable quality in the light of today's standards.

Pohlman (1941), Lorente de Nó and Harris (1933), Lorente de Nó (1933), Rubinstein, Feldman, Fischler, Frei, and Spira (1966), Wiener, Pfeiffer and Backus (1966), as well as Shambaugh (1967) reported that TM perforations produce small frequency independent hearing losses. Pohlman (1941) was mainly concerned with the Physics of the ear as it pertained to E. H. Weber's 1850 description. He mentioned only one case of a TM perforation; the size and location were not specified. The resulting air conduction hearing loss (shown on an audiogram) was essentially flat across the entire frequency range (128-8192 Hz); however, no bone conduction test results were shown. Although Pohlman mentioned a controversy then existing, i.e., that 1.) the low frequency loss may represent a conductive lesion and the high frequency loss a perceptive lesion or 2.) it may all be conductive, he stated that his data offered support for the latter alternative: when a cotton plug was placed over the perforation sensitivity was improved for <u>all</u> frequencies.

In their experiment on rabbits, Lorente de Nó and Harris (1933) used the lowest level of a test tone which produced a contralateral middle ear muscle contraction (both tensor tympani and stapedius) as a measure of threshold. When a large inferior perforation (one of three different sizes) was placed in the TM, these authors found a uniform loss of 20 dB across all frequencies; they concluded that the TM was just as important for receiving high frequencies as it was for receiving low frequencies. Their graphs however, showed flat losses largely limited to the low frequencies, and, if there was a high frequency loss at all, the low frequency losses were invariably greater than the high frequency losses.

Rubenstein, Feldman, Fischler, Frei and Spira (1966), in a study of stapedial displacement of cats with an unloaded system (cochlear fluid removed), found in one cat with a TM perforation (of no specific size or location) that there was a flat 10 dB reduction in stapedial displacement amplitude over the entire frequency range used. Wiener, Pfeiffer and Backus (1966) compared pre- and post perforation sound pressure levels at the TM for a constant CM in one cat which happened to have an unspecified TM perforation. They reported an essentially frequency independent response loss; 10-15 dB at 1 and 3.5 kHz and 5 dB losses at all other frequencies. Both of these studies reported the results found in one single cat which happened to have a perforation. Neither had set out to study the effects of experimentally induced perforations.

Shambaugh included a section on Perforation of the Tympanic Membrane in the chapter on Mechanics of Hearing in the second edition of Surgery of the Ear (1967). This section was identical to one that appeared in his first edition (1959). He cited the work of Payne and Githler (1951, to be discussed later) as the research results upon which his clinical findings (audiograms) could be based. He stated that there were hearing losses at all frequencies and that the size of the perforation was more important than the location in determining the extent of the hearing loss; clinically, there was a trend for larger perforations to produce more sizeable losses. However, Shambaugh showed six audiograms which represented pre- and post surgical repair air conduction thresholds, but he failed to present any bone conduction results. Four of these six audiograms showed predominantly flat low frequency hearing losses, while the remaining two showed small frequency independent hearing losses over the entire test range. His clinical evidence, then, only partially supported his conclusion, i.e., that there was a small hearing loss at every frequency.

Other investigators have reported that a TM perforation produces flat hearing losses or repsonse losses in the low frequencies. Bordley and Hardy (1937) had demonstrated in previous studies that CM changes paralleled hearing sensitivity changes. They then tested microphonic responses in cats, before and after setting TM perforations in one of four different locations. They evaluated responses in the following manner: 1.) by the examiner listening to speech via the animal's CM, as displayed over a loud speaker, 2.) by determining the response to tuning forks, 3.) by determining audiometric thresholds and 4.) by a balance method. The balance technique and the audiometric thresholds showed most severe losses. The least impairment was consistently found for the high frequencies and the largest impairment for the low frequencies. These experiments were done with an open bulla. The middle ear/bulla septum had been removed before hand and the TM perforation was made from below through the middle ear. These authors also found similar results on two human patients with TM perforations.

Kobrak (1959) described the hearing loss due to a TM perforation as a low frequency hearing loss. Three of the four audiograms he presented showed flat, low frequency losses, while one showed a low frequency loss that increased inversely with frequency (inverse, low frequency loss). He attributed these hearing losses primarily to the loss of TM area, but also suggested that the perforation might abolish the baffle effect of the TM, and that the RW then vibrated in the open air, thus reducing the preferential sound conduction to the OW via the ossicular chain. Wever (1950) also felt that a perforation produced a reduction in force applied to the ossicles which was proportional to the TM area lost. He suggested that the sound which was admitted through the perforation exerted a pressure on the TM from the inside and was therefore acting in opposition to the pressure acting on the TM from the outside.

Again, in human patients with TM perforations, Anthony and Harrison (1972) found hearing losses of approximately 20 dB; losses which were in general more marked in the low frequencies. They compared pre- and post operative air conduction thresholds; no bone conduction thresholds were given. In a population of 103 patients, they examined the nature of the loss according to the area (large or small) of the TM affected and the location of the lesion (central or peripheral). Large and small perforations produced hearing losses that were essentially flat in the low frequencies; larger perforations produced larger losses.

The study by Payne and Githler (1951) is most often cited as justification for the belief that a TM perforation produces a flat, low frequency hearing loss. However, there were some procedural oversights that were responsible for the results and conclusions of their experiments. These authors recorded the sound intensity that was necessary to elicit a constant 10μV CM. It was delivered from a loud speaker which was coupled to the TM by a long piece of tubing of an unspecified length. This, then, was a loosely coupled system. Measurements were made pre- and post perforation over a frequency range of 0.0 to 10 kHz. Three groups of three cats each were used. It is important to note that the cat's bulla was kept open throughout the experiment. The perforations were made by electro-cautery (initially small and then increased in size) in the anterior quadrant (A) for the first group, in the posterior quadrant (P) for the second group, and in the inferior quadrant (umbo - U) for the third group. The areas of all perforations were measured and recorded.

Response losses were averaged across the nine cats and expressed in relation to the percentage of TM removed. For small perforations, the rate at which the losses accrued was largest: with only the first 10% of the TM area gone, the transmission loss was already 12 dB and it was primarily limited to the low frequencies. With additional losses in area, the rate of the accruing response losses slowed down. Finally, 100% removal of the TM produced a 42 dB loss. When the greater part of the TM had been removed, the losses became almost flat, or had more emphasis in the high frequencies.

Concerning the location of the lesion, the percentage of the response loss was plotted against the percentage of the TM loss, separately for each type of lesion (P, A, U) and for four frequency ranges. Posterior quadrant perforations produced the largest losses in the low frequencies; the maximum low frequency loss was already reached when only 40% of the TM was removed. The anterior perforations produced a more gradual loss for the low frequencies, and the umbo perforations produced the least amount of loss at any frequency. Therefore, the authors concluded that, for small lesions, the location was the primary determinant of the response loss. An increase in the size of the perforation did not change the shape of the response loss curve until virtually all of the TM had been removed. (See also the citation of this study in Wever and Lawrence, 1954.)

The subsequent studies of Goto and Hibino (1954) and Kanabu (1954) essentially repeated Payne and Githler's study and came to similar conclusions. The bulla was also kept open throughout these latter experiments.

In retrospect, then, although Payne and Githler's (1951) study was well controlled, the results reported are somewhat questionable because of the open bulla. The same is true for the papers by Goto and Hibino and by Kanabu.

McArdle and Tonndorf (1968) demonstrated that when the bulla was kept open there was indeed a low frequency response loss. They explored the effect of a small TM perforation (5% of the TM area) for open and closed sound systems, with the bulla open and closed (three different size openings) in a model, and in a series of cats using CM responses as an indicator. The results of the model experiment suggested that the response loss was due to a change in differential pressure acting on the TM caused by a partial cancellation of the incident pressure. The direct admittance of sound to the back of the TM affected the sensitivity and controlled the slope of the loss: 1.) sensitivity improved as the TM perforation was gradually closed (by adding layers of acoustic resistance -- gauze), thus impeding the direct admittance of sound through the perforation: 2.) For the perforated condition and with a closed sound system, low frequency sensitivity improved as the bulla opening was enlarged or the resistance at the opening, impeding the direct passage of sound, was made lowest; 3.) For the intact condition and with an open sound system, the low frequency loss that increased with inverse frequency became steeper -- again due to the alteration of the middle ear sound pressure which also resulted from the direct access of sound to the back of the TM.

In the animal experiments, sound pressures at the TM, required to produce a 10μV RW CM, were recorded, before and after perforation, and the response-loss, in terms of the change in sound pressure was determined for open and closed sound systems, with the bulla open or closed. Since the closed sound system was a speaker coupled to the surgically shortened EAM by a hose (≅ 80 cc), the closed system had, as in the case of Payne and Githler (1951), some properties of an open system as the coupling between the speaker and the TM was quite loose. Sound pressures determined in the EAM and in the middle ear demonstrated once again the alteration of the normal differential sound pressure due to the perforation. In the low frequency region, the response losses for the open and closed sound systems, with the bulla closed, varied inversely with frequency at a rate of 10.2 dB/octave. However, with the bulla open, the response losses were relatively flat in the low frequencies. McArdle and Tonndorf determined that approximately 2/3 of this loss incurred with the bulla closed was due to the baffle effect of the TM.

Furthermore, in contrast to Payne and Githler (1951), McArdle and Tonndorf found very small differences in response loss for perforations of uniform size, made at five different locations. This is consistent with the curved membrane principle of TM vibrations (as a transformer), which states that for any position along the malleus, the product of the TM lever and the ossicular lever is a constant; therefore, the location of the perforation should not produce a more significant loss than one in the inferior quadrant, the lower fold of Bekesy (see Tonndorf and Khanna, 1972).

Bekesy (1936, 1939, 1960), by measuring TM displacements with a capacitive probe, has also found that an experimentally induced perforation (1 mm^2) produced low frequency response losses that varied inversely with frequency at a rate of approximately 10 dB/octave.

Scrutinizing the literature revealed that a number of investigators had found flat, low frequency response losses in animal experiments. However, in all these experiments, the bulla had been kept open. In contrast, McArdle and Tonndorf (1968) showed that with a closed bulla, for the open sound system and possibly also for their closed sound system (which was considerable larger than the normal ear volume, mainly 80 cc), there is a response loss that decreases with inverse frequency at approximately 12 dB/octave. Bekesy's findings (1936, 1939, 1960) are in principal agreement in this respect. Finally, the 'calibrated' tuning fork test data suggested that humans with TM perforations show low frequency losses that increase with inverse frequency or inverse, low frequency losses when tested in an open system. However, audiometric test results obtained in a closed system revealed flat, low frequency hearing losses. Therefore, there appears to be conflicting evidence concerning the effect of TM perforations on sound transmission in open and in closed systems. It was conjectured (see Chapter I) that the difference between the audiometric losses seen in humans (closed system) and the response losses seen in cats for open and "closed" (80 cc) systems might be due to the way the relation between the voltage across the transducer and the sound pressure in the EAM is affected by changes in middle ear impedance caused by the TM perforation, i.e., by changes in the load facing a transducer in a small closed, and thusly closely-coupled system. Furthermore, since in the animal experiments and in Bekesy's human cadaver experiments, the ear canals were surgically shortened or totally removed, it was also conjectured (see Chapter I) that the presence of an ear canal may be responsible for the flatness of the low frequency hearing loss determined audiometrically.

CHAPTER III. METHODS AND PROCEDURES

EXPERIMENT I

Introduction

The goal of Experiment I was to measure changes in middle ear transmission before and after a tympanic membrane (TM) perforation, in open and closed sound systems, using a criterion round window (RW) cochlear microphonic (CM) response as an indicator. The relation between the response loss, or rather the change in sound pressures (amplitude and phase) necessary to produce a 10μV RW CM in front of the TM, and the change in electrical voltage (attenuation) of the input signal were explored. Sound pressures were measured in the middle ear, directly behind the TM, as well as just in front of it, in order to calculate the effective force acting on the TM and to compare it with the amount of response loss produced by the perforation.

Subjects

Six healthy cats, of unknown age, weighing 1.7 to 4.0 kgm., were used in this experiment. Animals were only accepted when their external and/or middle ears were free of disease at the time of the experiment and also free of any signs of previous external and/or middle ear infections such as scarring or thickened tympanic membranes.

Anesthesia

General anesthesia was used throughout the experiment. It consisted of a combination of an initial intra-muscular injection of Thorazine (Smith, Kline and French--chlorpro mazine hydorchloride) and a second intra-thoracic injection of Nembutal Sodium (Abbott--sodium pentobarbitol) given 15 minutes after the first injection. The dosage of Thorazine was calculated on the basis of 14 mgm/kgm or 0.55 cc/kgm. The dosage of Nembutal was calculated on the basis of 22 mgm/kgm or 0.45 cc/kgm. Supplements of 10% of the initial Nembutal dosage were given intra-peritoneally, as required, to maintain a relatively constant anesthesia level as indicated by breathing pattern, muscle tonus, corneal reflexes, etc. Incision areas were infiltrated with Xylocaine (Astra Pharmaceutical Products--1% solution of lidocaine hydrochloride) and skin margins along the back were infiltrated with 20 cc of Ringers Irrigation Solution (Abbott--No. 6234) to minimize the effects of loss of body fluids. Normal body temperature was maintained by resting the animal on a temperature controlled, water circulating heat blanket (Gorman-Rupp Industries, Inc.--Model K-1).

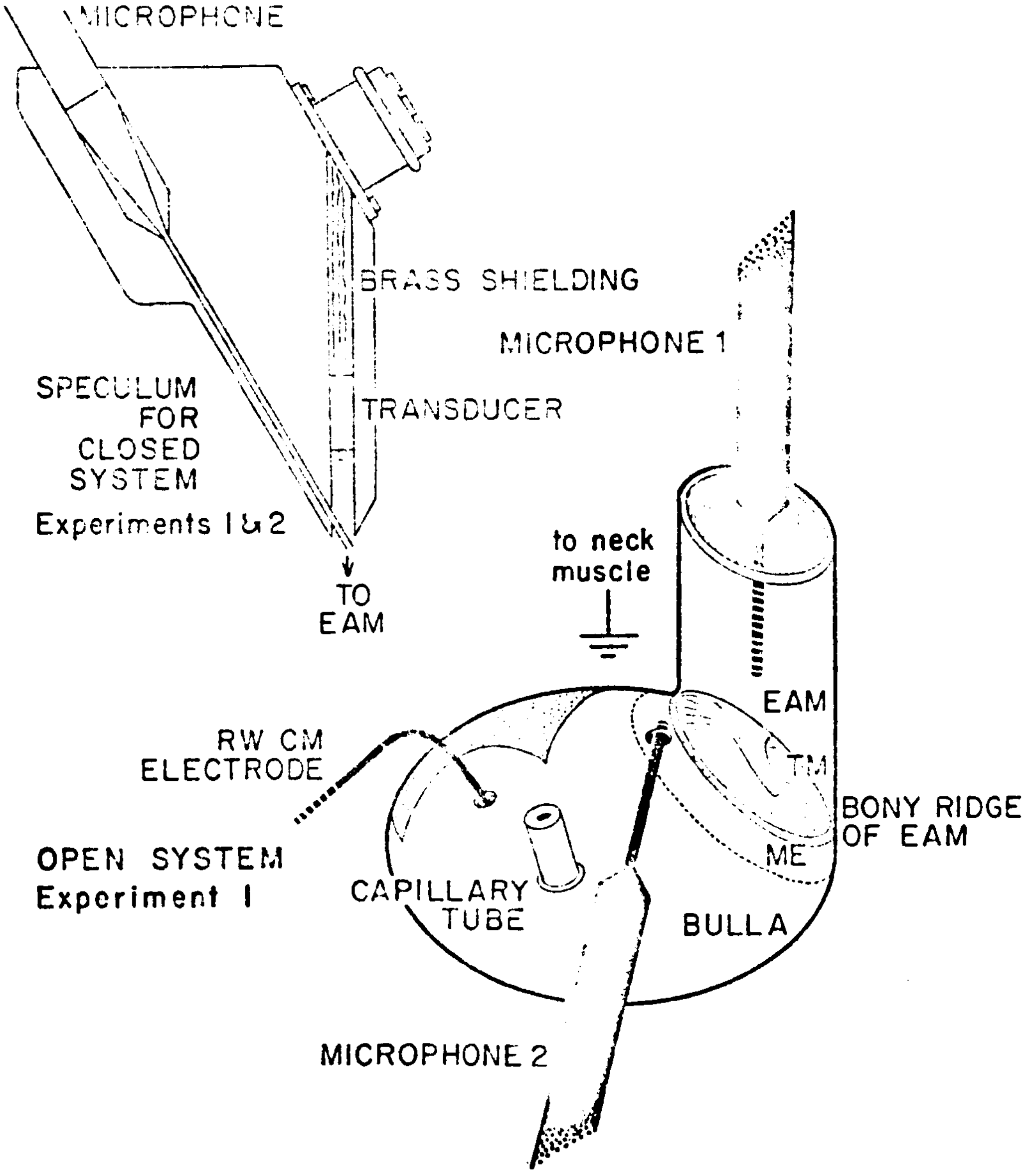
Surgical Procedure

A tracheotomy was performed on each cat, since the head holder used blocked the cat's pharyngeal air passage. After a tracheal canula was inserted, the cat's head was mounted in the head holder. The right bulla tympanica was then exposed in the manner described by Tonndorf (1952): the initial incision, circumscribing the pinna but extending longer ventrally, was retracted; the external jugular vein was exposed and ligated; the posterior lobe of the parotid gland was removed; the temporal, posterior auricular, and external carotid arteries were ligated; and the stylohyoid, the digastric, the styloglossus muscles, as well as the sternal and clavicular portions of the sternocleidomastoid muscle were disarticulated from their styloid or mastoid process respectively and retracted ventrally.

The external auditory meatus (EAM) of the cat has two sections. The lateral portion is long, narrow, and tortuous. The medial portion is short, wide, and cylindrical. Therefore, due to the difficulty of placing a microphone near the TM or placing a lesion in the TM through the lateral portion, the entire pinna and lateral portion of the EAM were surgically removed, leaving the EAM about 1 cm long.

The round window (RW) electrode used was a length of 100μ enameled silver wire (Sigmund Cohn and Co.) with its tip formed into a small spherical ball by holding the wire in contact with a flame. The electrode was placed on the RW, near its upper edge, through a hole drilled beneath the mastoid ridge of the outer wall of the bulla cavity (see Fig.1)

Fig. 1. Placement of RW CM electrode, capillary tube, and microphones - Experiment I. The RW CM electrode and capillary tube were placed through the bulla wall and the probe tube microphones were placed in the middle ear (Microphone 2) and in the EAM (Microphone 1 - Open and Closed Systems).


MICROPHONE
BRASS SHIELDING
MICROPHONE 1
SPECULUM
FOR
CLOSED
SYSTEM
Experiments 1 & 2
TRANSDUCER
TO
EAM
to neck
muscle
EAM
RW CM
ELECTRODE
TM
BONY RIDGE
OF EAM
ME
OPEN SYSTEM
Experiment 1
CAPILLARY
TUBE
BULLA
MICROPHONE 2

The electrode was cemented to the bulla bone with a water-repellent dental cement (L. D. "Grip" Caulk Co.: (1) Caulk Cavity Primer 1264-675900; (2) Cement Powder and Liquid 1264-63008). A hole drilled ventral to the RW electrode was used for visual inspection and guidance while placing the RW electrode. Then, a short capillary tube was cemented into that hole in order to equalize middle ear pressure throughout the experiment (see Fig. 1). The tube (Tonndorf and Khanna, 1968) is a low pass AC filter which has a cut-off frequency well below the region of interest (60 Hz), but it permits DC pressure exchanges, preventing alterations of middle ear pressure from developing during the experiment. An indifferent electrode (a 22 gauge stainless steel hypodermic needle) was inserted into the neck muscles to ground the animal.

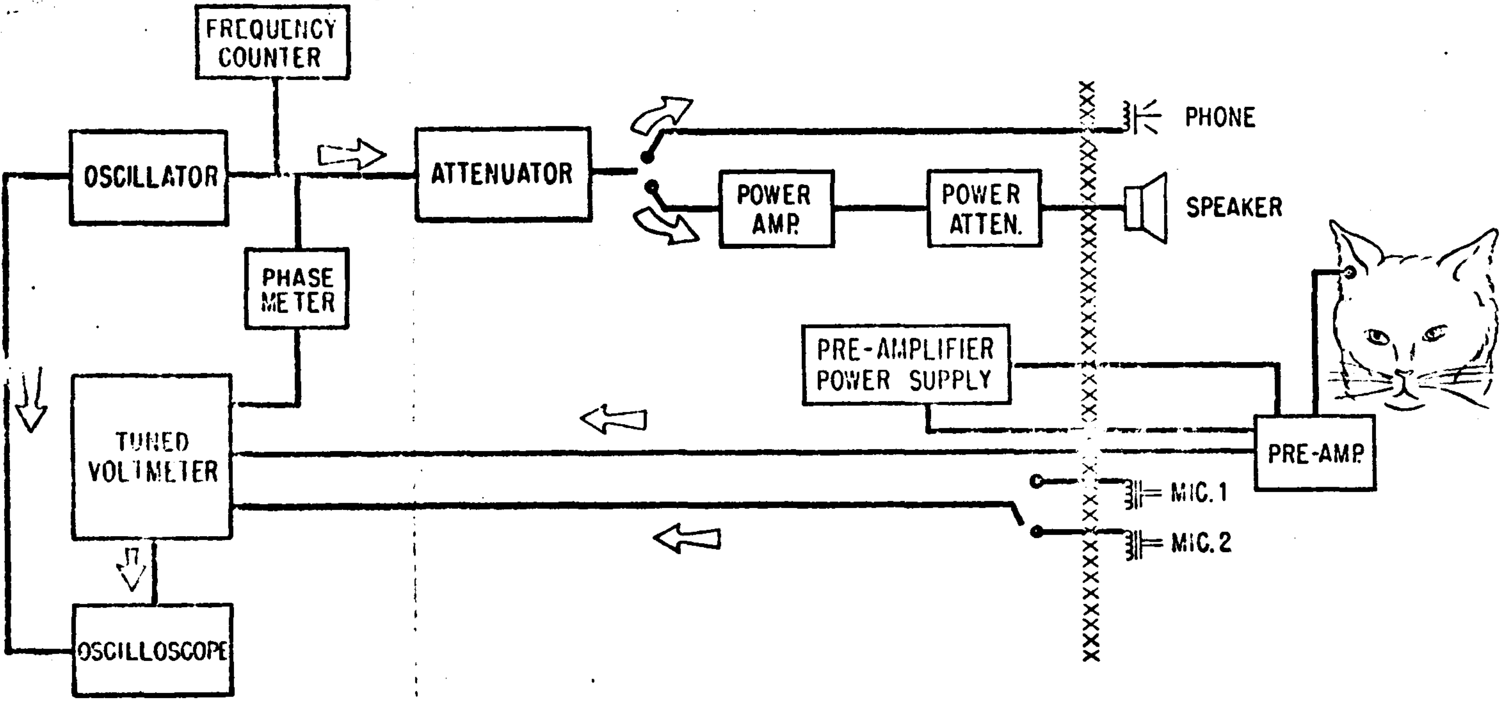
Two probe microphones (see Apparatus section) were used in this experiment. One microphone (Mic. 2) was placed into the middle ear (see Fig. 1) through a 1 mm diameter insulating sleeve of polyethylene tubing (Ace Scientific Supply Co.--PE160); the latter had been cemented into a hole drilled directly into the middle ear through the bulla's outer wall just anterior to the partition separating the tympanic cavity from the larger bulla cavity. (This insulation is necessary, since the microphone shell has a small potential against ground.) The other microphone (Mic. 1) was located in the EAM, and its placement will be described later.

At a later stage in the experiment, a 1 mm diameter perforation was placed in the posterior-superior quadrant of the TM. The lesion was made with a plug cutter constructed from a stainless steel hypodermic needle (#16 gauge); its tip had been revoved and a cutting edge made on the internal surface of the shaft. The plug cutter was inserted into the handpiece of a hand-held dental drill. The lesion was made under microscopic control.

Apparatus

Recordings were made with the cat inside a single-walled, shielded testing room (Industrial Acoustics Co. -- Series 400A). The cat was positioned on a surgical table with the test ear facing upward. The sound delivery systems for air conducted sine-wave signals and the system for recording the cochlear microphonic output of the RW are schematically shown in Fig. 2. The electrical signals were generated by a low frequency oscillator (Hewlett Packard Co. -- Model 202CR). The frequencies of the signals used (200-4000 Hz, at third octave intervals) were set precisely with the aid of a frequency counter (Hewlett Packard Co. -- Electronic Counter Model 522B) in parallel with the oscillator. The signals were then adjusted by an attenuator (Hewlett Packard Co. -- Attenuator Set, Model 350A) in series with the oscillator. The electrical signals were directed to either an "earphone"

Fig. 2. Schematic diagram of instrumentation.


FREQUENCY COUNTER
OSCILLATOR
ATTENUATOR
PHONE
POWER AMP.
POWER ATTEN.
SPEAKER
PHASE METER
PRE-AMPLIFIER POWER SUPPLY
TUNED VOLTMETER
PRE-AMP.
MIC. 1
MIC. 2
OSCILLOSCOPE

or to a loud speaker in the test room. The "earphone" was a Knowles miniature magnetic transducer (BP-1710) with a nominal electrical impedance of 600 ohms at 1000 Hz and a high acoustic impedance (see Appendix A: Transducer Specifications). It was mounted in a small lucite speculum, together with a probe microphone (Mic. 1). (See Fig. 1.) The speculum was tightly inserted into the surgically shortened ear canal in order to place the microphone tip about 3mm from the TM. The signal directed to the loudspeaker was amplified by a McIntosh 75 watt Power Amplifier and could be further attenuated by a 20 to 40 dB power attenuator in order to reduce hum. The loudspeaker was a Jensen 100 watt driver (Super Power Driver Unit--Model DD-100A) with a Jensen Hypex Horn (Model H240) located about 30 inches above and behind the animal's ear at an angle of 120°.

Microphonic responses were amplified 1000 times by the pre-amplifier located in the test room (Keithley Instruments--Amplifier 103). Its power supply was located outside the test room (Keithley Instruments--Power Supply 1031). The overall noise level across the recording electrodes, when the animal was connected in the circuit, was of the order of 10μV, with a 60 Hz component just below 1 mV. Overall noise levels and the 60 Hz noise level were noted for each experiment. Frequent checks were made to insure that the electrode would not pick up any voltages from the signal generating equipment.

Microphonic responses, as already stated, were recorded over a range from 200 Hz to 4000 Hz, at third octave intervals.

Two 12.5 mm condenser microphones with 1 mm diameter probe tubes (Bruel and Kjaer -- Microphone Cartridges Type 4134; Cathode followere, Type 2614/2615) were used in this experiment. Mic. 2 was located in the <u>middle ear</u> just behind the TM. Mic. 1 was located in the EAM at a 180°angle of incidence to the sound.[1] The EAM microphone, for both the open and closed sound systems, was lowered to a position approximately 3 mm in front of the TM. In the open system, Mic. 1 was held above the TM by a rubber insulated test tube holder. The probe tube of the microphone was fitted with a polyethylene insulating sleeve. This insulation, as was already noted, was neciessitated by the fact that the microphone housing is not grounded and has a small voltage against ground. In the closed system, Mic. 1 rode in a lucite speculum, designed to carry both the microphone and the transducer (see Fig. 1). The speculum was inserted into the EAM, occluding it and placing the microphone near the TM. The speculum had a volume of 0.562 cc. The average volume of the cat's shortened EAM was determined by filling it up with a known volume of alcohol. Alcohol was used because it has a low surface tension and would not adhere

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[1] It is well known that sound pressures at f>10-15 kHz are uniform in a small closed cavity of the size used in this experiment. Therefore, the angle of incidence of the sound does not play a role in determining microphone location. Furthermore, the frequency range used lies entirely below the <u>f</u> at which standing waves might interfere with the sound pressures in the canal.

to or remain on the canal wall. Three repeat measurements, on two cats, indicated that the volume of the average shortened EAM was 0.17 cc. Thirty percent of that volume was displaced when the speculum was inserted into the EAM, leaving 0.11 cc. Since the volume contained in the speculum was 0.56 cc, the whole, surgically shortened EAM including the speculum had a volume of 0.67 cc.

Both probe tube microphones were calibrated with a Bruel and Kjaer Type 4142 calibration apparatus using a substitution method. Sound pressures recorded with both Mic. 1 and 2 were corrected according to their respective microphone and probe tube calibration factors for all frequencies used in the experiment.

Both the CM response voltages and the sound pressure amplitudes, measured in front of the TM (Mic. 1) and behind it (Mic. 2) were read at the same tuned Mic. 1 or Mic. 2 were selected via a switch (Bruel and Kjaer--Two Channel Microphone Selector, Type 4408). Signal phases were read, relative to the generator, at the phase meter (Universal AD-YU Electronics, Inc.--Precision Phase Meter, Model 408). The input signals and the CM and microphone responses were monitored on the oscilloscope (Tektronix, Inc.--Type 533A) to make sure that only responses without distortion were recorded.

Stimulating and Recording Procedures

A constant criterion RW CM of 10μV was used as a reference. For each test frequency, spaced at third octave intervals, from 200 to 4000 Hz, the electrical voltage of the input signal was adjusted with the attenuator in order to produce the 10μV microphonic response. The voltage level necessary to produce the criterion CM response was transcribed on the data sheet in dB, as was the 10μV criterion amplitude of the CM and its phase. The sound pressures registered by both microphones and their phases were read, first for Mic. 1 and then for Mic. 2 (see Appendix B: Sample Data Sheets). The appropriate calibration factor (for each microphone and its probe tip) was added to each sound pressure reading to obtain absolute SPLs.

Therefore, in Experiment I, the following readings were obtained: 1.) the voltages of the electrical signal across the transducer, 2) the voltages (10μV) and phases of the RW CM, and 3.) the amplitudes and phases of the *acoustical* signal; sound pressures were measured both in the *ear canal*, directly in front of the TM (Mic. 1), and in the *middle ear*, just behind the drum membrane (Mic. 2). All these measurements were made a.) in the *open* system and b.) in the *closed* system, both i.) *before* and ii.) after the 1 mm diameter perforation was made in the posterior-superior quadrant of the TM. Two complete recordings were made for each condition, and the results were averaged. Intact conditions necessarily preceded perforated TM conditions. The order of the open system and closed system conditions varied as follows: half of the cats were run--open/intact, closed/intact, closed/ perforated, open/perforated (ABBA); and other half of the cats were run--closed/intact, open/intact, open/perforated, closed/ perforated (BAAB).

Statistical analyses of the data obtained included calculations of a.) the mean, b.) the standard deviation, c.) the Fisher t in order to determine the significance of the difference between the means of the two corrolated samples used, d.) the least square fitting of curves in order to determine their slopes and finally the t which determined the significance of the difference between least square slopes (H_O: $b=B_O$) (see Appendix B: Statistical Formulae).

EXPERIMENT II

Introduction

The goal of Experiment II was to determine the nature of the response-loss induced by a TM perforation, with an artificial EAM replacing and extending the surgically removed lateral portion of the EAM. The relation between the physical characteristics of length, volume, and leakiness of the artificial EAM and the response losses determined at the entrance of the artificial canal and at the TM were explored.

Subjects

Eleven healthy cats, of unknown age, weighing from 1.2 to 2.8 kgm were used in this experiment. The same criteria for selecting cats used in Experiment I were employed in this experiment.

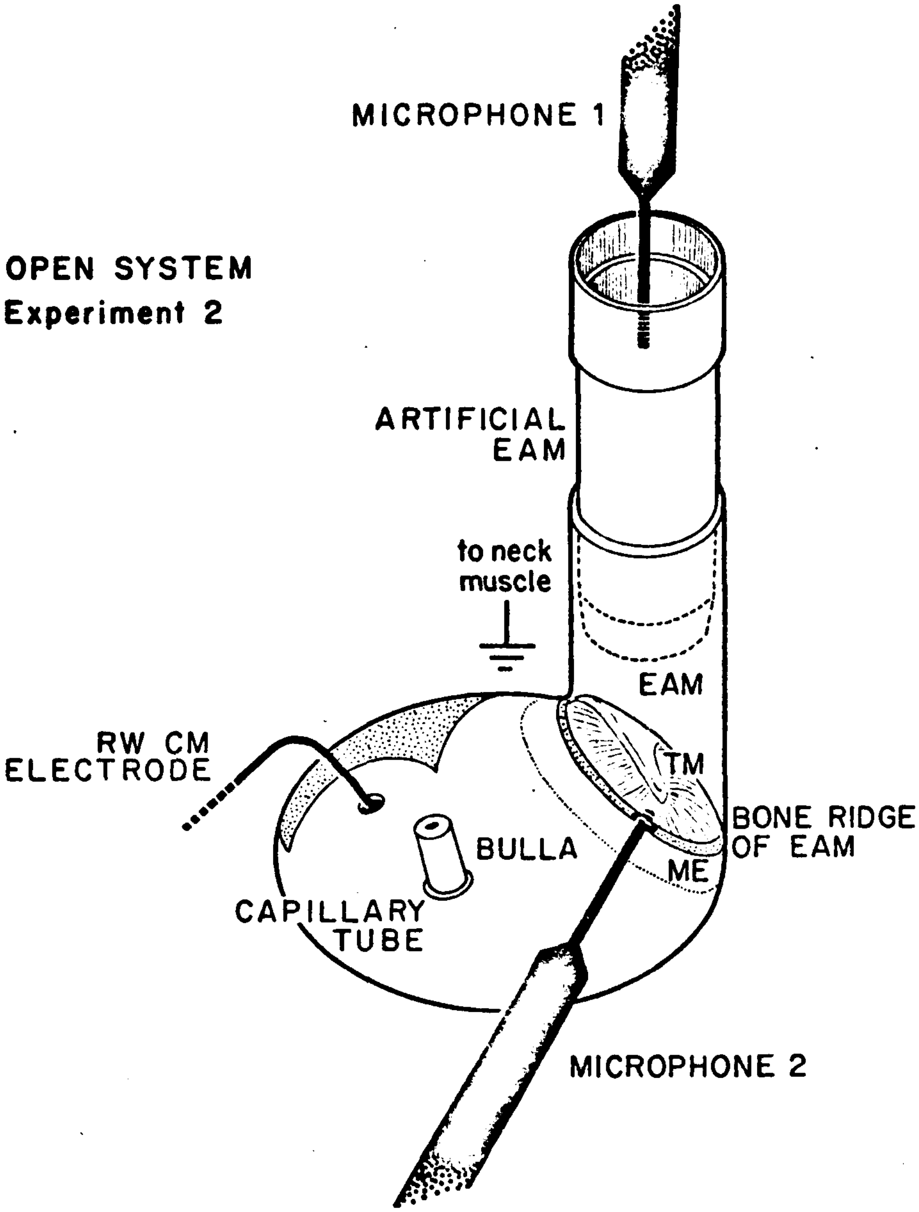
Anethesia

The same method used in Experiment I was used in Experiment II.

Surgical Procedure

Both microphones were now located in the EAM (see Fig. 3). Mic. 1 was placed at the outer opening of the artificial canal (inserted 2 mm into the tubes used as artificial

Fig. 3. Placement of RW CM electrode, capillary tube, and microphones - Experiment II. The RW CM electrode and capillary tube were placed through the bulla wall and the probe-tube microphones were placed in the EAM at the outer opening of the ear canal (Microphone 1) and at the TM (Microphone 2).


OPEN SYSTEM
Experiment 2
MICROPHONE 1
ARTIFICIAL EAM
to neck muscle
EAM
RW CM ELECTRODE
TM
BONE RIDGE OF EAM
BULLA
ME
CAPILLARY TUBE
MICROPHONE 2

canals). In the open condition, this microphone (with a polyethylene insulating sleeve on it when necessary) was held in place with a test tube holder. In the closed condition, the microphone rested in the speculum which occluded the outer opening of the artificial canal. Mic 2 was placed through a 1 mm diameter insulating sleeve which had been cemented into a hole drilled through the 2 mm wide inferior bony ridge of the cat's ear canal. This placed the probe microphone tip about 1-2 mm in front of the TM in the EAM.

Apparatus

The stimulating and recording equipment used in Experiment II was the same as that used in Experiment I. In this second experiment, however, artificial cavities were used to simulate the real cat EAM. In addition to the surgically shortened cat's EAM (Cavity 1: reference condition) four artificial cavities were used: two polyethylene tubes of different length and volume; and two copper tubes of different length and volume. All these tubes were firmly coupled to the surgically shortened EAM of the cat.

The volume of the EAM of the cat was determined to be 1 cc up to the tragus and 2 cc including the concha. The volume of Cavity 1 (the short, wide, cylindrical medial portion of the EAM) was 0.2 cc.

The artificial ear canals were specified according to length, volume, and leakiness (see Table 1). Since the closed system condition used the speculum, whose volume was 0.56 cc, the closed system volumes were always larger than the open system volumes. To approximate the volumes of the real cat EAM, the volumes of 1.1 cc for the open system and 1.6 cc for the closed system, were used for the smaller size cavity (Cavity 2), and the volumes of 1.6 cc for the open system and 2.0 cc for the closed system were used for the larger size cavity (Cavity 2). These two tubes (Cavity 2 and 3) were made of a leaky material (polyethylene). A leaky material was used to approximate the leakiness of the cartilaginous portion of the real external ear (Tonndorf *et. al.*, 1966).

Artificial ear canals of comparable length were also made out of copper--an essentially leakless material.

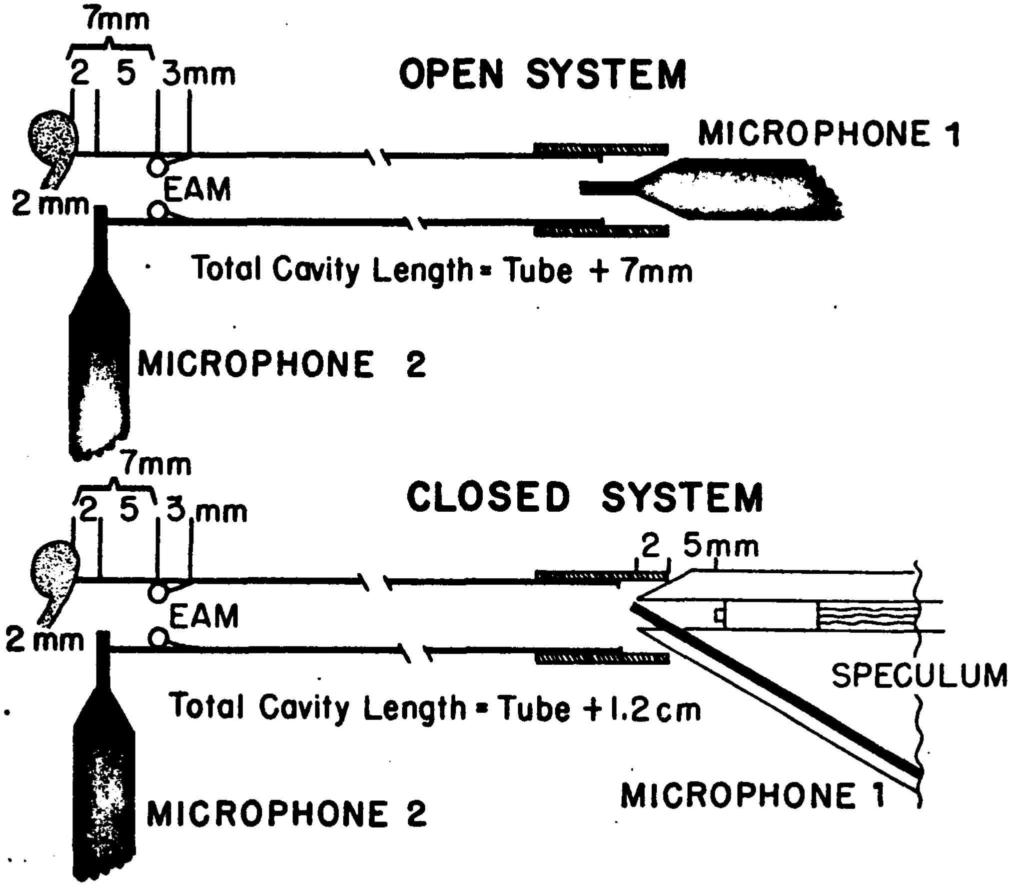
The volume of Cavity 4, however, was the same as that of the large polyethylene cavity (Cavity 3), although its length was the same as that of Cavity 2. These volumes were 1.6 cc in the open system and 2.06 cc in the closed system. The large copper cavity (Cavity 5) was as long as polyethylene Cavity 3, but the volumes of Cavity 5 were larger than those of Cavity 3 because of the larger internal diameter of the copper tubing; these volumes were 2.3 cc in the open system and 2.76 cc in the closed system. As shown in Fig. 4, the

TABLE 1

ARTIFICIAL EAR CANALS SPECIFIED ACCORDING TO LENGTH, VOLUME, AND LEAKINESS

ARTIFICIAL EAR CANAL			CAVITY LENGTH		TOTAL E.A.M. LENGTH		VOLUME	
#	Material	i. diam	Open	Closed	Open	Closed	Open	Closed
1	Cat's E.A.M.	5.9mm	1.0cm	1.0cm	1.0cm	1.0cm	0.2cc	0.6cc
2	Poly-ethylene	3.9mm	8.0cm	7.5cm	8.7cm	9.9cm	1.1cc	1.6cc
3	Poly-ethylene	3.9mm	12.7cm	12.2cm	13.4cm	14.6cm	1.6cc	2.0cc
4	Copper	4.7mm	8.3cm	7.8cm	9.0cm	10.2cm	1.6cc	2.0cc
5	Copper	4.7mm	12.7cm	12.2cm	13.4cm	14.6cm	2.3cc	2.7cc

Fig. 4. Comparison of _open_ and _closed_ system total cavity length.


7mm
2
5
3mm
OPEN SYSTEM
MICROPHONE 1
EAM
2 mm
Total Cavity Length = Tube + 7mm
MICROPHONE 2
7mm
2
5
3 mm
CLOSED SYSTEM
2
5mm
EAM
2 mm
SPECULUM
Total Cavity Length = Tube + 1.2 cm
MICROPHONE 1
MICROPHONE 2

cavities in the closed system were always shorter than those in the open system. These differences in length were due to the way the speculum was connected to the EAM in the closed system condition (for details see Table 1).

Bone wax (Ethicon Co. -- W-30) was applied to the lower end of the artificial cavities before they were inserted into the cat's ear canal, and then the canal cartilage was firmly tied around the base of the cavity.

Stimulating and Recording Procedures

The voltage of the electrical signal was adjusted by the attenuator to produce the criterion 10µV RW CM. Then, the sound pressures (amplitudes and phases) of the acoustic signal were recorded for Mic. 1 located at the outer opening of the EAM and for Mic. 2 at the TM, for both the open and closed systems, and before and after perforation. Two sets of independent measurements were taken for each frequency from 200 - 4000 Hz, at third octave intervals, for each condition, and averaged (see Appendix B: Sample Data Sheets).

All the above measurements were taken for each of the cavities, although not all 5 cavities were used on each cat. The cavities employed with each cat are listed in Table 2. Cavity 1 was used on 10 cats; Cavity 2 and 3, on 6 cats; and Cavity 4 and 5, on 4 cats.

TABLE 2

ARTIFICIAL EAR CANALS (CAVITIES 1-5)
USED WITH EACH EXPERIMENTAL ANIMAL

Cats	Cavities
C-3	1, 2, 3
C-4	1, 2, 3
C-6	1, 2, 3
C-7	1, 2, 3
C-8	1, 2, 3
C-11	1
C-14	2, 3, 4
C-15	1, 5
C-16	1, 4, 5
C-17	1, 4, 5
C-18	1, 4, 5

Again the ABBA... and BAAB... orders for open and closed system conditions were used. The order in which the cavities were used was not specified. However, there was no clear pattern to their order of selection such as length or volume.

The same statistical procedures used in Experiment I were used for the data obtained in Experiment II (see Appendix C: Statistical Formulae).

CHAPTER IV. RESULTS AND DISCUSSION

EXPERIMENT I

Nature of the Response-Loss

The first experiment examined the relation between the changes in the electrical voltage values of the input signal and the changes in the sound pressure in front of the tympanic membrane (TM) -- both of them necessary to produce a criterion round window (RW) cochlear microphonic (CM) -- due to a small TM perforation, in both an open and closed sound system.

As was already stated, absolute sound pressures were recorded in the external auditory meatus (EAM), just in front of the TM at Microphone 1 (Mic. 1), and in the middle ear, just behind the TM at Microphone 2 (Mic. 2), for open and closed system, both before and after perforation (See Table 3). These sound pressures were measured in a series of 6 cats, twice for each cat, and then averaged. The means and standard deviations of the absolute sound pressures, measured at third octave intervals from 200-4000 Hz, were calculated separately for each microphone location and each sound system, for both the intact and perforated conditions.

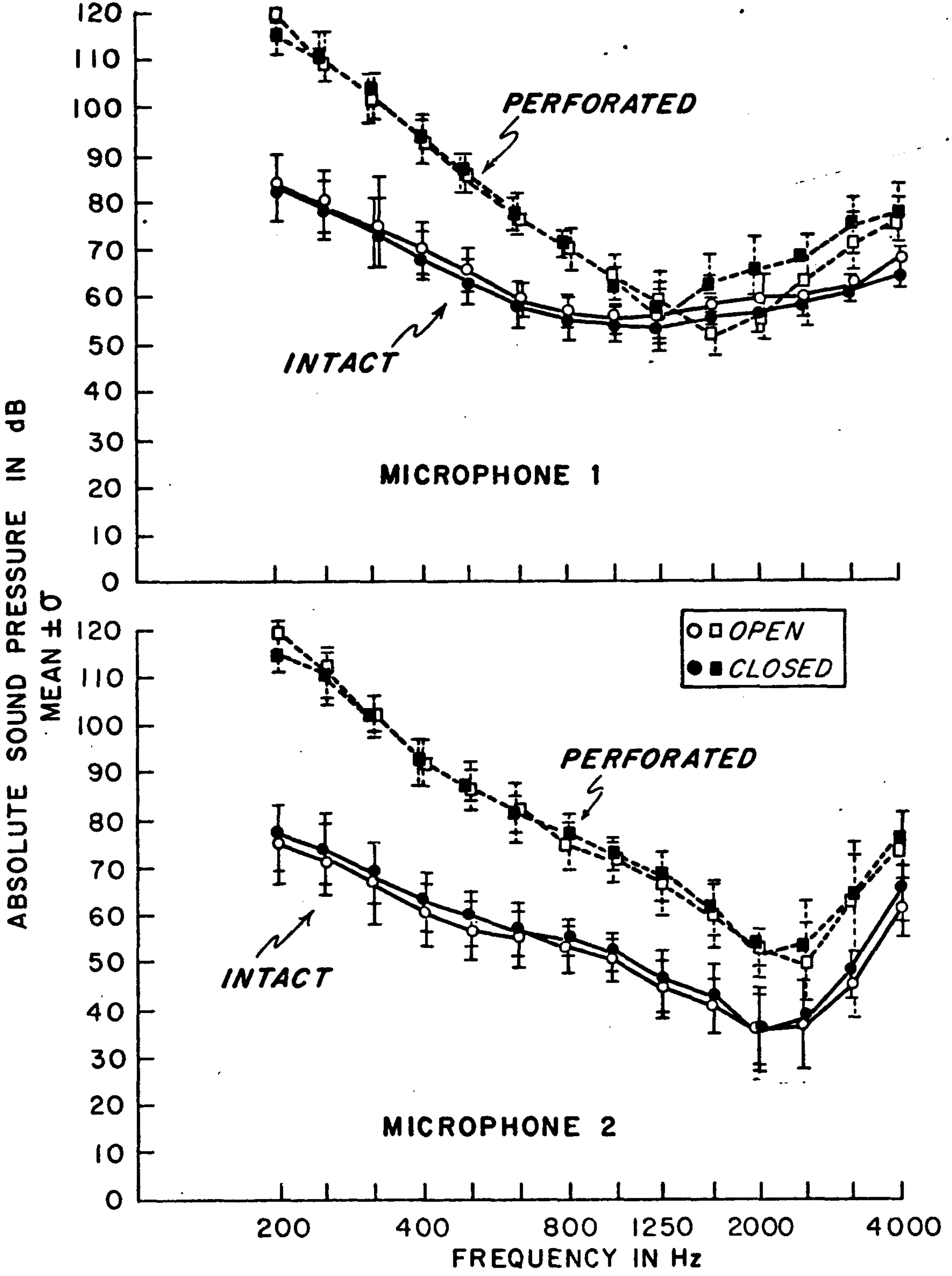
In Fig. 5, the mean absolute sound pressures ($\pm\sigma$), in dB, are plotted against frequency in Hz. Sound pressures in front of the TM in the EAM (Mic. 1) are plotted in the top

TABLE 3

ABSOLUTE SOUND PRESSURE MEASUREMENT CONDITIONS

Tympanic Membrane	Before Perforation		After Perforation	
Sound System	Open	Closed	Open	Closed
Microphone Location	Mic. 1 EAM	Mic. 1 EAM	Mic. 1 EAM	Mic. 1 EAM
	Mic. 2 Middle Ear	Mic. 2 Middle Ear	Mic. 2 Middle Ear	Mic. 2 Middle Ear

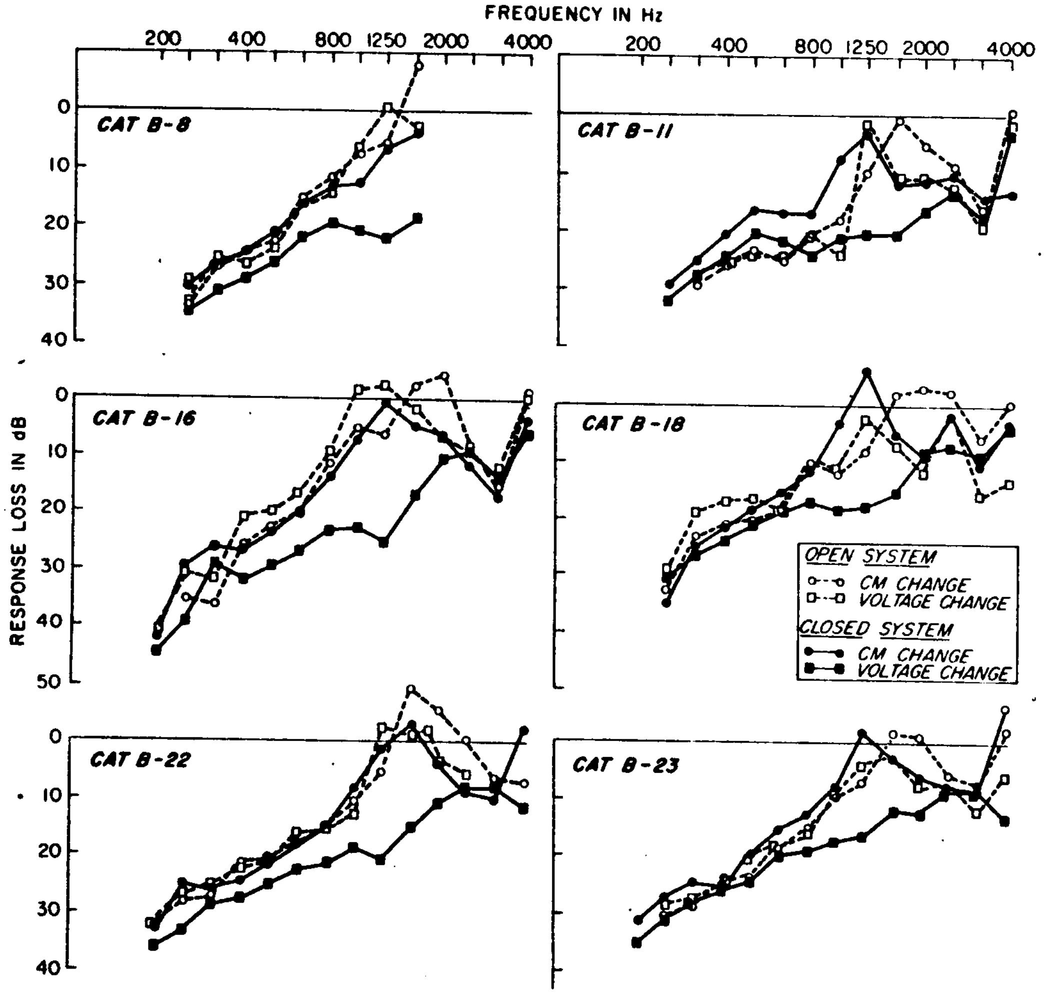
Fig. 5. Mean absolute sound pressures ($\pm\sigma$) plotted, in dB, against frequency, in Hz. Mean absolute sound pressures in the EAM, near the TM, (Microphone 1 - top graph) and in the middle ear (Microphone 2- bottom graph) are shown for intact (circles) TMs, recorded in an open (open symbols) and closed (closed symbols) sound system.


ABSOLUTE SOUND PRESSURE IN dB
MEAN ± σ
120
110
100
90
80
70
60
50
40
30
20
10
0
PERFORATED
INTACT
MICROPHONE 1
○□ OPEN
●■ CLOSED
PERFORATED
INTACT
MICROPHONE 2
200
400
800
1250
2000
4000
FREQUENCY IN Hz

graph and those just behind the TM (Mic. 2) in the bottom graph. (For diagrams of microphone locations see Fig. 1) Open symbols represent the open system measurements, while closed symbols represent the closed system measurements. (This policy is followed throughout the presentation of the results, unless stated otherwise.) The sound pressure for the intact condition, for either microphone, are represented by circles. For the perforated condition, sound pressures are represented by squares. The differences between the sound pressures for the perforated and intact conditions express the response-losses.

Response-losses, for each frequency, and for both the open and closed systems, were calculated from microphone readings in front of the TM, for each cat. In addition, also for each cat, the changes in signal voltage between the intact and perforated conditions were calculated for each frequency, for both the open and closed systems. In Fig. 6, the open and closed system response-losses (circles) and voltage changes (squares), both in dB, are plotted for each individual cat, against frequency, in Hz. As long as the CM output is within its linear range, the response-loss is the same whether it is expressed in terms of the sound pressure changes (at the TM), necessary to produce a constant 10μV RW CM, or in terms of the CM changes. In other words, within the linear range of the CM sound pressure relation, i.e., at low moderate levels,

Fig. 6. Open and closed system response-losses (circles) and voltage changes (squares) plotted, in dB, against frequency, in Hz, for each of six cats.


FREQUENCY IN Hz
200
400
800
1250
2000
4000
RESPONSE LOSS IN dB
0
10
20
30
40
50
CAT B-8
CAT B-11
CAT B-16
CAT B-18
CAT B-22
CAT B-23
OPEN SYSTEM
CM CHANGE
VOLTAGE CHANGE
CLOSED SYSTEM
CM CHANGE
VOLTAGE CHANGE

the changes in input sound pressure are proportional to the changes in CM output.

In Fig. 7, the response-losses, in dB, for each of the six cats, are plotted separately for the open (top graph) and closed (bottom graph) systems, against frequency, in Hz. Since Fig. 7 shows that, for either the open or closed systems, the response-losses of each cat are similar in shape and magnitude, mean data will be used for subsequent presentation of the results and their discussion.

In Fig. 8, the effect of a perforation on middle ear transmission is expressed as the mean response-loss, for a series of six cats. Mean sound pressure changes in the ear canal ($\pm\sigma$) are plotted, in dB, against frequency, in Hz. Below 1250 Hz for the closed system and below 1600 Hz for the open system, the response-loss varies inversely with frequency at a rate of approximately 12 dB/octave. There is no significant difference between the open and closed system response-losses (t=-0.11), at the 0.01 level.

For the response-loss data in Fig. 8, the standard deviation for each mean, at each frequency, was approximately 4 dB. The least squares method of curve fitting was used to fit a straight line (a regression line) to the curve of each cat in the low to mid-frequency region. The slopes of the straight-line fittings are listed in Table 4. As can be seen,

Fig. 7. Response-losses for each cat plotted, in dB, for the open (top graph) and closed (bottom graph) systems against frequency, in Hz.

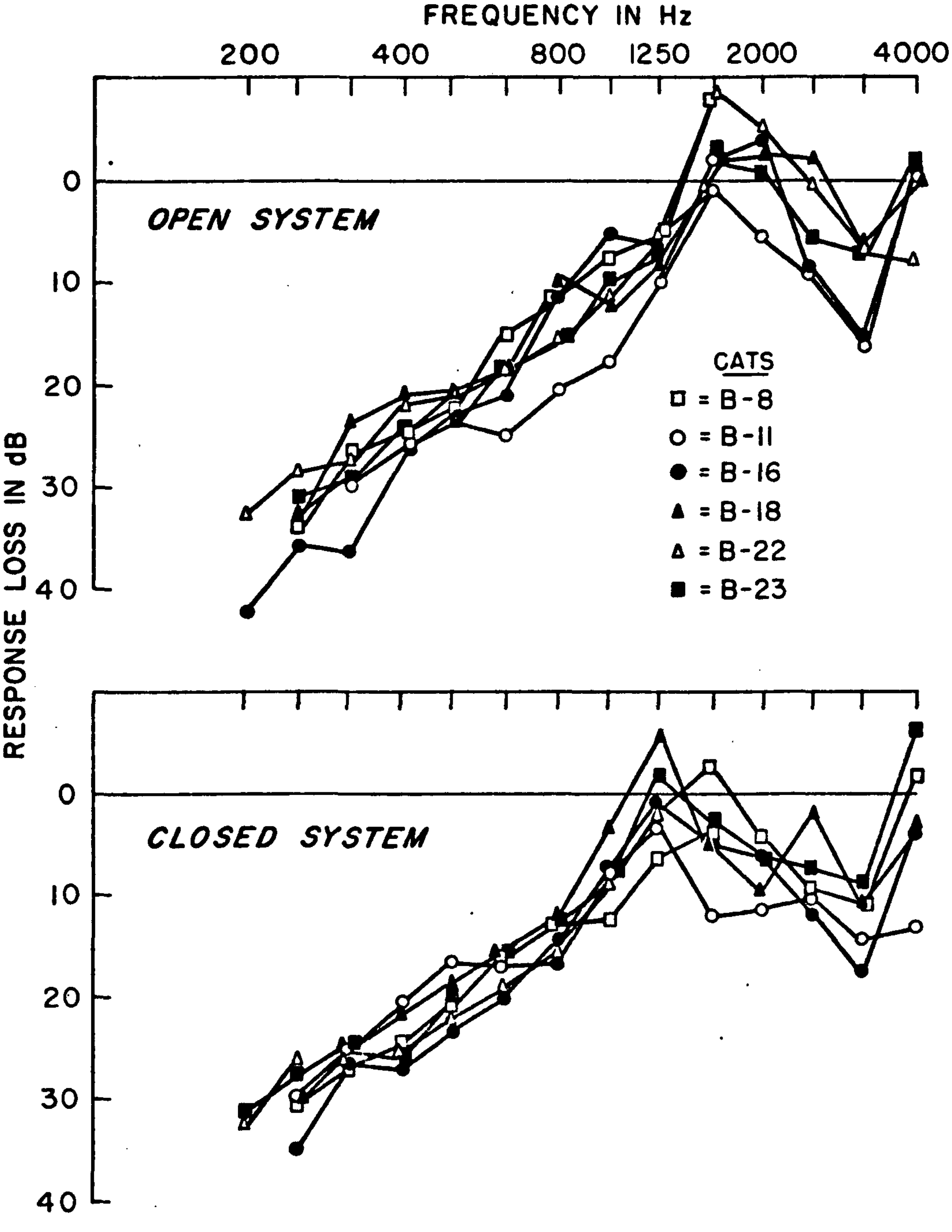

FREQUENCY IN Hz
200
400
800
1250
2000
4000
RESPONSE LOSS IN dB
0
10
20
30
40
OPEN SYSTEM
CATS
□ = B-8
○ = B-11
● = B-16
▲ = B-18
△ = B-22
■ = B-23
0
10
20
30
40
CLOSED SYSTEM

Fig. 8. Mean response-losses (±σ), in dB, for a series of six cats, plotted against frequency, in Hz, for the open (open circles) and closed (closed circles) systems.

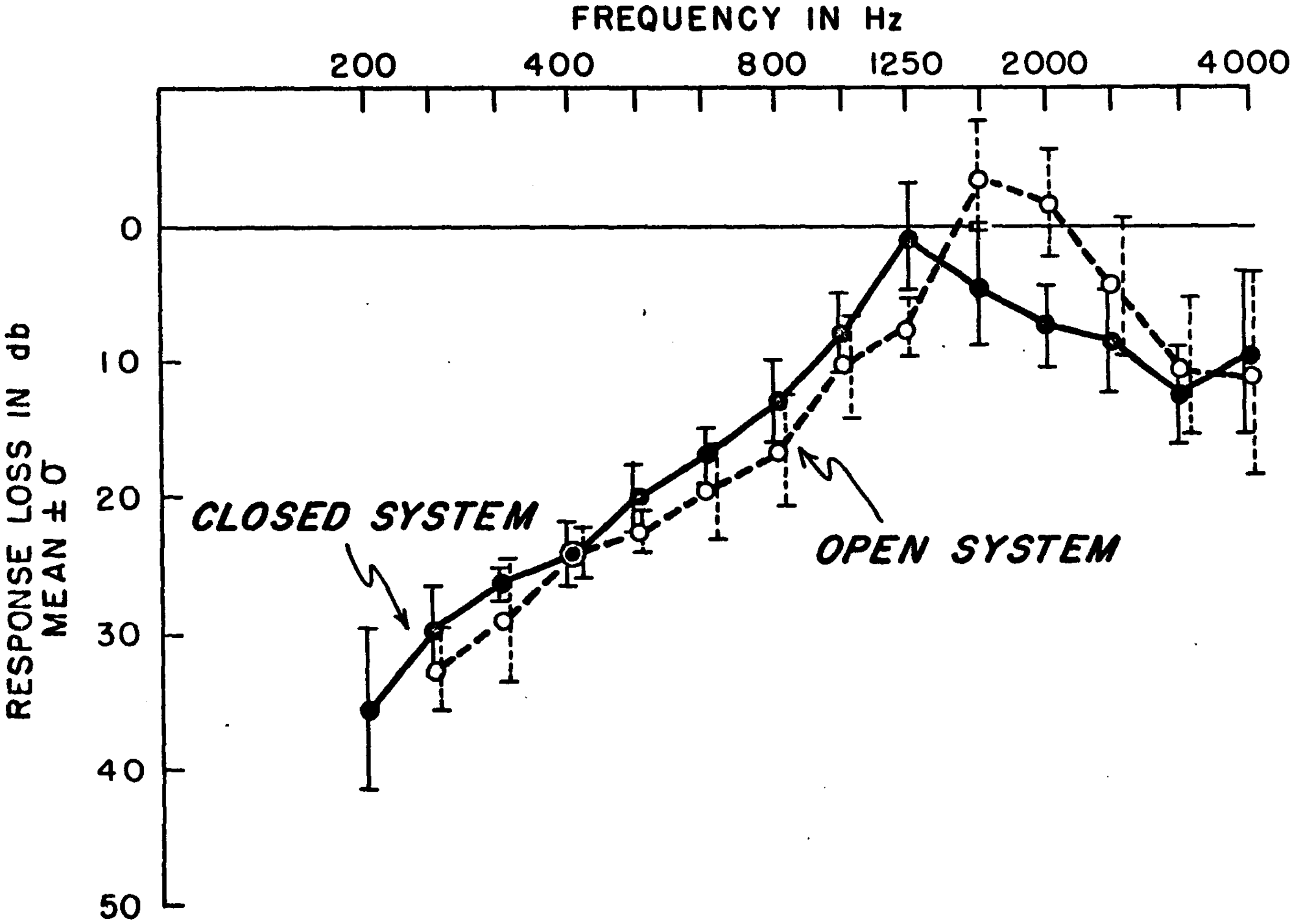

FREQUENCY IN Hz
200
400
800
1250
2000
4000
RESPONSE LOSS IN db
MEAN ± σ
0
10
20
30
40
50
CLOSED SYSTEM
OPEN SYSTEM

TABLE 4

LEAST SQUARE FIT SLOPES FOR THE OPEN AND CLOSED SYSTEM RESPONSE-LOSS CURVES OF EACH CAT, AND THEIR MEAN SLOPE (σ). OPEN AND CLOSED SYSTEMS WERE CONSIDERED SEPARATELY AND IN COMBINATION

	RESPONSE-LOSSES	
Cat #	Open System Slope (dB/octave)	Closed System Slope (dB/octave)
B-8	-13.9	-10.0
B-11	-10.8	-10.0
B-16	-14.2	-14.0
B-18	-10.7	-13.7
B-22	-11.7	-11.0
B-23	-11.5	-11.2
Mean Slope	-12.1	-11.7
SD	1.5	1.8

Open and Closed System Slope (dB/octave)

Mean Slope	-11.9
SD	1.6

a straight line with a slope of approximately -12 dB/octave fitted the curve of each cat. The mean slope for the open system response-loss curve was - 12.1 dB/octave ($\sigma =$ 1.5 dB/octave) The mean slope of the closed system response-loss data was -11.7 dB/octave ($\sigma =$ 1.8 dB octave). Since there was no significant difference between the open and closed system response-losses ($t = -0.11$), the open and closed system response-losses were considered as one group The mean of the combined open and closed system slopes is -11.9 dB/octave. The variation of these slopes was only 1.6 dB/octave. Therefore, as was to be expected, the slope is a better indicator of the changes found than the value at each individual frequency.

In the frequency region above 1600 Hz (see Fig. 8), there were additional small losses in both situations. These losses varied considerably between cats so that it is difficult to draw any conclusions about what may be happening in this region.

The nature and extent of the response-losses found in the low and mid-frequency region are identical to those found by McArdle and Tonndorf (1968). With either an open or closed system, there is no evidence of a flat, low frequency loss in cats with a small EAM of the size used in these experiments.

Relation between the Response-Losses and the Changes in Voltage across the Transducer

Fig. 9 shows the mean response-losses, combined for open and closed systems, plotted as a solid line (triangles), and the mean electrical voltage changes across the transducer plotted, *separately* for the open and closed systems (circles), as dashed lines, against frequency, in Hz. Only the voltage changes in the *open* system parallel the response-losses. They vary inversely with frequency at the rate of approximately 12 dB/octave. The mean open system voltage changes ($f \leq 1600$ Hz) were not significantly different, at the 0.01 level, from 1.) the mean *open* system response-losses ($t=2.59$), 2.) the mean *closed* system and closed system response losses ($t=-0.19$) or 3.) the mean combined open and closed system response losses ($t=-2.19$).

In the *closed* system, however, considerably larger voltage increments were required especially in the mid-frequency region -- from 630-2000 Hz. This curve is quite different from the other two. The mean closed system voltage changes varied inversely with frequency at an approximate rate of only 6 dB octave.

A straight line was fit by the least squares method to the open and closed system voltage change curves of each cat, in the low and mid-frequency region. The slopes are listed, separately for the open and closed system, in Table 5. The variation of these slopes was 2.7 dB/octave for the

Fig. 9. Mean *combined* (open and closed system) response-losses (triangles) and mean voltage changes for the open and closed system (circles), both plotted in dB, against frequency, in Hz.

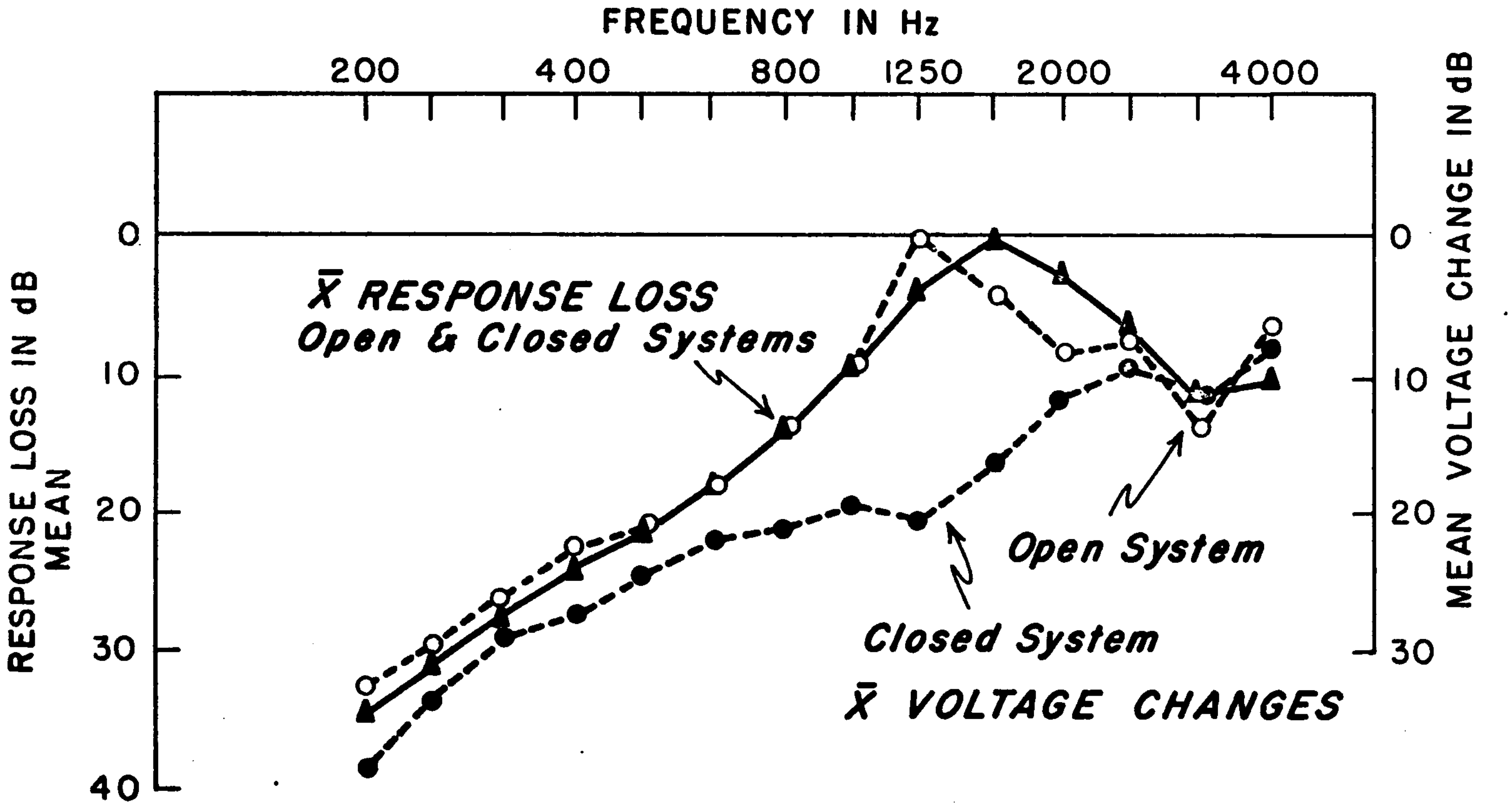

FREQUENCY IN Hz
200
400
800
1250
2000
4000
RESPONSE LOSS IN dB
MEAN
0
10
20
30
40
MEAN VOLTAGE CHANGE IN dB
0
10
20
30
X̄ RESPONSE LOSS
Open & Closed Systems
Open System
Closed System
X̄ VOLTAGE CHANGES

TABLE 5

LEAST SQUARE FIT SLOPES FOR THE OPEN AND CLOSED SYSTEM VOLTAGE CHANGES FOR EACH CAT, AND THEIR MEAN SLOPES (σ)

	VOLTAGE CHANGES	
Cat #	Open System Slope (dB/octave)	Closed System Slope (dB/octave)
B-8	-13.4	-5.8
B-11	-10.0	-4.8
B-16	-16.0	-7.8
B-18	-8.8	-6.0
B-22	-10.1	-6.1
B-23	-10.8	-5.8
Mean Slope	-11.5	-6.0
SD	2.7	1.0

open system voltage change and only 1.0 dB/octave for the closed system voltage change. Again, the slope is a better indicator of the changes found than the value at each frequency.

It was hypothesized (see Chapter I) that a TM perforation might affect the impedance into which an earphone looks in a tightly coupled system. Inspection of the data on Fig. 9 indicates that, indeed, there was an impedance change due to a small TM perforation, at least in a small tightly coupled cavity like that used in the present experiment. That is to say, the increment in voltage was larger than the change in sound pressure required at the TM to produce a 10µV RW CM. In other words, at least in the present situation, then, a perforation caused a drop in sound pressure when the voltage across the closed system transducer was held constant. This drop had to be compensated for by a rise in voltage across the transducer. When the middle ear impedance decreases due to a TM perforation, the pre-calibrated sound pressures (i.e., the voltages across the transducer) are no longer a good indicator of the actual sound pressure changes in front of the TM, but only in a closed system.

In electrical analog networks, similar effect is found. An analogous circuit consists of two resistors in series connected to the terminals of a battery. The first resistor represents the source impedance (i.e., that of the closed system transducer). The second resistor represents the load impedance (i.e., that of the middle ear) A voltmeter is then placed in parallel with the second resistor in order to read the voltage across the load impedance. When the load impedance decreases, there is a voltage drop across the resistor. Consequently, the total resistance of the system is decreased, and there is increased current flow. Therefore, the voltage across the load impedance is reduced. This voltage drop, or I·R drop, is the equivalent of a drop in sound pressure as was observed in the present experiment. There is only one case in which a voltage change would not occur when the load impedance changes: when the source impedance is infinitely high, as in the case of a constant current source.

It follows from the present experiment that it is inappropriate to assume that the voltage across the transducer correctly represents the sound pressure acting on the TM -- especially in the mid-frequency region. At least for the present closed system and for cats with a small TM perforation, the response-loss for the mid-frequency region will be overestimated when calculated on the basis of voltage changes across the transducer.

Interpretation of the Response-Loss

In order to justify a comparison between the sound pressures in front of and behind the TM, the following experiment was performed. In one cat, for frequencies between 0.2 and 4 kHz, sound pressures were measured in two independent runs, at three locations behind the TM. These measurements were made before and after the TM had been perforated. In Table 6, the largest difference among sound pressures, in dB, measured at the three locations are listed under "POSITION" and the largest difference between sound pressures measured in two repetitions are listed under "REPETITION". Data are given separately for the intact and perforated condition. For all but two high frequencies (Intact, 4000 Hz; Perforated, 1600 Hz), the repeat measurements were within 1 dB. It is clear that not only were the variations in the repeat measurements relatively small, but more importantly, there was no significant difference between the "REPETITION" and the "POSITION" variations. For this reason, one may safely assume that the sound pressures measured in *one* given location behind the TM, under these conditions and within the frequency range used, are representative of the sound pressures behind the *entire* membrane.

After this evaluation, sound pressures recorded in front of and behind the TM could be compared with each other. Intra-to-extra tympanic pressure ratios (amplitude ratio: Mic. 2 / Mic. 1) were calculated for each cat, for both the

TABLE 6

MAXIMUM SOUND PRESSURE VARIATIONS IN THE MIDDLE EAR FOUND FOR TWO REPEAT MEASUREMENTS (REPETITION) AT THREE POSITIONS BEHIND THE TM (POSITION). (FREQUENCY, IN KHZ.)

INTACT

f	.2	.25	.315	.4	.5	.63	.8	1	1.25	1.6	2	2.5	3.15	4
POSITION	0	0	0	0	0	.37	.37	.13	.13	.25	.25	1.0	.88	.25
REPETITION	0	0	.25	0	0	.5	.5	.25	.25	.25	0	.25	.5	1.15

PERFORATED

f	.2	.25	.315	.4	.5	.63	.8	1	1.25	1.6	2	2.5	3.15	4
POSITION	0	0	.07	.02	0	.07	.17	.25	.75	.6	.77	.33	.28	.63
REPETITION	0	.15	.15	0	0	.15	.25	.25	1.0	1.75	.4	.5	.25	.25

open and closed systems, and both before and after perforation. In Fig. 10, the mean intra/extra tympanic pressure ratios ($\pm\sigma$), are plotted, in dB, separately for the open and closed systems, for both the intact (circles) and perforated (squares) conditions, against frequency, in Hz. There was no significant difference between the open and closed system ratios at the 0.01 level for either the intact ($t=-0.58$) or the perforated ($t= 0.57$) condition. Therefore, the open and closed system pressure ratios were combined. The combined pressure ratios are plotted in Fig. 11 for the intact (closed squares) and perforated (open squares) conditions against frequency. There was clearly a significant difference between the two conditions, at the 0.01 level: open -- $t=-6.3$; closed -- $t=-6.6$; and open and closed -- $t=-7.0$. In the *intact* condition, the sound pressures in the EAM, in front of the TM, were greater than those in the middle ear. However, in the *perforated* condition, the middle ear sound pressures were not only greater than those in the intact condition, but they were greater than those in the ear canal, especially in the mid-frequencies.

Then, the amplitudes *and* phases of the sound pressures measured on both sides of the TM were used to calculate the *effective sound pressure* acting on the TM, for both the intact and perforated conditions (see Appendix D: Vectorial Analysis). It must be realized that the SPL in the EAM, as well as that in the middle ear cavity exert a force on the TM. These two pressures acting on the TM from

Fig. 10. Mean intra/extra tympanic pressure ratios, ($\pm\sigma$), plotted, in dB, separately for the open and closed systems, for both the intact (circles) and perforated (squares) conditions, against frequency, in Hz.

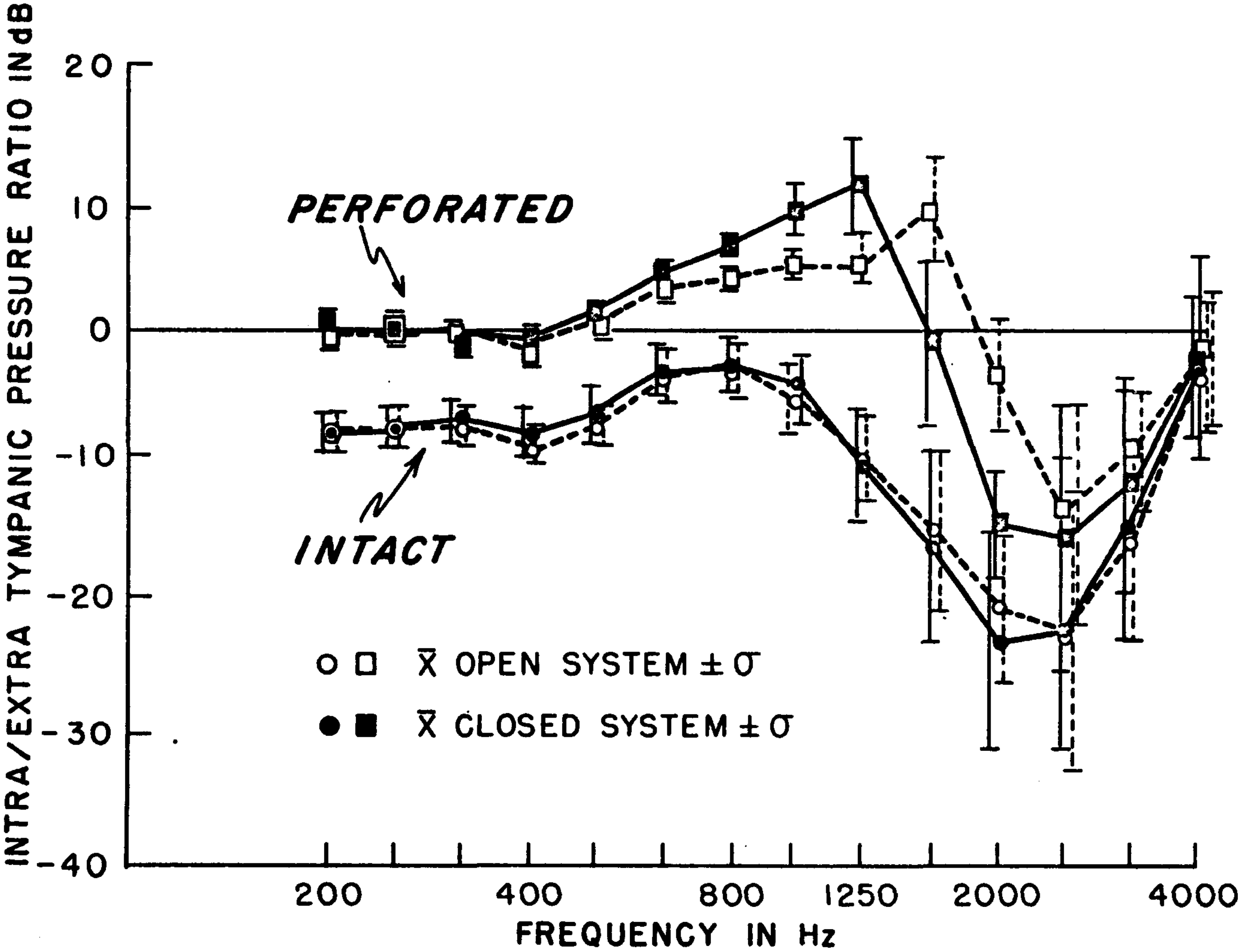
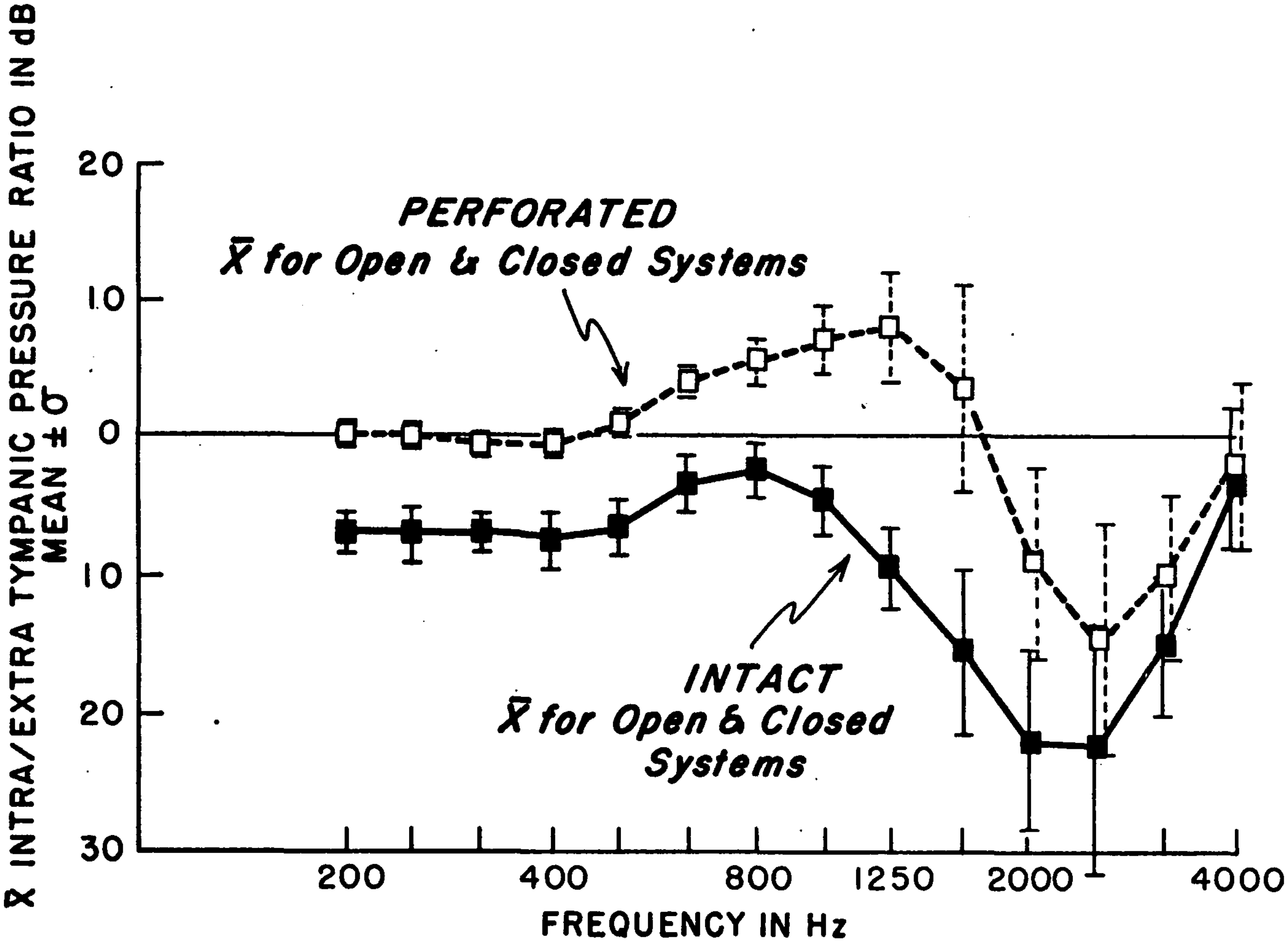

INTRA/EXTRA TYMPANIC PRESSURE RATIO IN dB
20
10
0
-10
-20
-30
-40
PERFORATED
INTACT
○ □ X̄ OPEN SYSTEM ± σ
● ■ X̄ CLOSED SYSTEM ± σ
200
400
800
1250
2000
4000
FREQUENCY IN Hz

Fig. 11. Combined (open and closed system) mean intra/extra tympanic pressure ratios, ($\pm\sigma$), plotted in dB, against frequency, in Hz, for both the Intact (closed squares) and perforated (open squares) conditions.

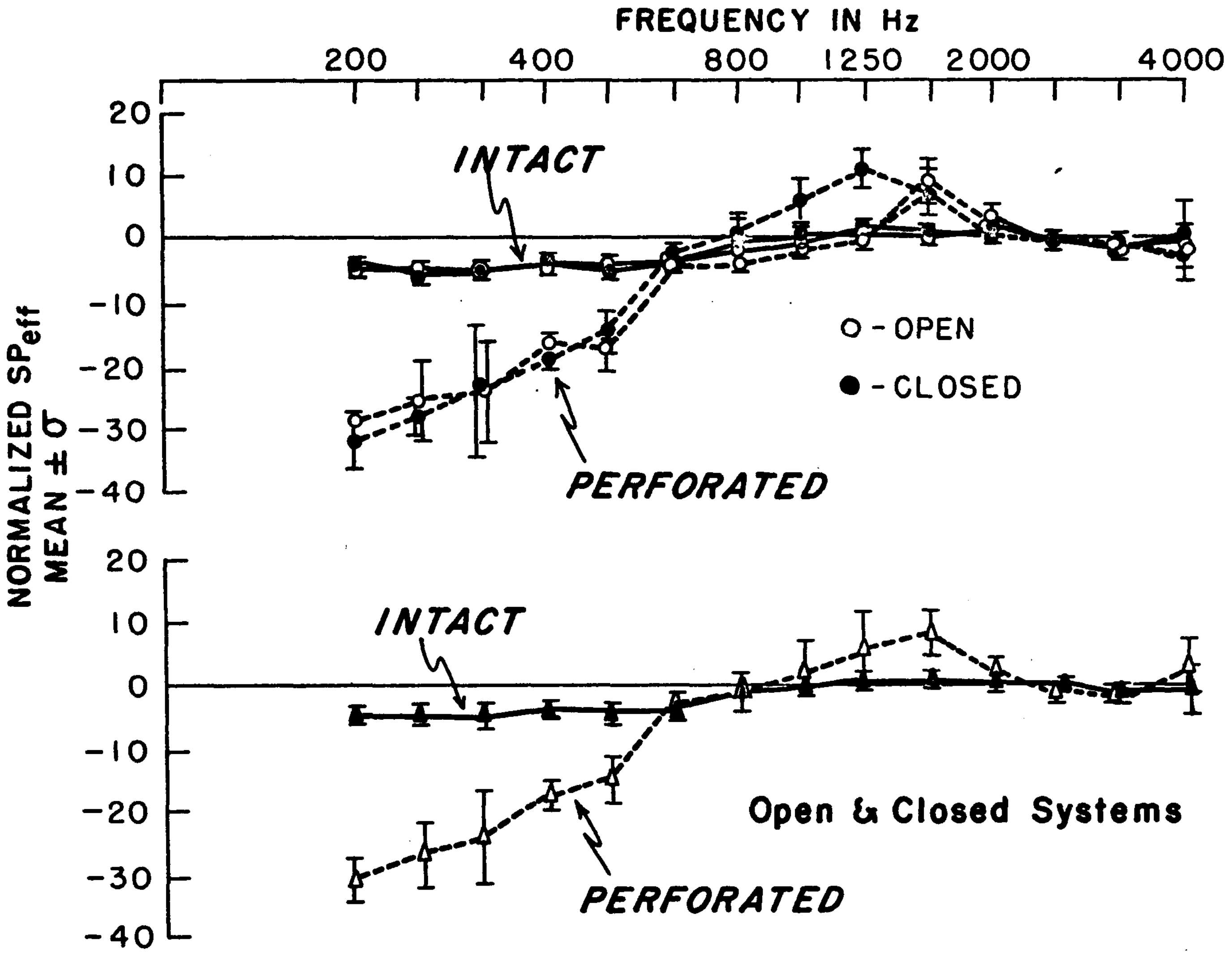

PERFORATED
X̄ for Open & Closed Systems
INTACT
X̄ for Open & Closed Systems
X̄ INTRA/EXTRA TYMPANIC PRESSURE RATIO IN dB
MEAN ± σ
20
10
0
10
20
30
200
400
800
1250
2000
4000
FREQUENCY IN Hz

both sides produce a net, "effective" sound pressure (SP_{eff}).

Such calculations must be performed by combining the magnitudes and phases of the sound pressures vectorially. (See Appendix D: Vectorial Analysis.) Fig. 12 shows the mean normalized effective sound pressure, in dB, plotted against frequency, in Hz. Data are given in reference to a constant sound pressure in front of the TM. In the top graph, the open and closed system results are plotted separately. Since there was no significant difference between them for the intact ($t=-1.69$) or the perforated ($t=-1.16$) conditions, the combined (open and closed system) results are presented in the bottom graph of Fig. 12. There was a significant difference between the intact and perforated conditions ($t= 3.8$) at the 0.01 level.

Before perforation, the normalized effective sound pressures are essentially frequency independent, even in low frequencies. For frequencies at and above 1000 Hz, these sound pressures are close to unity, i.e., at least 90% (-1 dB) of it. For frequencies below 1000 Hz, the normalized effective sound pressures are reduced to approximately 55-60% (-4.8 dB) of unity, but remain at the level toward the lower frequencies, i.e., they are essentially frequency independent. Extrapolation of the curve suggests that even at a frequency of zero Hz, there would still be a differential sound pressure capable of displacing the TM; a conclusion that is supported by fact.

Fig. 12. Mean normalized effective sound pressure (SP_{eff}), in dB, ($\pm\sigma$), acting on the TM plotted against frequency, in Hz. Data are in reference to a constant sound pressure input at the TM.


FREQUENCY IN Hz
200
400
800
1250
2000
4000
20
10
0
-10
-20
-30
-40
INTACT
PERFORATED
O - OPEN
● - CLOSED
NORMALIZED SP$_{eff}$
MEAN ± σ
INTACT
PERFORATED
Open & Closed Systems

After perforation, the normalized effective sound pressure is still essentially frequency independent in the high frequencies. It has the same value, in that region, as it had before perforation. There is a distinct maximum between 1250 and 1600 Hz reaching up to 240% (+7.7 dB) of unity. Below this maximum, the curve slopes downward toward the low frequencies at a rate of approximately 12 dB/octave -- precisely with 13.8 dB/octave for the combined open and closed system -- without an apparent limit. Extrapolation of this curve suggests that at a frequency of zero Hz, there would no longer be a differential sound pressure capable of displacing the TM, a conclusion that is again supported by fact.

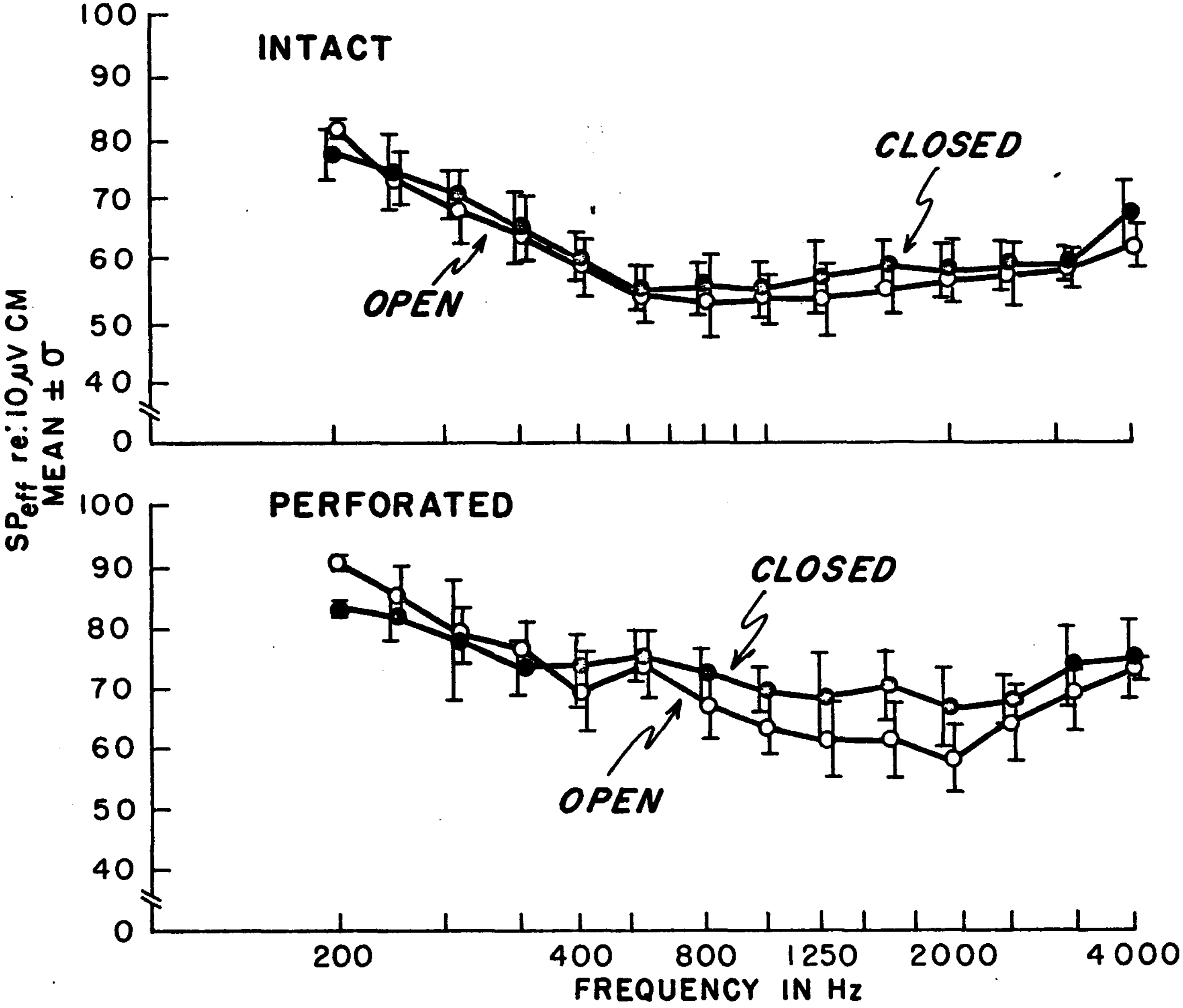
These data of Fig. 12, given for a constant sound pressure input at the TM, suggest further that the characteristic inverse, low-frequency response-loss, that is produced by the perforation, is due to the change in the effective sound pressure acting on the TM.

The normalized effective sound pressures of Fig. 12 were then converted into effective sound pressure levels, necessary to produce the criterion CM (see Appendix D: Vectorial Analysis). This was done by adding (logarithmically) each normalized value to its respective sound pressure level measured in front of the TM, separately for each frequency, for the open and closed systems, both before and after perforation. This effective sound pressure level represents the differential pressure level acting on the TM in reference to a constant CM.

In Fig. 13, the mean effective sound pressure *level* acting on the TM, necessary to produce the criterion microphonic, is plotted against frequency. Values are given (separately for the open and closed systems) for the intact condition in the top graph and for the perforated condition in the bottom graph of Fig. 13. For the *intact* condition and for the open system, these pressure levels varied inversely with frequency at a rate of 14.1 dB/octave for $f \leq 800$ Hz. For the *intact* condition and the *closed* system, they varied at a rate of 12.3 dB/octave. A *t* test demonstrated that there was no significant difference, at the 0.01 level, between the open and closed system data for the entire frequency range used ($t = 0.96$) For the *perforated* condition and for the open system the pressure levels varied inversely with frequency at a rate of 10.9 dB/octave for $f \leq 1000$ Hz. For the *perforated* condition and the closed system the pressure levels varied at a rate of 5.5 dB/octave. However, even though these latter slopes appear to vary some, there was no significant difference, at the 0.01 level between the open and closed system data over the entire frequency range used ($t = -0.14$).

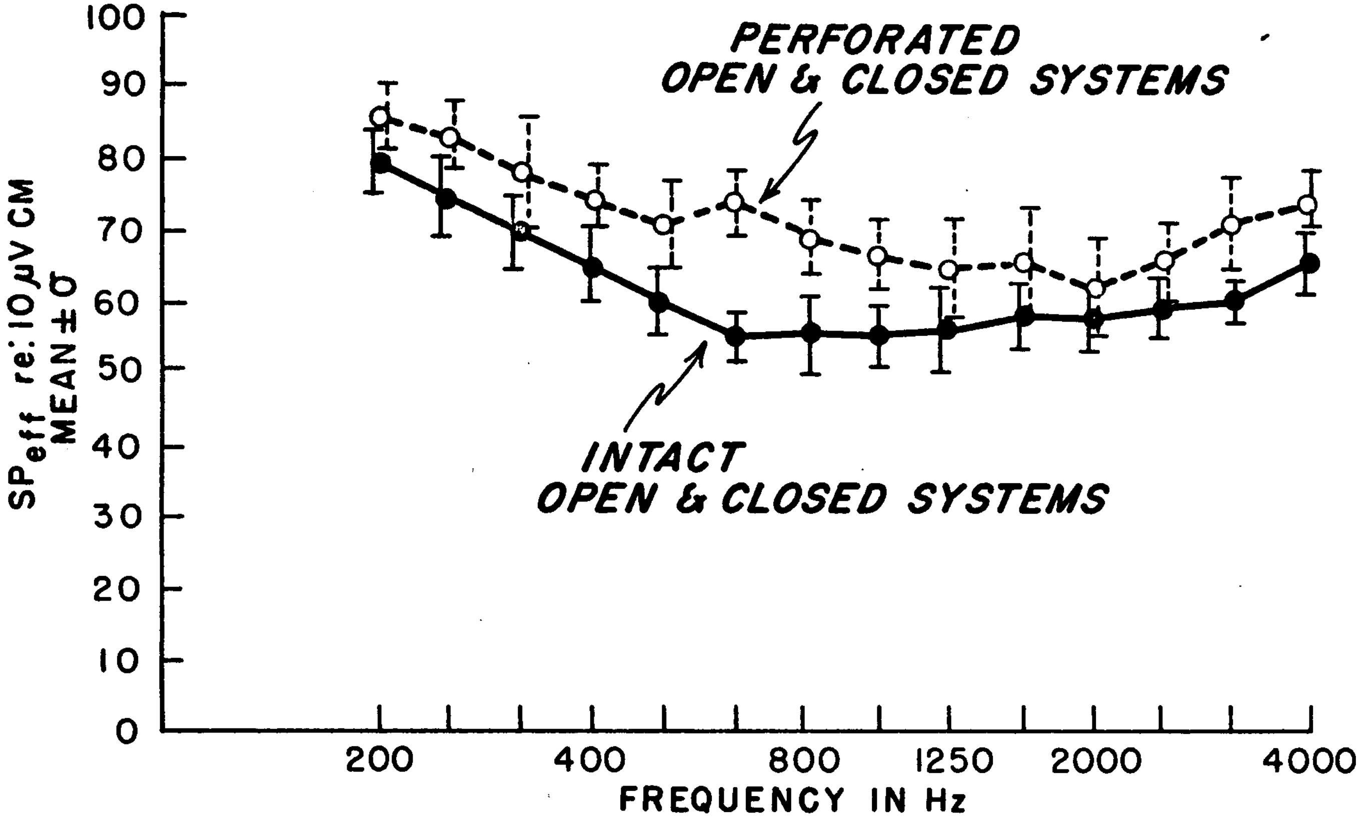
Therefore, since there was no significant difference between the open and closed system data, at the 0.01 level ($t = 0.11$), for either the intact of perforated conditions, the open and closed system results were combined. Fig. 14 shows the means and standard deviations of the combined effective sound pressure levels acting on the TM, for the intact

Fig. 13. Mean effective sound pressure levels acting on the TM ($\pm\sigma$) plotted separately for open and closed systems, for both intact and perforated conditions, against frequency, in Hz. These data are in reference to a constant 10μV RW CM.



INTACT
PERFORATED
CLOSED
OPEN
CLOSED
OPEN
SP$_{eff}$ re: 10 µV CM MEAN ± σ
100
90
80
70
60
50
40
0
200
400
800
1250
2000
4000
FREQUENCY IN Hz

Fig. 14. Mean combined (open and closed systems) effective sound pressure levels acting on the TM ($+\sigma$) for the intact (closed circles) and perforated (open circles) conditions plotted against frequency, in Hz. These data in reference to a constant 10μV RW CM.

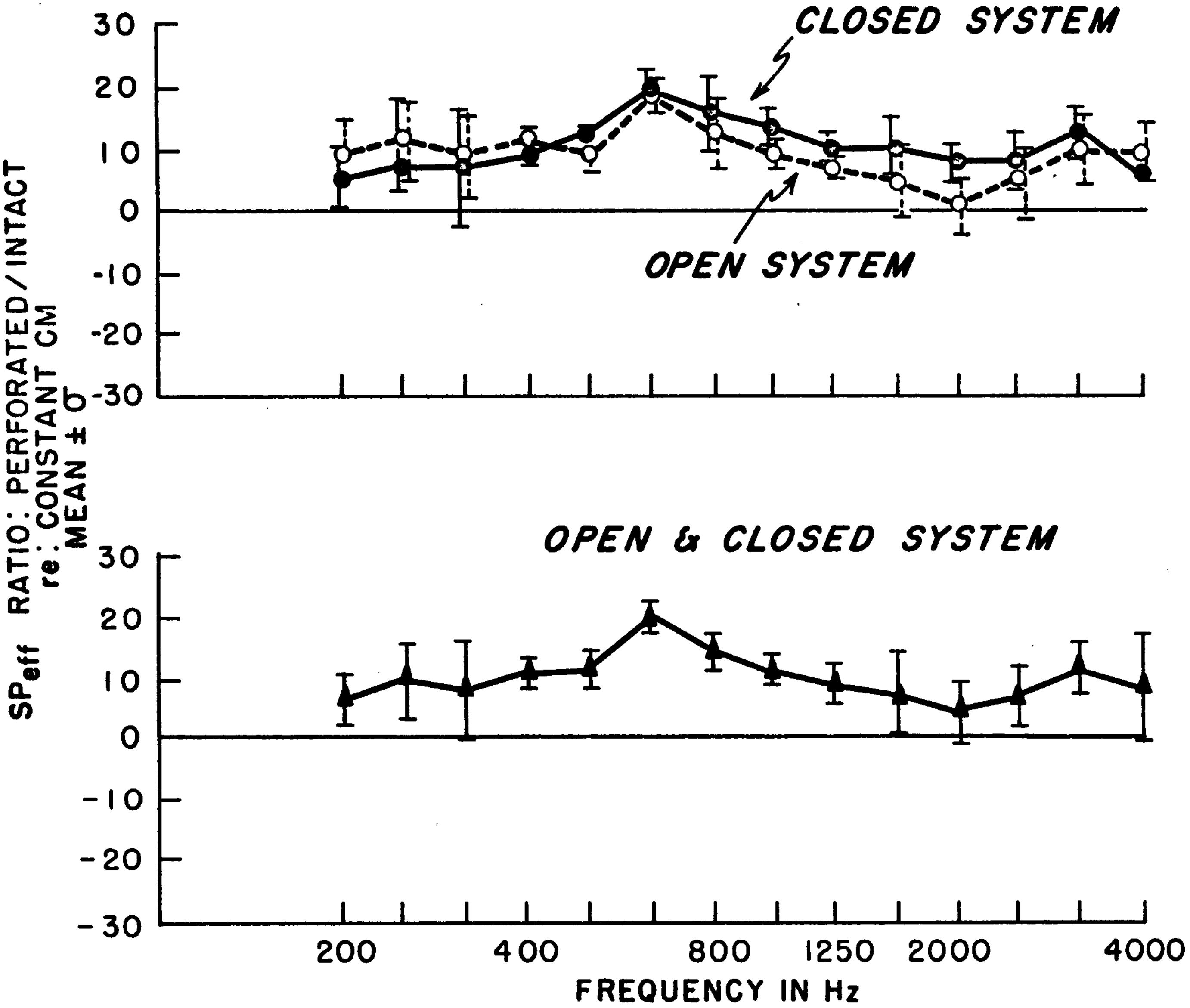

PERFORATED
OPEN & CLOSED SYSTEMS
INTACT
OPEN & CLOSED SYSTEMS
SP_{eff} re: 10 μV CM
MEAN ± σ
100
90
80
70
60
50
40
30
20
10
0
200
400
800
1250
2000
4000
FREQUENCY IN Hz

(closed circles) and the perforated (open circles) conditions, plotted against frequency, in Hz. For the intact condition pressure levels varied inversely with frequency at a rate of 11.4 dB/octave for $f \leq 1000$ Hz, and for the perforated condition they varied at a rate of 7.8 dB octave. There was a significant difference between the intact and perforated conditions ($t=6.4$), at the 0.01 level.

In order to assess the effect of the perforation, the ratios between the two different effective sound pressure levels of Fig. 14, calculated for each frequency, for each cat, and for both the open and closed systems. Fig. 15 shows means and standard deviations of these ratios plotted against frequency. The open and closed systems are given separately in the top graph of the figure to demonstrate their essential similarity. They are combined in the bottom graph because there was no significant difference between them at the 0.01 level ($t=-0.98$).

It is recalled that these effective sound pressure levels, for both the intact and perforated conditions have the constant 10µV microphonic as the reference -- the criterion of the original experiment. The curves expressing the effective sound pressure ratios between perforated and intact conditions (Fig. 15) are essentially frequency independent -- with a small peak at 630 Hz. The reason for this peak becomes obvious from inspection of Fig. 14. The curve for the intact

Fig. 15. Mean effective sound pressure level ratios ($\pm\sigma$) plotted against frequency, in Hz. Levels were in reference to a constant 10µV RW CM.


CLOSED SYSTEM
OPEN SYSTEM
OPEN & CLOSED SYSTEM
SP$_{eff}$ RATIO: PERFORATED/INTACT
re: CONSTANT CM
MEAN ± σ
30
20
10
0
-10
-20
-30
200
400
800
1250
2000
4000
FREQUENCY IN Hz

condition flattened at a higher frequency (at 1000 Hz) than that for the perforated condition (flattening at 630 Hz).

The curves of Fig. 15 are not only frequency independent, but also run at a level of approximately 10 dB. This finding indicates that, after a TM perforation, a greater effective sound pressure level is required to generate a constant CM, than was required before it.

Therefore, when a constant-input effective sound pressure acting on the TM is taken as the reference, a correction of 12 dB/octave for $f < 1000$ Hz is all that is needed to make the input signal the same for both the intact and perforated conditions. However, when a constant CM is taken as the reference (which then, by definition, includes the 12 dB low frequency correction), an increment of 10 dB in the effective sound pressure level is needed for all frequencies, to make the input signal the same for both the intact and perforated conditions. If the middle ear is considered a transmission line, it appears that there is, in first approximation, a 10 dB frequency-independent admission loss due to the perforation.

Recapitulation of the Experiment I Results

In summary, the results of the first experiment are:

1. The effect of a small TM perforation on middle ear transmission, as determined in terms of changes of sound pressure

in front of the TM, is a <u>response-loss</u> in the low and mid-frequencies that varies inversely with frequency at a rate of approximately 12 dB/octave.

2. There is no significant difference between open and closed system <u>response-losses</u>.

3. There is, however, a significant difference between open and closed system <u>voltage</u> changes. In an open system, the changes in voltage across the earphones i.e., in pre-calibrated sound pressures, are of the same magnitude as the response-losses determined in front of the TM. Nevertheless, in a small <u>closed</u> system, like the one used in the present experiment, voltage changes are not of the same magnitude as the response-losses in front of the TM and should therefore not be used as an indicator of sound pressure changes in front of the TM.

4. The nature of the response-loss can be interpreted in the following way:

a) If a constant sound pressure input to the middle ear is taken as the reference, the frequency characteristics of the response-loss are accounted for by the changes in effective sound pressure acting on the TM. Under this condition, a 12 dB/octave correction is needed at low frequencies to make the <u>input</u> effective sound pressure the same for both the intact and perforated conditions.

b) If, however, a constant CM <u>response</u> is taken as the reference -- which then includes the above 12 dB correction -- a small perforation is found to cause a frequency-independent admission loss of 10 dB.

EXPERIMENT II

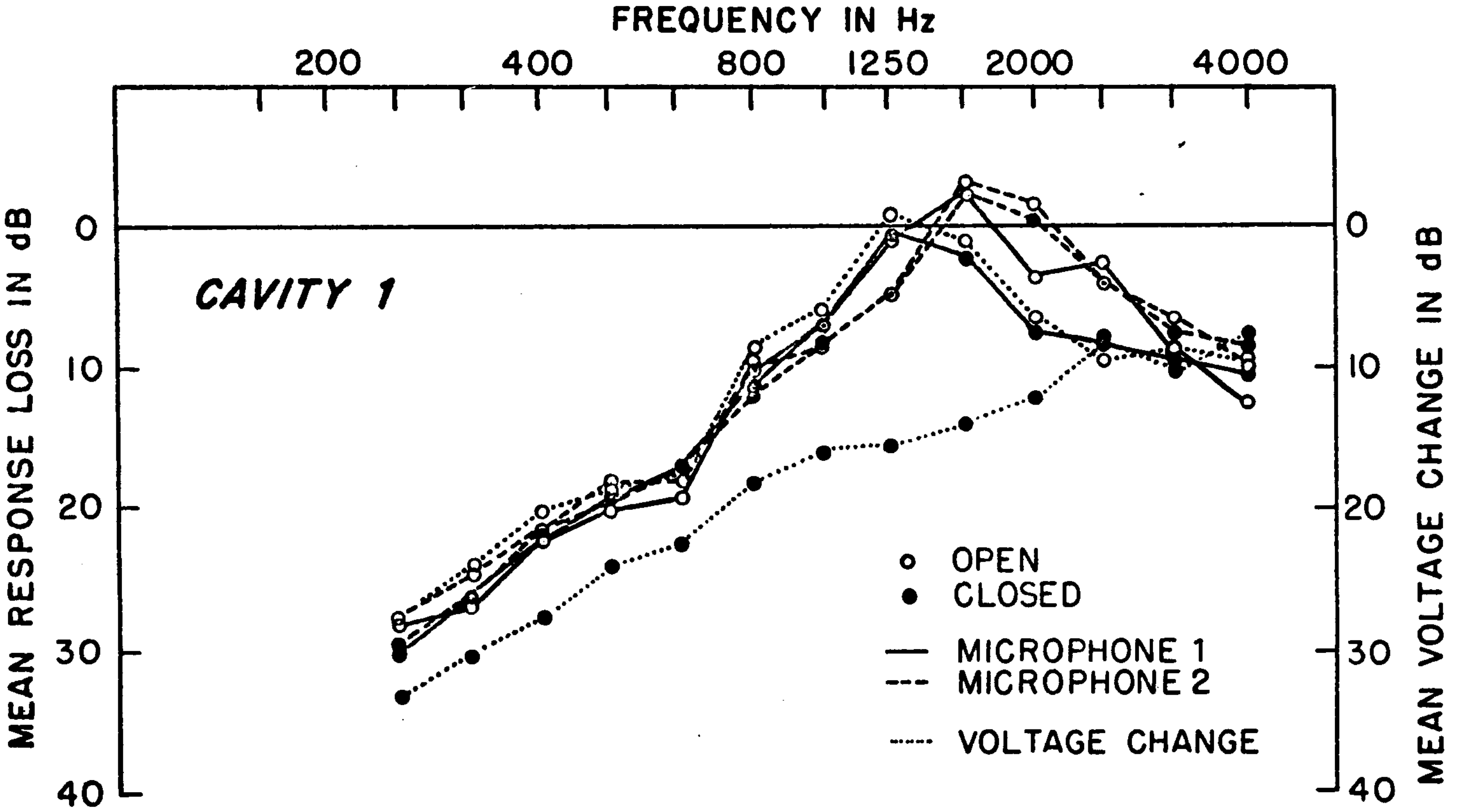
Introduction

The second experiment deals with the effect of a TM perforation on sound transmission in the presence of an ear canal. The surgically removed lateral portion of the cat's own ear canal was replaced by four different artificial ear canals that varied in their physical characteristics of length, volume and leakiness (see Table 1). The nature of the response-loss due to a perforation was examined with each of these artificial ear canals. Response-losses and voltage changes were determined for the open and closed systems at two locations in the EAM: either at the outer opening of the ear canal (Mic. 1), or at its medial end, just in front of the TM (Mic. 2).

The Reference Condition: Cavity 1

Cavity 1 (see Table 1) is the surgically shortened medial portion of the cat's own ear canal. The mean response-losses and mean voltage changes for the Cavity 1 condition, plotted against frequency, are shown in Fig. 16. (This experimental condition is essentially the same as that of Experiment I.) These data were collected on 10 cats (see Table 2). Again, open symbols represent the open system data and closed symbols the closed system data. Response-losses measured at the outer opening of the ear canal (Mic. 1) are represented

Fig. 16 Mean response losses and mean voltage changes (dotted line), both in dB, for the Cavity 1 condition plotted against frequency, in Hz. Microphones were located at the outer opening of the canal (Microphone 1-solid lines) and at the TM (Microphone 2 - dashed lines). Measurements were made both in the open (open circles) and closed (closed circles) system.


FREQUENCY IN Hz
200
400
800
1250
2000
4000
MEAN RESPONSE LOSS IN dB
0
10
20
30
40
MEAN VOLTAGE CHANGE IN dB
CAVITY 1
○ OPEN
● CLOSED
— MICROPHONE 1
--- MICROPHONE 2
······ VOLTAGE CHANGE

by a solid line. Response-losses measured at the TM (Mic. 2) are represented by a dashed line. The voltage changes that accompanied these response losses, for either the open or closed system, are represented as dotted lines. The experimental results obtained with Cavity 1 are essentially the same as the results of Experiment 1. Fig. 16 shows, therefore, that the open and closed system response-losses, measured at either location, as well as the open system voltage changes, vary inversely with frequency at a rate of approximately 12 dB/octave at $f \leq 1250$ and 1600 Hz. A straight line, with a slope of approximately 12 dB/octave was fitted by the least squares method to the curve of each cat. Table 7 lists these slopes for each cat, by measurement condition. All the slopes, except that for the open system voltage changes, were fitted only to the *low* and *mid*-frequency region. The slopes of the open system voltage changes were fitted to the *entire* frequency region, since the slopes were determined for the region of straightness. It should be noted that, between cats, the variation in the slopes of the straight lines fitted was 3 dB/octave or less, while the standard deviation of the data points for each individual frequency was approximately 7 dB. The variations of the slopes of the straight lines fitted to the closed system voltage change data of each cat was only 1.7 dB/octave. Again, the slope is a better indicator of the changes found than the values at each individual frequency.

TABLE 7

CAVITY 1 LEAST SQUARE FIT SLOPES LISTED BY MEASUREMENT CONDITION, FOR EACH CAT. THE MEAN SLOPES AND THEIR STANDARD DEVIATIONS ARE ALSO GIVEN

	Response-Losses				Voltage Changes	
	Microphone 1		Microphone 2			
Cats	Open	Closed	Open	Closed	Open	Closed
C-3	-14.5	-14.8	-13.0	-15.4	-13.5	-6.9
C-4	-12.1	-9.0	-6.6	-8.6	-8.2	-7.0
C-6	-11.9	-12.3	-11.5	-10.9	-14.9	-6.8
C-7	-11.5	-10.6	-8.6	-11.0	-9.4	-4.3
C-8	-12.2	-11.7	-11.0	-11.0	-12.2	-6.1
C-11	-14.8	-14.3	-13.7	-13.8	-15.0	-7.3
C-15	-10.8	-11.9	-10.9	-9.6	-13.1	-3.8
C-16	-11.8	-11.9	-9.4	-9.0	-10.6	-5.8
C-17	-12.3	-16.4	-12.9	-9.5	-13.0	-5.0
C-18	-14.9	-16.4	-15.8	-15.7	-18.7	-9.6
Mean Slope	-12.7	-12.3	-11.3	-11.5	-12.9	-6.3
SD	1.5	2.3	2.7	2.6	3.0	1.7

Once more, considerably larger voltage increments were required, in the closed system, especially in the mid-frequency region, than in the open system. Over the frequency range used, the closed system voltage changes varied inversely with frequency at a rate of approximately 6 dB/octave (see Table 7). Then, it can again be seen, that in a closed system of this size it is improper to assume that the voltage across the transducer correctly represents the sound pressure acting on the TM, when there was a change in middle ear impedance.

The data of Fig. 16 also show that in such a small cavity there is no difference in the response-losses recorded at either of its ends, in both the open or closed systems.

This Cavity 1 condition, then, served as the reference condition to be compared with the response-losses and voltage changes found with the artificial ear canals.

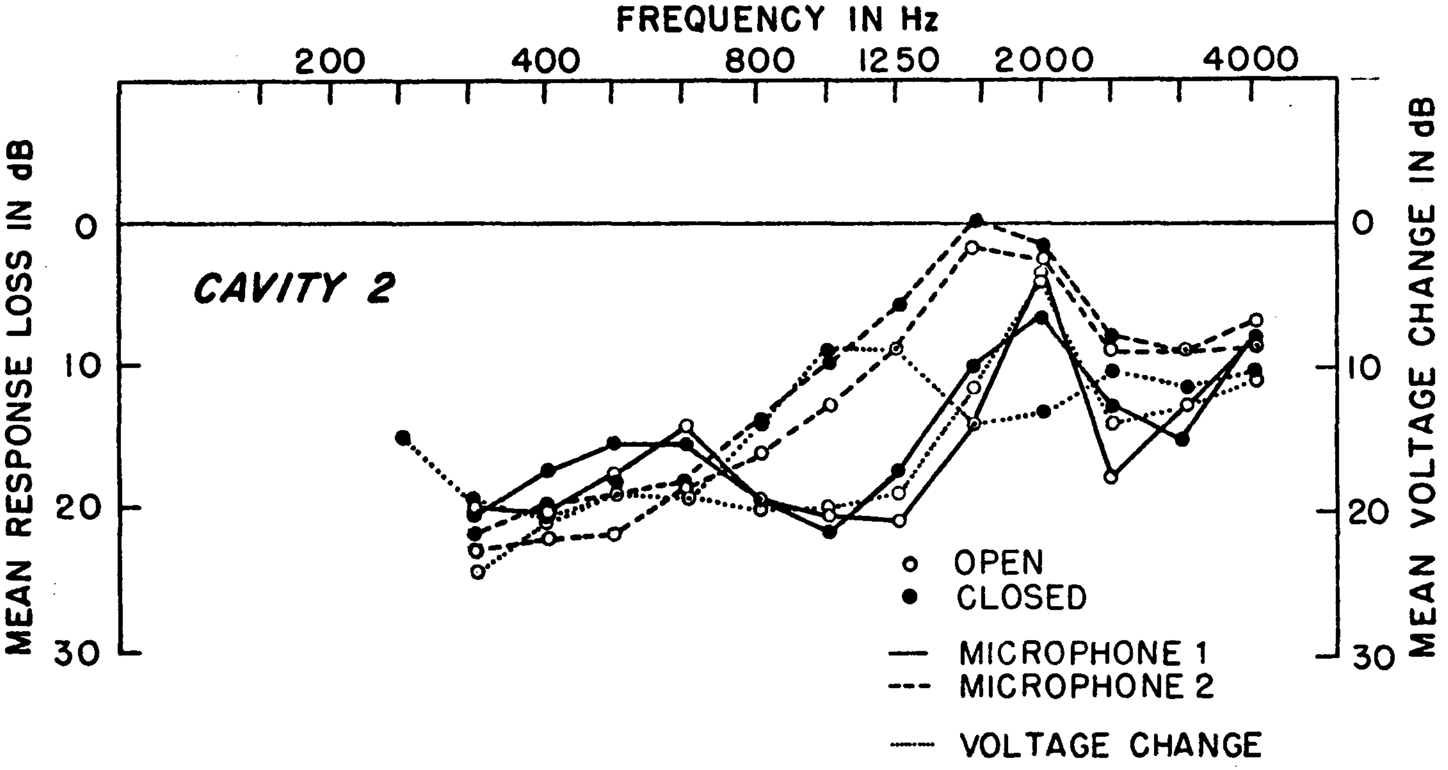
The Effects of the Presence of an Ear Canal

Cavity 2: the short, "leaky" ear canal

Cavity 2 was the short, "leaky," polyethylene artificial ear canal (see Table 1). Fig. 17 shows the mean response-losses and mean voltage changes, both in dB, for Cavity 2 plotted against frequency, in Hz. Data were collected on six cats (see Table 2).

Common effects.-- There are four effects apparent in the

Fig. 17. Mean response losses and mean voltage changes (dotted line), both in dB, for the Cavity 2 condition plotted against frequency, in Hz. Microphones were located at the outer opening of the canal (Microphone 1-solid line) and at the TM in the EAM (Microphone 2 - dashed line). Measurements were made in both open (open circles) and closed (closed circles) systems.


FREQUENCY IN Hz
200
400
800
1250
2000
4000
MEAN RESPONSE LOSS IN dB
0
10
20
30
MEAN VOLTAGE CHANGE IN dB
0
10
20
30
CAVITY 2
○ OPEN
● CLOSED
— MICROPHONE 1
--- MICROPHONE 2
······ VOLTAGE CHANGE

Cavity 2 data (Fig. 17) that were found with all the artificial cavities used, regardless of their differences in length, volume and leakiness. These common effects are:

1. The <u>open and closed system response-losses</u> run together. There was never a significant difference between them.

2. The <u>open system voltage changes</u> always traveled together with the response-losses determined at the <u>outer</u> opening of the ear canal (Mic. 1) over the entire frequency range used. The <u>closed system voltage changes</u>, however, always traveled together with the response-losses determined at the TM (Mic. 2), but only into the mid-frequency region where the voltage curve invariably departed from the others. (Here, in Cavity 2, this departure occurred at 1250 Hz - see Fig. 17.)

3. In the mid-frequency region, the Mic. 2 response-losses and closed system voltage changes both had slopes that were the same as those found in Cavity 1 (or in Experiment 1), without extended ear canals. These slopes varied inversely with frequency at a rate of approximately 12 dB/octave.

4. In the mid-frequency region, the response-losses differed according to the location at which they were determined. In other words, there was always a significant difference between the slopes of the Mic. 1 response-losses and the open system voltage changes on the one hand and the slopes

of the Mic. 2 response-losses and the closed system voltage changes on the other.

Distinguishing effects.-- In order to describe the effects which distinguish the short polyethylene cavity (2), as well as to discern the common effects described above, straight lines were fitted by the least squares method, to specified low and mid-frequency regions of the mean response-losses and mean voltage changes. Table 8 lists these slopes fitted to the low frequency region ($\leq$630 Hz), the mid-frequency region (630-1250 Hz and 630-1600 Hz) and the low and mid-frequency region ($\leq$1250 Hz). (Also, refer to Fig. 17.)

With this short, "leaky" polyethylene canal, the low frequency portions of the loss curves tended to flatten. Below 630 Hz, the Mic. 1 response-losses and the open system voltage changes flattened to approximately -6 dB/octave. In the low and mid-frequencies (below 1250 Hz), the Mic. 1 response-losses and open system voltage changes were very close to a 0 dB/octave slope. However, the curves were not absolutely flat. There was a small rise followed by a dip. The small rise has a negative slope below 630 Hz, and a positive one, above 630 Hz. The mean Mic. 2 response-losses and closed system voltage changes flattened to approximately -3 dB/octave,

TABLE 8

LEAST SQUARE FIT SLOPES FOR THE LOW FREQUENCY REGION (≤630 Hz), MID-FREQUENCY REGION (630-1250 Hz) AND (630-1600 Hz), AND THE LOW AND MID-FREQUENCY REGION (≤1250 Hz) OF THE MEAN RESPONSE-LOSSES AND MEAN VOLTAGE CHANGES OBTAINED FOR CAVITY 2

		Least Square Slopes (dB/Octave)			
		Low Frequency ≤630 Hz	Low & Mid-Frequency ≤1250 Hz	Mid-Frequencies	
				630-1250	630-1600
Response Losses	Open	-5.7	0.6	6.1	-3.6
Mic. 1	Closed	-5.3	0.4	2.8	-3.4
Voltage Changes	Open	-5.7	-1.9	0.05	-4.7
Response Losses	Open	-4.3	-7.1	-9.5	-13.0
Mic. 2	Closed	-3.9	-6.3	-11.9	-12.2
Voltage Changes	Closed	250-630 2.5 315-630 -0.5	-6.3	-11.1	

but only in the low frequency region. The single point for the closed system boltage changes at 250 Hz (see Fig. 17) represents data from only two cats: the average of a moderate voltage change (21 dB - Cat C-6) and of a small voltage change (8.9 dB - Cat C-4). Therefore, since it is not representative, the 250 Hz data were excluded for the purposes of curve fitting. Under that condition, the slope of the closed system voltage changes between 315 and 630 Hz was -0.5 dB/octave.

Although the similarities and differences among the measurement conditions are apparent from inspecting the response-losses or voltage changes plotted in Fig. 17, or from the slopes listed in Table 8, the significances of the differences between these slopes were determined.[1]

Table 9 lists calculated _t_ values, degrees of freedom (_df_) and significances at the 0.01 level for a comparison between closed system Mic. 2 response-losses and all other

---

[1] It should be noted that this statistic is appropriate in principle (Huntsberger, 1961, Chapter 8). However, it is not a sufficiently powerful test for the present purpose. The frequency segments to which straight lines could be fitted were too short. These segments had as few as four mean values that contributed to the slope. Therefore, since the _t_ statistic used to determine the significance of the difference between regression lines had _n-2_ degrees of freedom, the _t_ values for significance were large. The few results that are only significant at the 0.05 level might have been significant at the 0.01 level if the frequency segments for the slopes had been longer.

TABLE 9

SIGNIFICANCE OF THE DIFFERENCES BETWEEN LEAST SQUARE FIT SLOPES FOR CAVITY 2. FREQUENCY REGIONS, CALCULATED t VALUES, DEGREES OF FREEDOM (df), AND SIGNIFICANCES AT THE 0.05 LEVEL ARE GIVEN FOR EACH PAIRED MEASUREMENT

H: b=Bo

Frequency	Slope b	Slope B_o	t calc.	df	Significance at 0.01 level
Low Frequency (≤630 Hz)	Mean Closed Mic. 2 Response-Loss	Mean open Mic. 1 Response-Loss	2.6	2	NS
		Mean closed Mic. 1 Response-Loss	2.0	2	NS
		Mean open system Voltage Change	2.5	2	NS
		Mean open Mic. 2 Response-Loss	0.6	2	NS
		Mean closed system Voltage Change	-4.7	2	NS
Mid-Frequency (630-1250 Hz)	Mean Closed Mic. 2 Response-Loss	Mean open Mic. 1 Response-Loss	-36.3	2	S
		Mean closed Mic 1 Response-Loss	-29.6	2	S
		Mean open system Voltage Change	-4.6	2	NS
		Mean open Mic. 2 Response-Loss	-24.1	2	S
		Mean closed system Voltage Change	-1.6	2	NS

response-losses and voltage changes separately for the low and mid-frequency region. In the low frequency region, there was not only no difference among the various response-losses and voltage changes, but there was also no significant difference between the closed system response-losses at Mic. 2 and any of the other response-losses or voltage changes at the 0.01 level.

In the mid-frequency region, the common effects referred to above are quite apparent. The closed system Mic. 2 response-losses (630-1250 Hz) were significantly different from the Mic. 1 response-losses (open and closed) and from the open system voltage changes at the 0.01 level, but they were not significantly different from the open system Mic. 2 response-losses and closed system voltage changes.

In addition, in the mid-frequency region, the slopes of the Mic. 2 response-losses (open: -13.0 dB/octave; closed: -12.2 dB/octave) were similar to those found for the reference Cavity 1 condition, as well as in Experiment I.

The closed system voltage changes tended to travel together with both the open and closed system response-losses determined at Mic. 2, up to and including 1250 Hz. Thereafter, the voltage curve departed from the other two. Above 1250 Hz, larger voltage increments were required. Then, for a slightly larger closed system than Cavity 1 (see Table 2) when there was a change in middle ear impedance, the voltages across the transducer once more did not represent the sound pressure acting on the TM, in the mid-frequency region and above. However, in the low frequencies and the lower mid-frequencies, the voltage changes across the closed system transducer and the sound pressure changes in front of the TM, induced by the TM perforation, were in good agreement.

Cavity 4: the short, "leakless" ear canal

Cavity 4 is the short, essentially "leakless," copper artificial ear canal (see Table 1). This cavity had the same length as the short "leaky" polyethylene cavity (2) just discussed. Their major distinguishing characteristic is leakiness. Fig. 18 shows the mean response-losses and mean voltage changes, both in dB, for this Cavity 4 condition plotted against frequency, in Hz. Data were collected on four cats (see Table 2). With the short, "leakless" artificial ear canal, there is no low frequency flattening either of the response-losses or of the voltage changes. Least square slopes, determined for the mean response-loss and mean voltage change data, are listed in Table 10. These slopes substantiate numerically the lack of flatness in the low frequency region.

In the mid-frequency region, the common effects were demonstrated once more for the Mic. 2 response-losses and the closed system voltage changes. In that region the two curves

Fig. 18. Mean response-losses and mean voltage changes (dotted line), both in dB, for the Cavity 4 condition plotted against frequency, in Hz. Microphones were located at the outer opening of the canal (Microphone 1 - solid line) and at the TM (Microphone 2 - dashed line). Measurements were made in the open (open circles) and closed (closed circles) system.

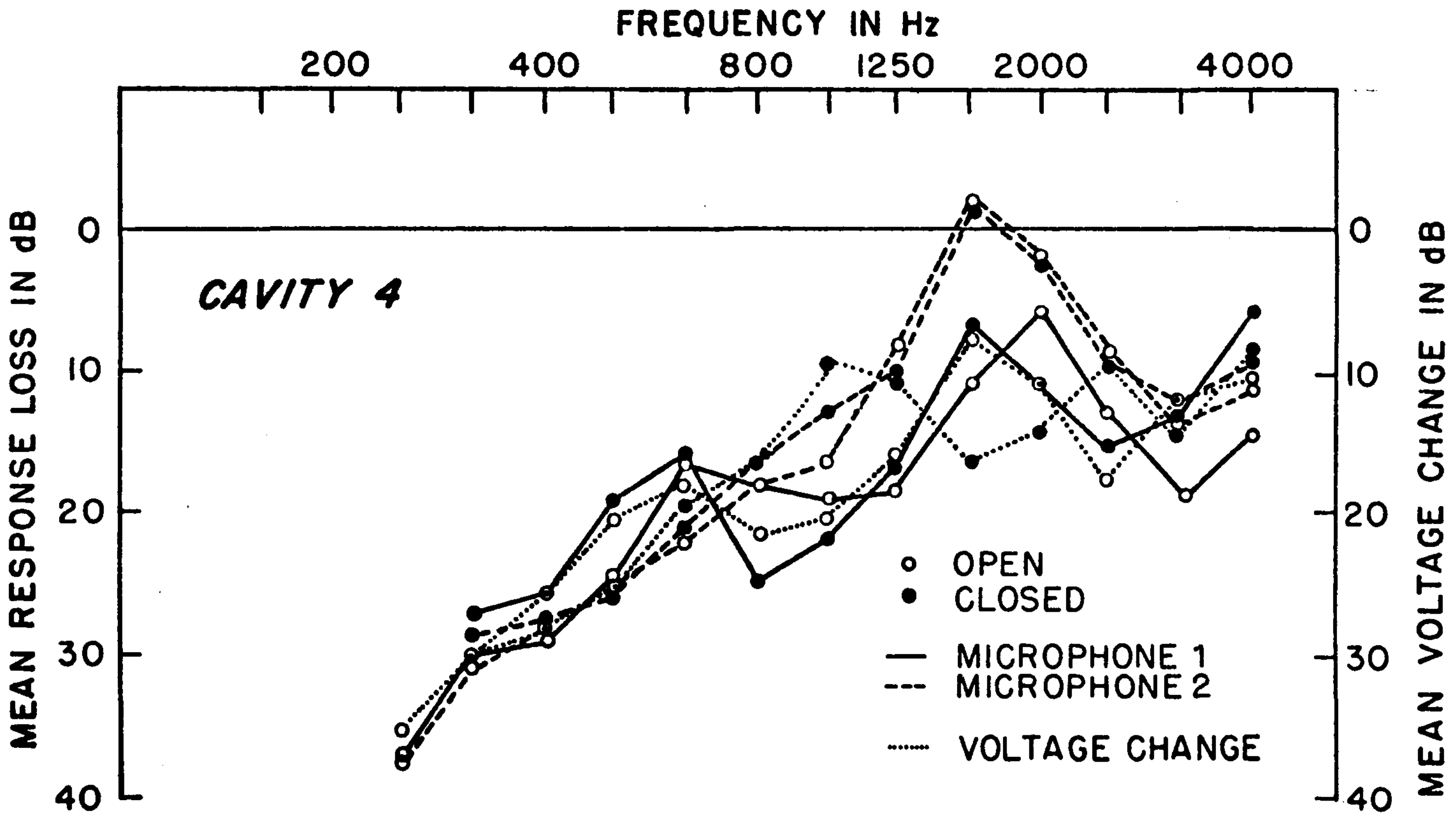

FREQUENCY IN Hz
200
400
800
1250
2000
4000
MEAN RESPONSE LOSS IN dB
0
10
20
30
40
MEAN VOLTAGE CHANGE IN dB
CAVITY 4
○ OPEN
● CLOSED
— MICROPHONE 1
--- MICROPHONE 2
······ VOLTAGE CHANGE

TABLE 10

LEAST SQUARE FIT SLOPES FOR THE LOW FREQUENCY REGION (≤630 HZ) AND THE MID-FREQUENCY REGION (630-1250 HZ) MEAN RESPONSE-LOSSES AND MEAN VOLTAGE CHANGES OBTAINED FOR CAVITY 4

		Least Square Slopes (dB/Octave)	
		Low Frequencies (≤630 Hz)	Mid-Frequencies (630-1250 Hz)
Response Losses Mic. 1	Open	-13.8	3.5
	Closed	-11.4	-0.1
Voltage Changes	Open	-13.3	-2.1
Response Losses Mic. 2	Open	-10.9	-13.0
	Closed	-9.1	-10.9
Voltage Changes	Closed	-10.3	-9.3

had essentially the same slopes as those obtained for the reference Cavity 1. More importantly, however, in this latter frequency region, there was a flattening of the Mic. 1 response-losses and the open system voltage changes. These curves flattened to approximately 0 dB/octave (0.43 dB/octave), although there were some variations (σ =2.8 dB/octave).

From the data in Table 11, it can be seen that in the low frequency region, there is no significant difference between the open system Mic. 2 response-losses and the other response-losses or voltage changes, respectively, at the 0.05 level. In the mid-frequency region, however, there are significant differences between the open system Mic. 2 response-losses and a.) the Mic. 1 response-losses or b.) open system voltage changes, but not between the open system Mic. 2 response-losses and the closed system voltage changes.

The closed system voltage changes tended to travel with both the open and closed system response-losses assessed at Mic. 2 up to and including 1250 Hz before it departed from them (see Figs. 17-20). As in Cavity 2, when the middle ear impedance was changed by a small perforation, and when an ear canal was present, the pre-calibrated voltage value across the closed system transducer still represented the sound pressure acting on the TM in the low frequencies and in most of the mid-frequencies. At higher frequencies, however, there

TABLE 11

SIGNIFICANCE OF THE DIFFERENCES BETWEEN LEAST SQUARE FIT SLOPES FOR CAVITY 4. FREQUENCY REGIONS, CALCULATED *t* VALUES, DEGREES OF FREEDOM (*df*), AND SIGNIFICANCES AT THE 0.05 *LEVEL* ARE GIVEN FOR EACH PAIRED *MEASUREMENT*

H: $b=B_o$

Frequency	Slope b	Slope B_o	*t* calc.	*df*	Significance at 0.05 level
Low Frequency (≤630 Hz)	Mean Open Mic. 2 Response-Loss	Mean open Mic. 1 Response-Loss	2.5	3	NS
		Mean closed Mic. 1 Response-Loss	0.4	3	NS
		Mean open system Voltage Change	2.1	3	NS
		Mean closed Mic. 2 Response-Loss	-1.5	3	NS
		Mean closed system Voltage Change	-0.5	3	NS
Mid-Frequency	Mean open Mic. 2 Response-Loss	Mean open Mic. 1 Response-Loss	-8.7	2	S
		Mean closed Mic. 1 Response-Loss	-6.8	2	S
		Mean open system Voltage Change	-5.8	2	S
		Mean open Mic. 2 Response-Loss	-1.1	2	NS
		Mean closed system Voltage Change	-2.0	2	NS

was no longer such a correlation between these two entities.

When the short, "leaky," polyethylene, artificial ear canal and the short, "leakless," copper, artificial ear canal are contrasted, leakiness rather than length appears to be the distinguishing characteristic. (Volume will be discussed later.) Leakiness tended to cause the low frequency portion of the loss curves to flatten. The short, leaky cavity (2) yielded flat, low frequency losses, regardless of whether the readings had been obtained at the outer opening of the ear canal or at the TM, while the short, "leakless" cavity (4) produced no such flattening in the low frequencies.

The human ear canal is known to be leaky (Tonndorf, et. al., 1966). Furthermore, as was discussed above, audiograms of patients with TM perforations show flat, low frequency hearing losses. Note: a.) that such audiograms are obtained in closed systems, and b.) that the ear canals are always present. It is also recalled that there were some testing conditions that had yielded low frequency losses varying inversely with frequency. In two cases, tests were performed in the absence of ear canals: 1.) in McArdle and Tonndorf's (1968) experiments on cats, and 2.) in Bekesy's (1941) manubrial displacement studies on human cadavers. Only the results obtained from tuning fork tests in the late 1800s and early 1900s (Ostmann, 1909; see also Kobrak, 1959; Feldman,

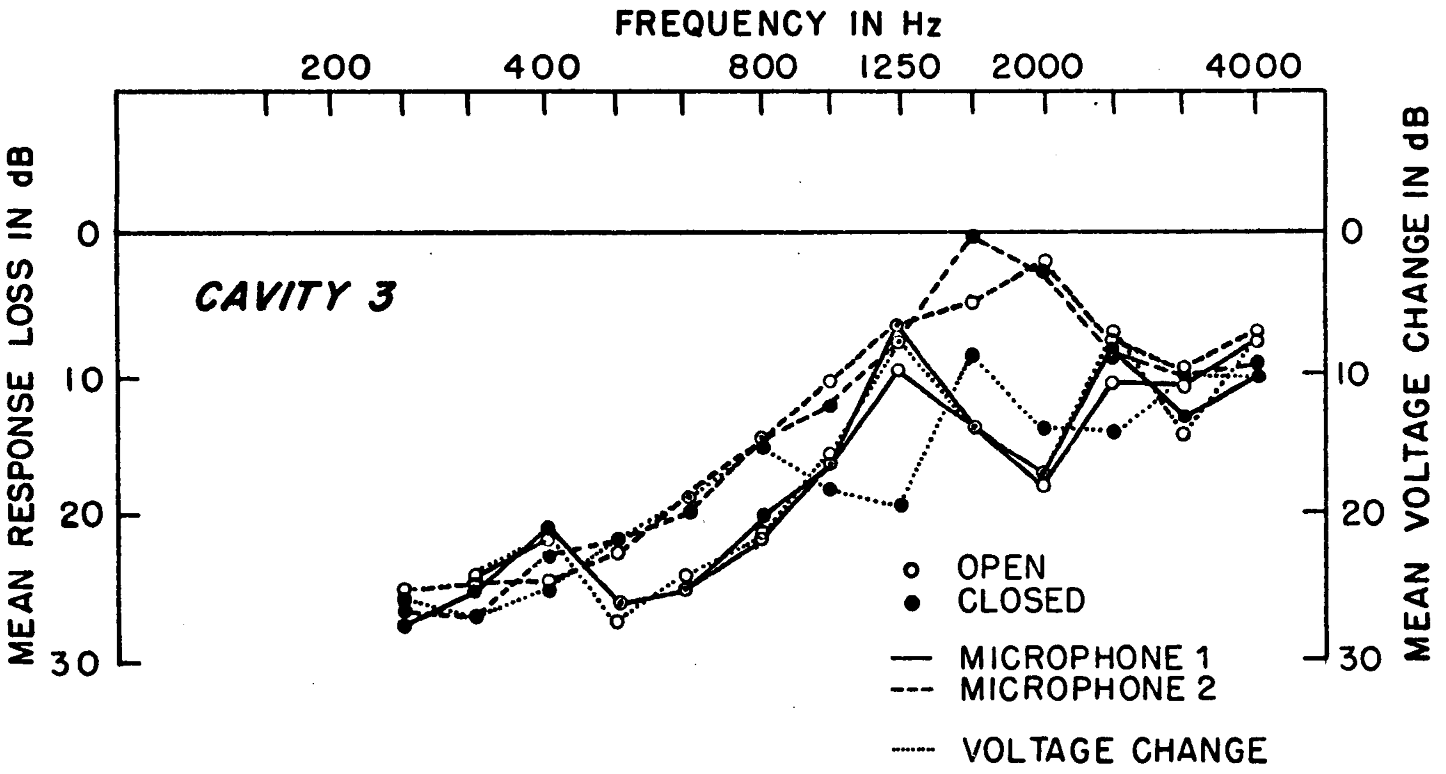
1970) suggest that patients (with ear canals and when tested in an open system), may have low frequency hearing losses after TM perforations, and that such losses may vary inversely with frequency. The present study, however, showed no differences between the results obtained either with open or closed sound delivery systems -- or with or without ear canals.

The present findings suggest that the flat, low frequency hearing loss detected by audiometric testing in a person with a TM perforation may be due to the presence of an ear canal which is also leaky. In addition, it should be noted that both short cavities (the polyethylene Cavity 2 and the copper Cavity 4) produced mid-frequency flattening of the response-losses when these were assessed at the outer opening of the canal (Mic. 1) and also of the open system voltage changes. These common results were due to the similarity in the length of both canals. The fact that, for both of these cavities, the closed system voltage changes departed at f=1250 Hz from the response-losses, assessed at the TM (Mic. 2), may also have to do with the similarity in length of these two canals.

Cavity 3: the long, "leaky" ear canal

Cavity 3 is the long, "leaky," polyethylene, artificial ear canal (see Table 1). Fig. 19 shows the response-losses and voltage changes, both in dB, for the Cavity 3 condition

Fig. 19. Mean response-losses and mean voltage changes (dotted line), both in dB, for the Cavity 3 condition plotted against frequency, in Hz.


FREQUENCY IN Hz
200
400
800
1250
2000
4000
MEAN RESPONSE LOSS IN dB
0
10
20
30
MEAN VOLTAGE CHANGE IN dB
0
10
20
30
CAVITY 3
○ OPEN
● CLOSED
— MICROPHONE 1
--- MICROPHONE 2
······ VOLTAGE CHANGE

plotted against frequency in Hz. Data were collected on six cats (see Table 2). With this longer leaky ear canal, there is again a flattening in the low frequency region but the flat portions tend to be limited to lower frequencies ($\leq$ 500 Hz). Furthermore, in contrast to the shorter leaky cavity, there was a difference between the response-losses determined at the outer opening of the ear canal (Mic. 1) and at the TM (Mic. 2). The least square fit slopes determined for the mean response-loss and voltage change curves are listed in Table 12. The curve of the Mic. 2 response-losses and closed system voltage changes reduced their slopes to only -5 dB/octave, while the curves of the Mic. 1 response-losses and the open system voltage changes attained slopes of approximately 0 dB/octave. Again, there is a small rise followed by a dip. Below 400 Hz, the slope is negative, and above 400 Hz, it is positive. The rise and dip, however, falls entirely within the low frequency range for the longer leaky tube. With the shorter leaky tube, as may be recalled, the rise and dip extended throughout most of the mid-frequency range. This shift to lower frequencies with the longer tube appears to be due to their difference in length.

The significance of the differences between the least square fit slopes for Cavity 3 is shown in Table 13. In the low frequency region, the slopes of the response-losses depended on the location at which readings had been obtained.

TABLE 12

LEAST SQUARE FIT SLOPES FOR THE LOW FREQUENCY REGION (≤630 HZ) AND THE MID-FREQUENCY REGION (630-1250 HZ) MEAN RESPONSE-LOSSES AND MEAN VOLTAGE CHANGES OBTAINED FOR CAVITY 3

		Least Square Slopes (dB/Octave)	
		Low Frequencies (≤630 Hz)	Mid-Frequencies (630-1250 Hz)
Response Losses Mic. 1	Open	2.4	-15.5
	Closed	-1.1	-17.8
Voltage Changes	Open	1.6	-17.6
Response Losses Mic. 2	Open	-4.5	-11.7
	Closed	-5.6	-11.5
Voltage Changes	Closed	-5.6	2.0

TABLE 13

SIGNIFICANCE OF THE DIFFERENCES BETWEEN LEAST SQUARE FIT SLOPES FOR CAVITY 3. FREQUENCY REGIONS, CALCULATED *t* VALUES, DEGREES OF FREEDOM (*df*), AND SIGNIFICANCES AT THE 0.05 LEVEL ARE GIVEN FOR EACH PAIRED MEASUREMENT

H: $b=B_o$

Frequency	Slope b	Slope B	*t* calc.	*df*	Significance at 0.05 level
Low Frequency (≤630 Hz)	Mean Open Mic. 2 Response-Loss	Mean open Mic. 1 Response-Loss	-4.9	3	S
		Mean closed Mic. 1 Response-Loss	-4.0	3	S
		Mean open system Voltage Change	-4.3	3	S
		Mean closed Mic. 2 Response-Loss	0.8	3	NS
		Mean closed system Voltage Change	0.2	3	NS
Mid-Frequency (630-1250 Hz)	Mean Open Mic. 2 Response-Loss	Mean open Mic. 1 Response-Loss	49.2	2	S
		Mean closed Mic. 1 Response-Loss	78.1	2	S
		Mean open system Voltage Change	75.8	2	S
		Mean open Mic. 2 Response-Loss	-2.8	2	NS
		Mean closed system Voltage Change	-175.7	2	S

The slope of the open system Mic. 2 response-losses (at the TM) is significantly different at the 0.05 level from that of the open and closed system Mic. 1 response-losses (at the outer opening of the canal) and also from that of the open system voltage changes, but at that level it is not significantly different from that of the closed system Mic. 2 response-losses or that of the closed system voltage changes.

In the mid-frequency region, while the Mic. 2 response-losses have a slope of approximately 12 dB/octave (similar to the reference Cavity 1 condition), the Mic. 1 response-losses and open system voltage changes have much steeper slopes (approximately 17 dB octave). This is probably due to the fact that the entire Mic. 1 response-losses and open system voltage change curves are shifted toward the low frequencies (compare Figs. 17 and 19). For Cavity 2, the least response-loss occurred at 2 kHz, whereas for Cavity 3 it occurs at 1250 Hz. The most compression of the response curve in the frequency domain took place in the mid-frequency region, making the curves for the Mic. 1 response-losses and the open system voltage changes rather steep in that region.

The closed system voltage changes traveled with the Mic. 2 response-losses, but only up to 800 Hz, where it departed from the latter curve. This point of departure was a lower frequency than it had been for the two shorter cavities

(2 and 4), a finding that is consistent with the shift of the whole curve toward the low-frequency region.

For the mid-frequency region, the slope of the open system Mic. 2 response-losses is not only significantly different at the 0.01 level from the steeper slopes of the open and closed system Mic. 1 response-losses and from the open system voltage changes (see Table 13), but it is also significantly different from the closed system voltage changes. This was so because the mean closed system voltage changes tended to flatten at 800 Hz and departed at that frequency from the Mic. 2 response-losses. The slope of the open system Mic. 2 response losses, however, is not significantly different from the closed system response-losses at the 0.05 level.

For the longer cavity condition (3), it appears that when the middle ear impedance was altered by a TM perforation the pre-calibrated voltage across the closed system transducer correctly represented the sound pressure acting on the TM only in the low frequencies, but in the mid- and high frequencies, there was no longer such a correlation between these two entities.

Comparison of Cavities 2, 3 and 4 demonstrates that the differences in response-losses do not appear to be related to volume (see Table 1). The long, polyethylene cavity (3) and the short copper cavity (4) have identical volumes in the closed system (2.0 cc) but they differ in material and length. The short polyethylene cavity (2) (with the system closed) and both the long polyethylene cavity (3) and the short copper cavity (4) (with the system open) also have the same volume (1.6 cc). There were, however, no similarities between the results obtained with any of the cavity conditions that had equal volumes. Therefore, none of their differencies can be attributed to volume.

Cavity 5: the long, essentially "leakless" ear canal

Cavity 5 is the long, "leakless," copper artificial ear canal (see Table 1). Fig. 20 shows the response-losses and voltage changes, both in dB, plotted for this condition against frequency, in Hz. Data were collected on four cats (see Table 1). At 250 Hz, there was only one cat out of the four that yielded information in the closed system. These results are shown as single data points in Fig. 20. However, due to the steepness of the curve in the low frequency region, these single data points were included in the calculation of the least square slopes. The latter slopes are listed in Table 14, for the low frequency region (250-630 Hz) and for the mid-frequency region (630-1250 Hz).

The data presented in both Fig. 20 and Table 14 demonstrates that the Mic. 2 response-losses (at the TM) varied with frequency at a rate of approximately 12 dB/octave in both

Fig. 20. Mean response losses and mean voltage changes (dotted line), both in dB, for the Cavity 5 condition plotted against frequency, in Hz.

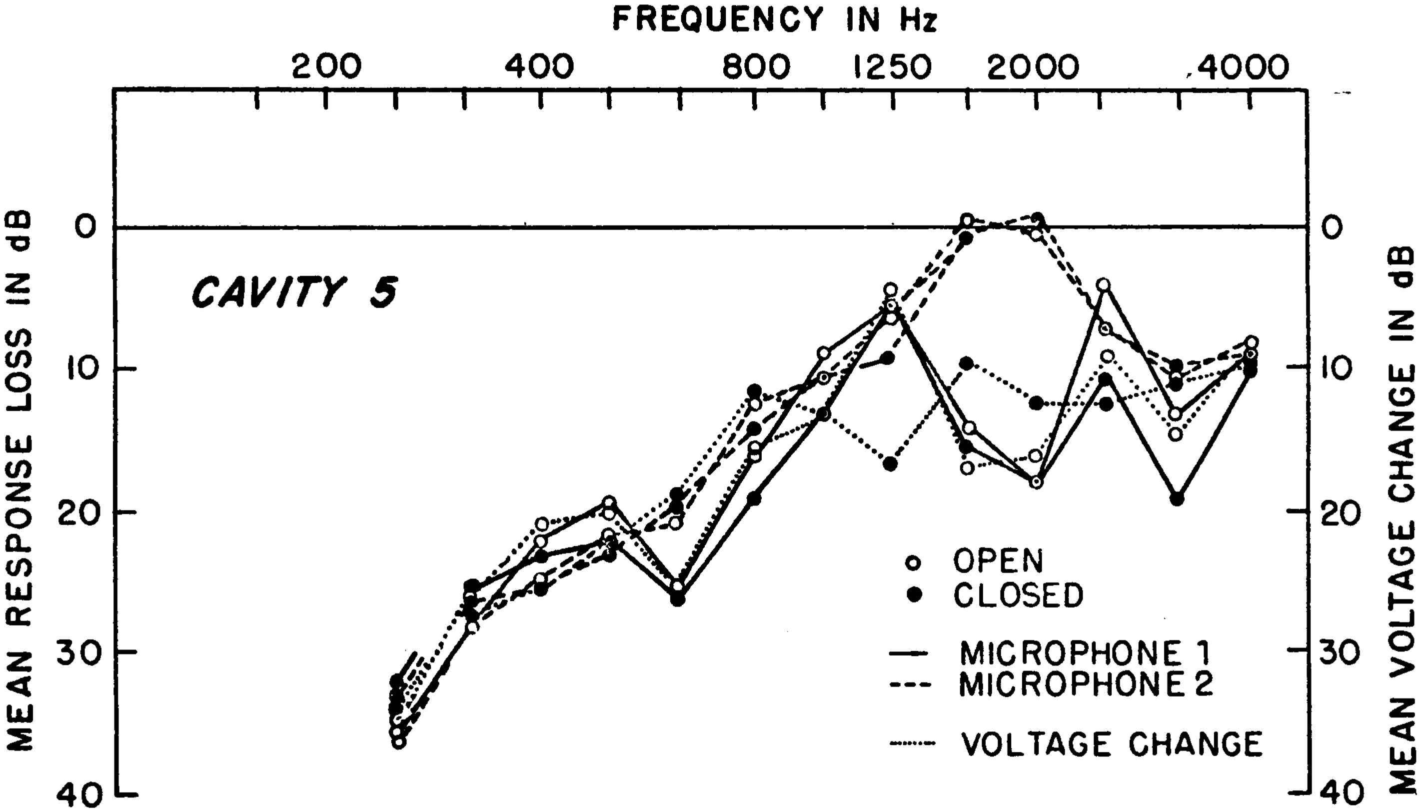

FREQUENCY IN Hz
200
400
800
1250
2000
4000
MEAN RESPONSE LOSS IN dB
0
10
20
30
40
CAVITY 5
MEAN VOLTAGE CHANGE IN dB
0
10
20
30
40
○ OPEN
● CLOSED
— MICROPHONE 1
--- MICROPHONE 2
······ VOLTAGE CHANGE

TABLE 14

LEAST SQUARE FIT SLOPES FOR THE LOW FREQUENCY REGION (≤630 HZ) AND THE MID-FREQUENCY REGION (630-1250 HZ) MEAN RESPONSE-LOSSES AND MEAN VOLTAGE CHANGES OBTAINED FOR CAVITY 5

		Least Square Slopes (dB/Octave)	
		Low Frequencies (250-630 Hz)	Mid-Frequencies (630-1250 Hz)
Response Losses Mic. 1	Open	-8.8	-19.9
	Closed	-7.1	-20.2
Voltage Changes	Open	-7.6	-19.7
Response Losses Mic. 2	Open	-11.1	-14.1
	Closed	-10.1	-11.1
Voltage Changes	Closed	-8.6	-1.7

the low and mid-frequency regions. There was no flattening in the low frequency region. The curves for the Mic. 1 response-losses and open system voltage changes had reduced slopes of approximately -8 dB/octave in the low frequency region, while their mid-frequency region slopes were quite steep (approximately -20 dB/octave). This steepness appears to be due to a mid-frequency compression of the Mic. 1 response-losses and open system voltage changes much like that found with Cavity 3 - the long polyethylene ear canal.

The significance of the differences between least square fit slopes for Cavity 5 are shown in Table 15. Although there is a slight low frequency flattening of the curves for Mic. 1 response-losses and for the open system voltage changes, there is no significant difference between slopes of the closed system Mic. 1 response-losses and those of any other response-losses or voltage changes. In the mid-frequency region, however, the closed Mic. 1 response-loss curve, with its steep slope, was significantly different, at the 0.01 level, from that of the Mic. 2 response-losses; but it was not significantly different from the likewise steeper curves of the open system Mic. 1 response-losses and of the open system voltage changes.

This is an essentially leakless cavity. When it is contrasted with the leaky cavity of the same length (3), certain differences and similarities became apparent. The major difference is that in Cavity 5 the response-loss curves as determined

TABLE 15

SIGNIFICANCE OF THE DIFFERENCES BETWEEN LEAST SQUARE FIT SLOPES FOR CAVITY 5. FREQUENCY REGIONS, CALCULATED *t* VALUES, DEGREES OF FREEDOM (*df*), AND SIGNIFICANCES AT THE 0.05 LEVEL ARE GIVEN FOR EACH PAIRED MEASUREMENT

H: $b=B_o$

Frequency	Slope b	Slope B_o	*t* calc.	*df*	Significance at 0.05 level
Low Frequency (=630 Hz)	Mean Closed Mic. 1 Response-Loss	Mean open Mic. 1 Response-Loss	1.0	3	NS
		Mean open system Voltage Change	0.6	3	NS
		Mean open Mic. 2 Response-Loss	1.6	3	NS
		Mean closed Mic. 2 Response-Loss	1.3	3	NS
		Mean closed system Voltage Change	0.4	3	NS
Mid-Frequency (630-1250 Hz)	Mean Closed Mic. 1 Response-Loss	Mean open Mic. 1 Response-Loss	1.0	2	NS
		Mean open system Voltage Change	-0.9	2	NS
		Mean open Mic. 2 Response-Loss	-10.9	2	S
		Mean closed Mic. 2 Response-Loss	-16.3	2	S
		Mean closed system Voltage Change	-32.9	2	S

at the TM did not flatten (Fig. 20). Although there was no significant difference in the low frequency region between the slopes of response-losses determined at the TM and at the outer opening of the canal, there was a slight flattening of the Mic. 1 curves. However, it is suggested that this flattening was due to the common characteristic of length and not to leakiness, since the Cavity 3 data showed differences in slope between the low frequency response-losses depending on the locations at which measurements had been obtained. In Cavity 3, there was also slightly more flattening of the curves of the Mic. 1 response-losses and the open system voltage changes in the low frequency than those of the Mic. 2 curves. With the long, leaky ear canal (3), however, there was a significant difference between the losses assessed at either location, whereas with the long, "leakless" ear canal (5), there was no such difference at the 0.01 level.

Furthermore, in Cavity 5, the closed system voltage changes traveled together with the Mic. 2 response-losses in the mid-frequency region only up to 800 or 1000 Hz and then departed from there. There was clearly a significant difference between the slopes of the closed system Mic. 1 response-losses and those of the closed system voltage changes at the 0.01 level. Again, this latter difference suggests that, when the middle ear impedance decreases due to a TM perforation, and when there is an ear canal present, the pre-calibrated voltage across the transducer correctly represents the sound pressure acting on the TM only in the low frequency region but not in the mid and high frequency regions.

Recapitulation of the Experiment II Results

In summary, the results of Experiment II are:

Leakiness - The findings of this experiment suggest a partial explanation for the low frequency hearing loss seen in human patients: a.) there is a relatively long ear canal, and b.) it is leaky. In Experiment II, the flatness of the low frequency response-losses, as assessed both at the outer opening of the ear canal and at the TM, was mainly due to the leakiness of the polyethylene material. Cavities 2 and 3, the short and long polyethylene cavities, showed low frequency flattening while Cavities 4 and 5, the two copper cavities, did not show such a flattening.

Volume - Volume does not appear to be related to the configuration or the extent of the response-losses assessed at either location, or voltage changes.

Length - The length of the artificial ear canal accounts for the differences in response-losses, assessed at the opening of the ear canal and at the TM, and for some additional flattening. For the short length cavities (2 and 4) there was flattening of the response-losses assessed at the outer opening of the ear canal in the mid-frequency region, whereas the response-losses assessed at the TM varied inversely with frequency at a ratio of approximately 12 dB/octave. In the low frequency region: for the longer length cavities (3 and 5), there was slightly more flattening of the response-losses assessed at the opening of the ear canal than at the TM, the flattening of the response-losses determined at the canal opening were significantly different from those determined at the TM only for Cavity 3. In addition, in the mid-frequency region for both Cavities 3 and 5, the response-losses assessed at the opening of the canal had steeper slopes than the response-losses assessed at the TM.

Relation Between Response-losses and Voltage Changes

In the open system, the pre-calibrated voltages across the transducer correctly represent the sound pressures at the outer opening of the canal but not at the TM. In the closed system, the pre-calibrated voltages across the transducer appear to correctly represent the sound pressures acting at the TM in the low and mid-frequency regions for the two shorter cavities (2 and 4) and only in the low frequency region for the two longer cavities (3 and 5). However, in the high frequency region for the shorter cavities, and in the mid- and high frequency regions for the longer cavities, there was no correlation between the pre-calibrated voltages across the transducer and the sound pressures acting on the TM, after perforation. In these latter frequency regions, then, the response-losses would be overestimated if they were based upon pre-calibrated voltage values.

CHAPTER V. GENERAL DISCUSSION

The results of these two experiments indicate that the response-losses produced by a small TM perforation differ according to the length and leakiness of the EAM present, and that the relation between voltage changes (precalibrated sound pressures) and response-losses is not unity, at least for certain frequency ranges.

With the surgically shortened cat's EAM, used both in Experiment I and, as Cavity I in Experiment II, the response-losses (which varied inversely with frequency at a rate of 12 dB octave) were not only identical in extent and magnitude for both open and closed systems, but were also essentially similar to the inverse, low frequency, response-losses found for the open and closed systems by McArdle and Tonndorf (1978), who observed 10.2 dB/octave slopes.

The present study, for the first time, explains the frequency characteristics of the above response-losses. When a constant sound pressure input to the middle ear is taken as a reference, the changes in effective sound pressure require a 12 dB/octave correction, at low frequencies, in order to produce an effective sound pressure equivalent for both the intact and perforated conditions. The net effective sound pressure acting on the TM was calculated from sound pressures measured in front of and behind the TM. This calculation was justified by determining that the sound pressures recorded in the middle ear at three locations, just behind the TM, and in two repetitions, differed by less than 1 dB; in fact, the "REPETITION" and "POSITION" variations were not significantly different from each other. Furthermore, the changes in effective sound pressure acting on the TM, with a constant CM as reference (which includes this 12 dB/octave low frequency correction, showed by a frequency independent admission loss of 10 dB.

The 10 dB admission loss is clearly the result of the TM area lost due to the 1 mm^2 perforation. The area of the cat's TM is 41.8 mm^2 according to Wever and Lawrence (1954) and Kirikae (1960). Therefore, the percentage of area lost is 2.5%. Since the total loss of the TM (100%) produces a CM loss of 40 dB (Payne and Githler, 1951; Tonndorf and Khanna, 1967), a 2.5% area loss should produce an 8 dB loss in energy reception. The 10 dB admission loss found, at first approximation, is consistent with the extent of the expected loss. The loss in energy reception is only slightly larger than expected (but within $\pm\sigma$) throughout most of the frequency range; an exact 10 dB loss in energy reception would be expected to result from a 3.2% area loss. Only at 630 Hz was there a sizeable difference between the expected change and the extent of effectvie sound pressure change; there was a 20 dB loss in energy reception which would be expected to result from a 10% area loss, but not from a 2.5% area loss. Therefore, especially at 630 Hz, the perforation is effectively larger than 1 mm^2

For this reason, it is suggested that the vibration pattern of the perforated TM be studied holographically in order to determine the effective area of vibration and to compare it with the amount of receiving area lost. Such a study should compare perforations of different sizes produced by a plug cutter (as in the current experiments) and by electrocautery (Payne and Githler, 1951). With the latter technique, not only is it harder to control the size of the lesion, but there is probably also a stiff rim formed around the perforation, due to the cautery, which may affect the vibration pattern. Perhaps, there is slightly less TM area vibrating effectively at 630 Hz than indicated by the percent area lost due to parts of the TM flapping in the path of the incident sound which are then essentially decoupled from the TM (transformer system).

It was originally hypothesized that the use of voltage changes (or precalibrated SPLs) as an indicator of actual sound pressure changes (response-losses re: 10μV RW CM) might account for the essentially flat, primarily low frequency hearing loss found in the audiograms of human patients with TM perforations. When relying on voltage changes, under the present experimental conditions, it was found that, for the open system, the voltage changes were good predictors of the response-losses assessed at the outer opening of the canal for all cavity conditions. However, for the closed system, and for *all* cavities, voltage changes tended to flatten in the mid- and high frequencies, above 1250 Hz for the shorter canals and 800 Hz for the longer canals, while the response-losses changed at the rate of $\gtrsim$ 12 dB/octave. For the extremely short, natural canal, the voltage changes flattened, but remained at 6 dB/octave over the entire frequency range. This is strikingly different from the response-loss changes of 12 dB/octave at $f<2000$ Hz. Therefore, relying on *voltage changes as predictors of response-losses (due to TM perforations)*, in the *closed* system, for the *mid- and high frequencies*, appears *unwise*. In the *low* frequencies, however, the closed system voltage changes seem to parallel the response-losses, especially when assessed at the TM; the response-losses from either location are actually similar. In this frequency range, then, the closed system voltage changes are good predictors of the response-losses at the TM.

Furthermore, it was found that the *closed* system voltage changes followed the response-losses assessed at the TM, while the *open* system voltage changes followed the response-losses assessed at the *outer opening* of the canal. Perhaps this is due to the fact that, for the open cavities, there is an impedance step in the transmission system, at the outer opening of the canal (the neck of the artificial canals is a point of considerable narrowing from the environment to the canal's inner diameter of <0.5 cm). For the closed cavities, there is no impedance change at the outer opening of the canal.

The variations in response-losses and voltage changes due to the leakiness and length of the canal present were systematic. The flatness of the response-losses (and voltage changes) in the low frequency region appeared to be due primarily to the leakiness of the canal. When the EAM was leaky (Cavities 2 and 3), flattening extended into the lower frequencies, for voltages *and* SPLs, especially when the latter were registered at the *outer* opening (Mic.1) of the EAM. It should be noted that calibration for voltages ("precalibrated SPL") is usually made with a microphone under (or in) the earphone cushion, which means that such assessments are made at the *outer* opening of the canal. In contrast, there was no real flattening of the low frequency voltage changes or the low frequency response-losses when the EAM (Cavities 4 and 5) was "leakless"; there was approximately a 12 dB/octave slope.

The length of the canals introduced additional variation as did the location at which the response-losses were assessed. With the leaky canals, for the response-losses assessed at the TM *and* for the shorter canal, the low frequency extended to the mid-frequency region (630 Hz), whereas for the longer canal, the flatness was limited to the low frequency region ($f <$ 400 Hz). The entire response-loss curve shifted slightly to the lower frequency region with the longer canal, regardless of material. This follows from the fact that the resonant frequency (_f_) of a longer tube is at a lower frequency.

Furthermore, for all the artificial canals, the response-losses determined at the outer opening of the canal and at the TM differed primarily in the mid-frequency region. The open and closed system _response-losses_ determined at the _outer opening_ of the canal and the _open system voltage_ changes remained flat until just above the 1/4 λ frequency was reached, and then rose. Although the open and closed system _response-losses_ determined at the _TM_ _and_ the _closed system voltage_ changes were flat in the low frequencies, in the _mid-frequencies_, they varied inversely with frequency at the rate of 12 dB/octave for the short canals and at 18 dB/octave for the long canals. The closed system voltage changes followed the response-losses assessed at the TM again to the frequency just above that corresponding to 1/4 λ of the canal (length) used. The frequencies at which the closed system voltage changes began to depart from the response-losses determined at the TM are higher for the shorter canals (Cavities 2 and 4) and lower for the longer canals (Cavities 3 and 5) used. It is suggested that this point of departure may be related to the resonant frequency of the canals. Above the latter point, the voltage changes are no longer a good predictor of response-losses.

For the non-leaky canals, there was a small hump at about 630-800 Hz for the short canal and at 400 Hz for the long canal, otherwise the low and mid-frequency response-losses varied inversely with frequency at a rate of approximately 12 dB/octave. Consistent with the shift of the hump to a lower frequency for the longer canal, is the slightly steeper slope found in the mid-frequency region for the response-losses assessed at the outer opening of that canal. Response-losses determined at the TM are smoother; they varied inversely with frequency at a rate of 12 dB/octave below 1600 Hz with no evidence of a hump at either 400 or 630 Hz.

There are, however, several facts which must be considered in critically evaluating these studies. Firstly, for the open system, the artificial canals used were not provided with a 'baffle' around their outer opening (Harris, personal communication, 1974) The baffle (to simulate the head shadow effect), however, would have only been effective for frequencies above 4000 Hz; for 344 meters/sec. as the speed of sound at 20° C, and for the width of cat's head (between the ears) taken as 8 cm, therefore, if the λ equals 8 cm, f=4300 Hz. Furthermore, the response-losses for the open or closed systems, for <u>all</u> canals (artificial, as well as natural), were in very close agreement. Consequently, although the inclusion of a baffle was neglected, it appears that correcting the oversight would make no significant difference in the results for the frequency range tested.

Secondly, there should have been more carefull control of the physical variables of length, volume and leakiness of the artifical canals used. Canal sizes (lengths) were determined in order to reproduce volumes of 1.5 and 2.0 cc based on measurements of the cat's EAM volume, with available polyethylene and copper tubing (which determined the diameter). Instead, since λ appears related to the relation between voltage changes and response-losses, canal lengths approximating real cat and human EAM lengths should have been used, and then, tubing with appropriate inner diameters used to yield the measured volumes. This oversight places a certain reservation on the generalization of these data to the real situation since they are based on longer than natural canal lengths. The *general* effect of canal leakiness, however, is still valid.

Thirdly, the statistics used were not sufficiently powerful with respect to the fitting of least square straight lines to too few data points for the artificial EAM data, and, then, to the determining of the significance of the differences between these slopes when the degrees of freedom (*df*) were typically ≤ 3. However, examination and description of the *trend* of the response-loss and voltage change curves for each experimental condition led to essentially the same conclusions arrived at via the statistics used. Also, in the same conditions, with more data (frequency) points for the slopes, and therefore, greater _df_, the level of significance might have been greater.

Clinically, audiograms for human patients with TM perforations show essentially frequency independent hearing losses especially in the low frequency region and often some relatively flat hearing losses in the mid- and high frequency region (Shambaugh, 1967). The present experiments substantiate the clinical findings, i.e., in the low frequency region, at least, the flatness is primarily due to the presence of a leaky ear canal, while in the mid- and high frequency region, the flatness might be due to the audiometric determination of hearing losses which are based on the use of "precalibrated SPLs" (voltage changes). These conclusions, however, apply to _both_ open and closed system results; there was never a significant difference between open and closed system response losses, and open and closed system voltage changes were only significantly different in the mid- and high frequency region, but not in the low frequency region.

Therefore, the initial discrepancy noted between human and cat data is open to question. In other words, 1.) McArdle and Tonndorf (1968) found that open and closed system response-losses, determined in surgically shortened EAMs, varied inversely with frequency at the rate of 10.2 dB/octave, in the low and mid-frequency region (a finding corroborated by the present study), and 2.) Bekesy (1936, 1939, 1960) found similar shaped response-losses for manubrial displacements on human cadavers without EAMs, while in humans with TM perforations there are flat, low frequency hearing losses audiometrically (closed system), but the low frequency losses seemed to vary inversely with frequency when tested with tuning forks (open system).

In fact, then, the tuning fork data are suspect and deserve further scrutiny. Calibration of tuning forks is essentially a "precalibration" since it involves a comparison of abnormal performance with normal capacity in terms of the duration that the tone is heard. It does not, however, assess correct SPL. In this sense, it is analogous to the use of voltages which determine precalibrated SPLs in clinical audiometry. Therefore, a closer look at the auditory chart configuration associated with TM perforations (Ostmann, 1909) suggests that, the loss increases with decreasing frequency, but that the slope of the hearing loss cannot be determined. The tuning fork data, then, could be considered to be more closely in agreement with the open system results of the present experiments -- and in fact would not be discrepant from the closed system results.

Therefore, it is recommended that the results of these experiments be used, at least in kind, as substantiation of clinical audiometric findings (e.g., Shambaugh, 1967), instead of the results of Payne and Githler (1951) whose flat, primarily low frequency response-loss was merely due to an open bulla as demonstrated by McArdle and Tonndorf (1968). However, it must be remembered that caution is advised in quantitatively generalizing to humans because the canal lengths used in the present experiments were considerably longer than those found in humans, or in cats for that matter.

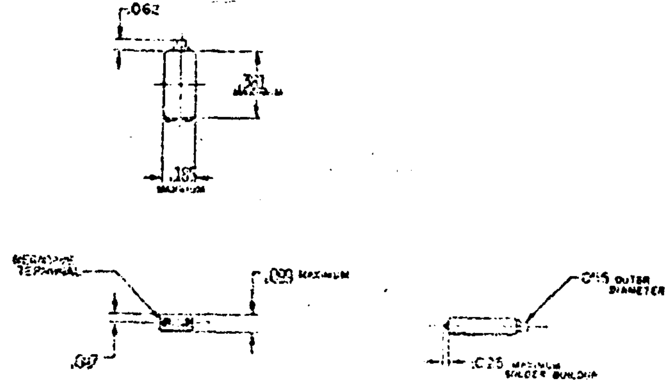
These experimental conclusions suggest further exploration of the relation between precalibrated SPLs (voltage changes across the transducer) and hearing losses determined not only for patients with TM perforations, but expecially for cases of other middle ear disorders which, in some way, change the middle ear impedance. One may deduce (from the present experiments) that precalibrated SPLs overestimate hearing losses associated with decreased middle ear impedance *and* underestimate hearing losses associated with increased middle ear impedance. However, for each specific transducer, the quantitative relation for both frequency and intensity remains to be investigated. In addition, concerning clinical patients with TM perforations, it is suggested that the relation between hearing loss and precalibrated SPLs be considered in relation to the resonant frequency for the patient's EAM.

Moreover, until the results of such investigations are known, the findings of the present experiments regarding the nature of the response-loss and, particularly, the relation between precalibrated SPLs and the actual sound pressures produced at the TM suggest that the Audiologist should use caution in assessing the handicap of a patient with a conductive hearing loss. Although diagnostic conclusions concerning the loss are still valid, the extent of the loss may not be accurately assessed audiometrically (in a closely coupled system) when the determination of the hearing loss is based on precalibrated SPLs. Therefore, it follows that the degree of the handicap may not be properly reflected. This would be especially pertinent in the case of an ossicular discontinuity that resulted from an accident, particularly if compensation is a factor. (The accompanying impedance change suggests overestimation of the loss.) Furthermore, it should be remembered by the Audiologist and the Otolaryngologist that there is a hearing loss produced by a small TM perforation and, in fact, that such a hearing loss is induced when myringotomy tubes are inserted in cases of chronic otitis media and also when electrical responses are recorded directly from the promontory in Electrocochleography.

The present data also suggest 1.) that hearing losses (determined behaviorally) be compared with RW CM response-losses, for the same cats with TM perforations, both with and without their natural canal, and 2.) that an electrical analog of the outer ear be developed to explore and/or account for the fine detail concerning: a.) the way the EAM loads the TM down; b.) how the EAM and the perforated TM act as a low pass filter; and c.) the extent to which the perforation eliminates the TM's role as a baffle, permitting low frequencies to pass through the TM and cancel the incident sound waves (McArdle and Tonndorf, 1968).

APPENDIX A: TRANSDUCER SPECIFICATIONS

TENTATIVE



DIMENSIONS IN INCHES

Miniature magnetic transducer which can be used as a receiver. For use in head-worn hearing aids and other applications requiring high sensitivity, small size, and broad band response.

Self-shielded to reduce magnetic radiation.

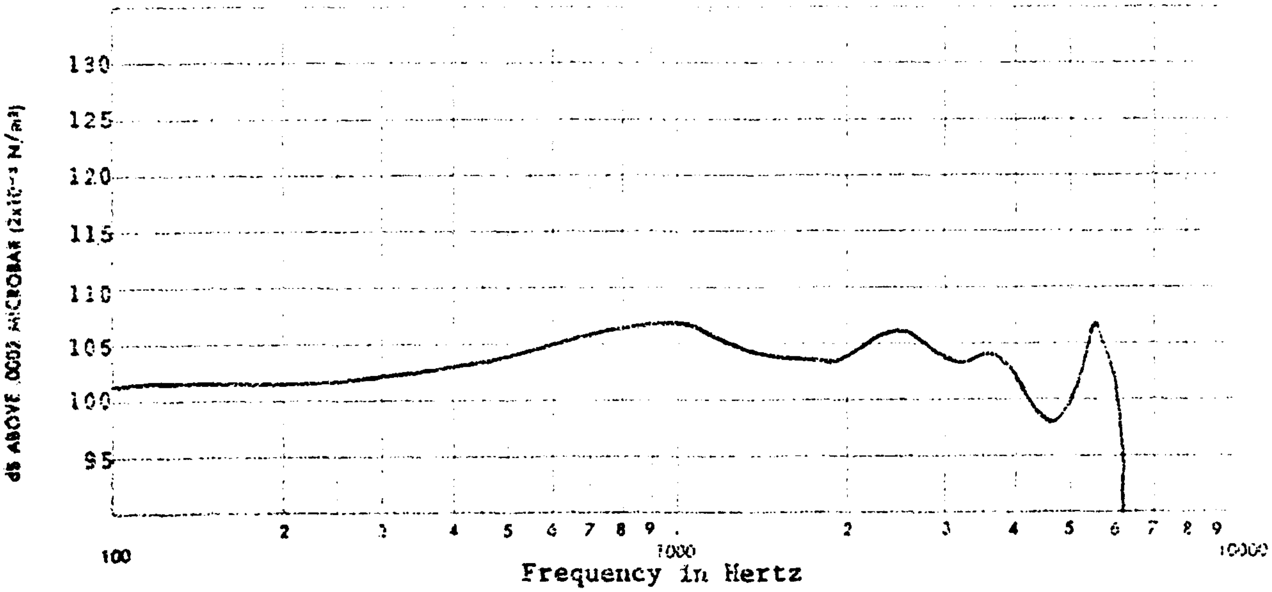
Bias range: 0.2 to 1.3mA DC

Nominal impedance at 1000 Hertz: 600 Ohms

Nominal DC resistance at 20°C: 167 Ohms

Model BP patents pending

1.0mA DC bias with an input of 0.96 Volts RMS (0.19mw) and a 1200 Ohm source impedance. 32mm of 1.5mm plus 25mm of 2.0mm tubing into an HA-2 coupler with two BF-1540 dampers located in the 2.0mm tubing at either end.



BP-1710

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5-10-73

BP-1710 DE

TENTATIVE

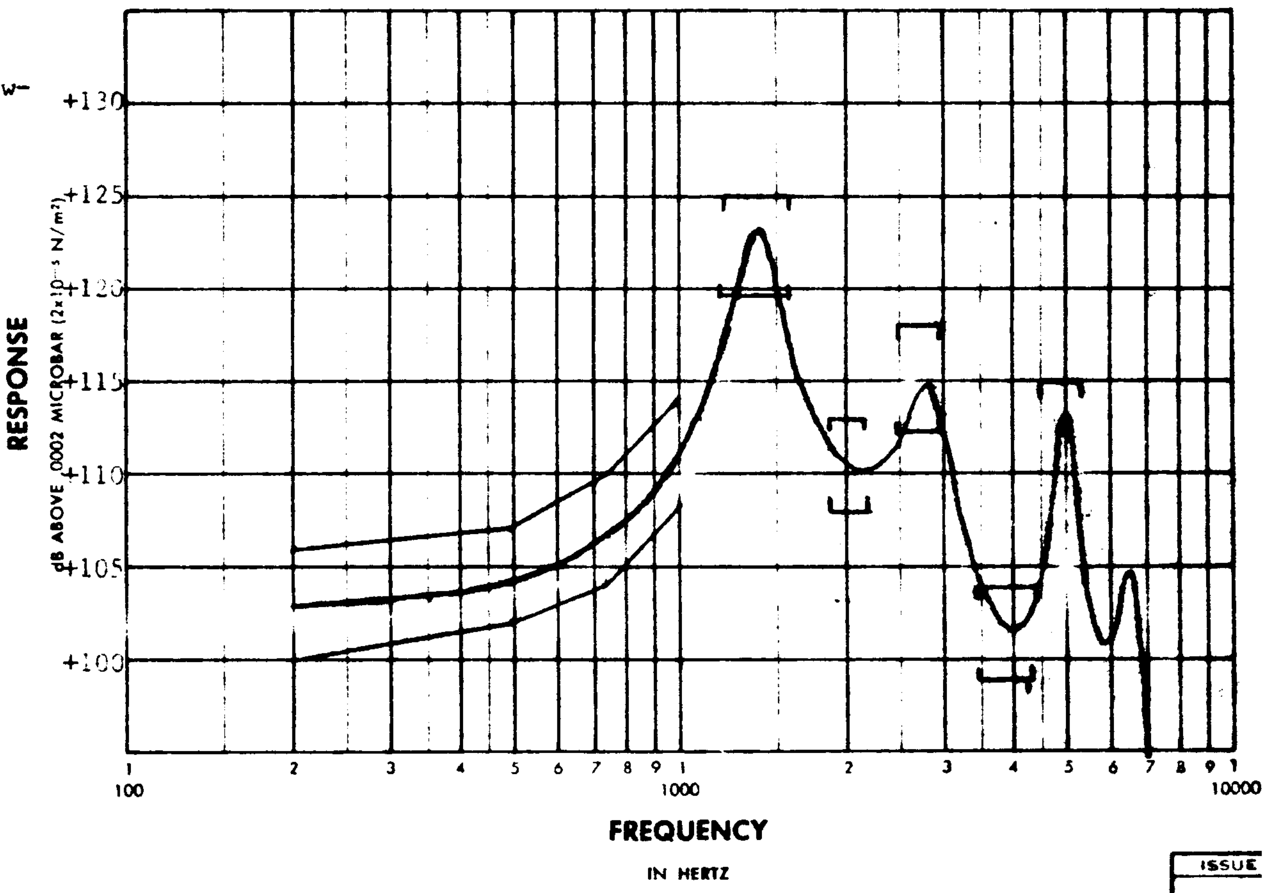
BP-1710

Typical response measured under the following conditions: 1.0mA MCM (1.0mA DC with 0.7mA RMS AC superimposed from a high impedance source). 1.97 inches (50mm) of .0787 inch (2mm) ID tubing connected to an HA-3 coupler.

Nominal Impedance:
600 Ohms at 1000 Hertz

Nominal DC Resistance at 20°C:
167 Ohms

Distortion Specification:
At 500 Hz, 1.0 mA MCM, and the acoustical termination listed above, the total harmonic distortion shall not exceed 10%.



ISSUE	A

MATERIAL	DR BY DATI
FINISH	RMC 12-1-7
	CH'BY DATI

NOTE:

APPENDIX B: SAMPLE DATA SHEETS

EXPERIMENT I

Cat: B

Condition:

Date: / /

Open/Closed Sound System

Intact/Bilateral ICM

Total Correction = Mic. Calib. Corr + 20 dB
since 0 dB = 20 µPa SPL with a
reference 10 µV (at level setting)

	FREQ	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
	Elect. (RWCM) Voltage	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	
RW	dB re 10µV	60*	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
	ϕ																
	Elect. Alkn.	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Rw	dB re 10µV	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
	ϕ																
	Averaged Elect. Alkn.																
	Aver. ϕ																
Mic #1 #24293 32 mm probe	dB re 10µV																
	Total Corr	35.15	35.0	34.75	34.5	33.5	32.25	29.62	26.37	29.5	35.75	40.62	44.62	47.0	47.87	46.0	41.0
	Tot. Corr. SPL																
	ϕ																
	dB re 10µV																
	Total Corr	32.25	35.0	34.75	34.5	33.5	32.25	29.62	26.37	29.5	35.75	40.62	44.62	47.0	47.87	46.0	41.0
	Tot. Corr. SPL																
	ϕ																
Gain #1 15.8	Aver. Tot Corr SPL																
	Aver ϕ																
Mic #2 #142773 35.5 mm probe	dB re 10µV																
	Total Corr	39.0	35.2	34.7	34.2	31.25	39.0	27.5	27.5	32.0	37.0	40.5	43.5	44.5	42.75	37.25	45.75
	Tot. Corr SPL																
	ϕ																
	dB re 10µV																
	Total Corr	34.0	35.2	34.7	34.2	31.25	37.0	27.5	27.5	32.0	37.0	40.5	43.5	44.5	42.75	37.25	45.75
	Tot Corr SPL																
	ϕ																
Gain #2 14.1	Aver. Tot. Corr SPL																
	Aver ϕ																
	Corr SPL re to M2-M1																
Δϕ	ϕ2 - ϕ1																
	M1 - Elect Alkn																
	M2 - Elect Alkn																

Notes:

---

* For the particular equipment used, the criterion 10µV RW CM amplitude was read as "60 dB".

EXPERIMENT II

Cal. – C
Condition:

Date: / /
Open/Closed Sound System
Intact/Reloaded IM

Total Correction = Mic Calib Corr +20dB
since 0dB = 20dB SPL with a
reference 10µV (at level settings)

		125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
	FREQ	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
RH	Elect. Atten	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
	dB re 10µV	60*	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
	φ																
RW	Elect. Atten.	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
	dB re 10µV	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
	φ																
	Averaged Elect Atten																
	Avg. φ																
Mic #1 · #164290 32 mm	dB re 10µV																
	Total Corr	34.25	34.0	33.75	33.5	32.5	31.25	28.62	25.37	28.5	34.75	34.62	43.62	46.0	46.87	45.0	40.0
	Tot. Corr. SPL																
	φ																
	dB re 10µV																
	Total Corr	34.25	34.0	33.75	33.5	32.5	31.25	28.62	25.37	28.5	34.75	34.62	43.62	46.0	46.87	45.0	40.0
	Tot. Corr. SPL																
	φ																
Ears 14.8	Avg. Tot Corr SPL																
	Avg. φ																
Mic #2 · #142773 35.5 mm	dB re 10µV																
	Total Corr	34.0	35.2	34.7	34.2	31.25	29.0	27.5	27.5	32.0	37.0	40.5	43.5	44.5	40.75	37.75	45.75
	Tot. Corr SPL																
	φ																
	dB re 10µV																
	Total Corr	34.0	35.2	34.7	34.2	31.25	29.0	27.5	27.5	32.0	37.0	40.5	43.5	44.5	42.75	37.75	45.75
	Tot Corr SPL																
	φ																
Ears 14.1	Avg. Tot. Corr SPL																
	Avg. φ																
	Corr SPL ratio M₂–M₁																
	Δφ $\phi_2 - \phi_1$																
	M₁ – Elect Atten																
	M₂ – Elect Atten																

Notes:

* For the particular equipment used, the criterion 10µV RW CM amplitude was read as "60 dB".

APPENDIX C: STATISTICAL FORMULAE

Mean

$$X = \frac{1}{N} \sum_{i=1}^{N} x_i$$

Standard Deviation

$$= \sqrt{\frac{1}{N-1} \sum x^2 - \frac{(\sum x)^2}{N}}$$

(cf Huntsberger, 1961 p. 50)

Fisher's t Test

The significance of the difference between the means of two correlated samples: for a single group of subjects in a pre-/post-test condition.

Calculate:

1. the mean of the differences,

$$M_D = \frac{\sum D}{N} = \frac{\sum M_1 - M_2}{N}$$

2. the standard deviation of the difference,

$$D = \sqrt{\frac{\sum D^2}{N} - \frac{\sum D}{N}^2}$$

3. the standard error of the mean of the differences,

$$MD = \frac{D}{\sqrt{N-1}}$$

4. the ratio of the mean of the differences to the standard error of this mean

$$t = \frac{M_D}{D}$$

Use Fisher's table of t (two tailed) to determine significance. (cf Smith, 1946, Chapter 9, 65-70)

Least Square Method of Curve Fitting: Linear Regression

The least square method was used because it produces the straight line around which there is least scatter; scatter is defined in terms of the sum of the squares of the vertical deviation of the data points from the line. The assumptions that the X values (frequency) are known constants and that the Y values (response-losses) are normally and independently distributed are met by this experimental condition. Therefore, the best (least quare) estimators of the slope (b) and the y intercept (a) in the formula Y = a + bx are given by:

$$b = \frac{\sum (Xi - \bar{X})(Yi - \bar{Y})}{\sum (Xi - \bar{X})^2}$$

$$a = \bar{Y} - b\bar{X}$$

The machine formula for b is as follows:

$$b = \frac{\sum XiYi - \frac{\sum Xi \sum Yi}{n}}{\sum Xi^2 - \frac{(\sum Xi)^2}{n}}$$

(cf Huntsberger, 1961, pgs. 193-194)

t Test of the Significance of the Differences of Least Square Slopes

$$t = \frac{b - B_o}{s_b} \qquad df = n-2,\ H_o:\ b = B_o$$

where

$$s_b = \frac{s^2{}_{x \cdot y}}{(Xi - \bar{X})^2}$$

(s_b is the standard deviation of the regression coefficient b)

(cf Huntsberger, 1961. pgs. 197-199)

APPENDIX D: VECTORIAL ANALYSIS

The vectorial sum of two sound pressures acting from both sides of the TM, but 180° out of phase, is actually calculated as the vectorial difference between the magnitude and phase of the sound pressure acting on the TM from the EAM and the magnitude and phase of the sound pressure acting on the TM from the middle ear.

The following fromulae are used to obtain the resultant magnitude (R) and phase angle ( ) of the effective sound pressure acting on the TM:

$$R = \overline{A^2 + B^2 - 2AB\cos\phi}$$

$$\text{arc tan}\ \frac{-A\sin\phi}{B-A\cos\phi}$$

where

A magnitude of the sound pressure at Mic. 1
B magnitude of the sound pressure at Mic. 2
ϕ difference in phase between vectors A and B

In order to obtain data in reference to a constant input sound pressure acting on the TM, the intra/extra tympanic pressure ratios were normalized. Normalization sets the reference value equal to 1 (A=1) and the intra/extra tympanic pressure amplitude ratio (Mic. 2 - Mic. 1) equal to B. Normalization, in fact, divides both sound pressure magnitudes (Mic. 1 and Mic. 2) by the magnitude of A. The resultant is the effective sound pressure acting on the TM relative to a constant sound pressure input in front of the TM.

REFERENCES

American National Standard Method for Coupler Calibration of Earphones. A.N.S.I , S3.7, 1-32, (1973).

Anthony, W. P., and Harrison, C. W. Tympanic Membrane Perforation Effect on Audiogram. *Arch. Otolaryng.*, 95, 506-510, (1972).

Bauer, B B., Rosenheck, A. J., and Abbagnaro, L. A. External-Ear Replica for Acoustical Testing. *J.A S.A.*, 42, 204-207, (1967).

Baust, W., and Berlucchi, G. Reflex Response to Clicks of Cat's Tensor Tympani during Sleep and Wakefulness and the Influence thereon of the Auditory Cortex. Arch. *Ital. Biol.*, 102, 686-712, (1964).

Bekesy, G. von, Zur Physik des Mittelohres and über das Hören bei fehlerhaftem Trommelfell. *Akust*, Z., 1, 13-23, (1936).

______. Über die mechanisch-akustischen Vorgange beim Horen, *Acta. Otolaryng.*, 27, 281-296, (1939).

______. Über die Messung der Schwingungsamplitude der Gehorknochelchen mittels einer kapazitiven Sonde. *Akust. Zeits.*, 6, 1-16, (1941).

______. The Structure of the Middle Ear and the Hearing of One's Own Voice by Bone Conduction. *J.A.S.A.*, 21, 217-232, (1949).

______. *Experiments in Hearing*. McGraw-Hill, New York, (1960).

Bezold, F . and Siebenmann, F. *Text-Book of Otology for Physicians and Students*. translated by J. Holinger, E. H. Colegrove Co., Chicago, (1908).

Bingham, W. V. D. The Role of the Tympanic Mechanism in Audition. *Psychol. Rev.*, 14, 229-243, (1907).

Blevins, C. E. Studies on the Innervation of the Stapedius Muscle of the Cat. *Anat. Rec.*, 149, 157-172, (1964).

Bordley, J. E. and Hardy, M. Effect of Lesions of the Tympanic Membrane on the Hearing Acuity. Arch. Otolaryng., 26, 649-657, (1937).

Carmel, P. W., and Starr, A. Acoustic and Non-acoustic Factor Modifying Middle-Ear Muscle Activity in Waking Cats. J. Neurophysiol., 26, 598-616, (1963).

Corliss, E , and Cook, C. A Cavity Pressure Method for Measuring the Gain of Hearing Aids. J.A.S.A., 20, 131-136, (1948).

Cooper, A. Observations on the Effects Which Take Place from the Destruction of the Membrana Tympani of the Ear, in a letter to Everard Home. Philosophical Transaction, W. Bulmer and Company, London, 151-158, (1800).

Crowe, S. J., and Hughson, W. Eine neue Methode zur Untersuchung der Physiologie and Pathologie des Ohres, Ztschr. Hals-, Nasen- u. Ohrenh. 30, 65-76, (131); Experimental Investigation of the Physiology of the Ear, Using the Method of Wever and Bray, Tr. Am. Otol. Soc., 22, 125-136, (1932).

Cullen, Jr., J. K., Ellis, M. S., Berlin, C. I., and R. J. Lousteau. Human Acoustic Nerve Action Potential Recordings From the Tympanic Membrane Without Anesthesia. Acta Otolaryng., 74, 15-22, (1972).

Dahman, H. Zur Physiologie des Hörens: experimentelle Untersuchungen über die Mechanik der Gehorknochelchenkette sowie uber deren Verhaltenauf Ton und Luftdruck. Z. Hals.- Nasen- u. Ohrenh. 24, 462-497, (1929); 27, 329-368, (1930).

Dallos, P. On the Generation of Odd-Fractional Subharmonics. J.A.S.A., 40, 1381-1391, (1966).

______. Cochlear, Potential: A Status Report. Int. Audiol., 11, 29-41, (1972).

______. The Auditory Periphery: Biophysics and Physiology Academic Press, New York, (1973).

______. and Cheatham, M. Travel time in the Cochlea and its Determination from Cochlear Microphonic Data. J.A.S.A., 49, 1040-1143, (1970).

______. and Durant, J. D. On the Derivative Relationship between Stapes Movement and Cochlear Microphonic. J.A.S.A., 52, 1263-12165, (1972).

______. and Linnell, C. O. Subharmonic Components in Coclear-Microphonic Potentials. J.A.S.A., 40, 4-11, (1966a).

______. Even-Order Subharmonics in the Peripheral Auditory System. J.A.S.A., 40, 561-564, (1966b).

Davis, H. Biophysics and Physiology of the Inner Ear. Physiol. Rev., 37, 1-49, (1957).

Davis, H. Mechanism of the Inner Ear. Ann. Otol., 77, 644-656, (1968).

Djupesland, G. and Zwislocki, J. Sound Pressure Distribution in the Outer Ear. Scandanavian Audiology, 1, 197-203, (1972).

Elliot, D. N., Stein, L., and Harrison, M. J. Determination of Absolute-Intensity Thresholds and Frequency-Difference Thresholds in Cats. J.A.S.A., 32, 380-384, (1960).

Engelbretson, A. M., and Eldredge, D. H. Model for the Nonlinear Characteristics of Cochlear Potentials. J.A.S.A., 44, 548-554, (1968).

Erber, N. P. Variables that Influence Sound Pressures Generated in the Ear Canal by an Audiometric Earphone. J A.S.A., 44, 555-562, (1968).

Feldman, H. A. A History of Audiology: A Comprehensive Report and Bibliography from the Earliest Beginning to the Present. Translations of the Beltone Institute for Hearing Research, 22, 7-109, (1970).

Fischler, H., Frei, E. H., Spira, D., and Rubinstein, M. Dynamic Response of Middle Ear Structures. J.A.S.A., 41, 1220-1231, (1967).

Flynn, W. E. Role of the pinna in hearing. J.A.S.A., 38, 104-105, (1965).

Fowler, E. P. Drum Tension and Middle Ear Air Pressures, their Determination, Significance and Effect upon Hearing. Ann. Otol., 29, 688-694, (1920).

Funnell, W. R. J. Comment on 'The Function of the Mastoid'. Eye, Ear, Nose, and Throat Monthly, 53, 41-42, (1974).

Gardner, M. B., and Hawley, M. S. Effect of Physical Detail on the Response of the External Ear. J.A.S.A., 49, 120, (1971).

______. Network Representation of the External Ear. J.A.S.A., 52, 1620-1628, (1972`

Goto, S., and Hibino, N. Effects of Lesions of the Tympanic Membrane on Cochlear Potentials. Nagoya J. Med. Sci., 17, 277-285, (1954).

Guinan, J. J. and Peake, W. T. Middle Ear Characteristics of Aneshtetized Cats. J.A.S.A., 41, 1237-1261, (1967).

Hartman, W. F. Error in Helmholtz's Calculation of the Displacement of the Tympanic Membrane. J.A.S.A., 49, 1317, (1971).

Helmholtz, H. Die Mechanik der Gehorknorchelchen und des Trommelfells. Pfluegers Ges. Physiol. Arch. 1. (1968), (Trans. as: The mechanism of the ossicles of the ear and the membrana tympani, William Wood and Co., New York, (1873).

Holst, H E., Ingelstedt, S., and Örtegren, U. Ear-drum Movements following Stimulation of the Middle Ear Muscles. Acta Otolaryng., Suppl., 182, 73-89, (1963).

Jepsen, O. The Threshold of the Reflexes of the Intratympanic Muscles in a Normal Material Examined by Means of the Impedance Method. Acta Otolaryng., 39, 406-408, (1951).

Johnson, E. W. Tuning Forks to Audiometers and Back Again. Laryngoscope, 30, 49-68, (1970).

Kanabu, M. J. Japanese Oto-Rhino-Laryng. Soc., 57, 33, (1954).

Karlan, M. S , Tonndorf, B., and Khanna, S. M. Dual Origin of the Cochlear Microphonics Inner and Outer Hair Cells. Ann. Otol., 81, 696-704, (1972).

Khanna, S. M., and Tonndorf, J. Middle Ear Power Transfer. Arch. Klin. Exp. Ohr. Nas., -u Kehlk Heilk, 193, 78-88, (1969).

______. Tympanic Membrane Vibrations in Cats Studied by Time Averaged Holography. J.A.S.A., 51, 1904-1920, (1972).

Kirikae, I. The Structure of the Middle Ear. University of Tokyo Press, Tokyo, (1960).

Kobrak, H. The Middle Ear. The University of Chicago Press, Chicago, (1959).

Larson, V. Sound Pressure Levels Measured in Ear-Canals and Couplers. University Microfilms, #7406963, 1-123, (1973).

Lawrence, M. Recent Investigations of Sound Conduction: Part I. The Normal Ear. Ann. Otol., 59, 1020-1036, (1950).

______. Hearing. Ann. Rev. of Physiol., 23, 485-500, (1961).

______. Ear Mechanics and Surgery for Deafness. J.A.S.A., 34, 1509-1513, (1962).

______. Wolsk, D., and Schmidt, P. Inner Ear Response to High-Level Sounds. J.A.S.A., 34, 102-108, (1962).

Lim, D. J. Human Tympanic Membrane. Acta Otolaryng., 70, 176-186, (1970).

Loeb, M. Psychophysical Correlates of Intratympanic Reflex Action. Psych. Bull., 61, 140-152, (1964).

Lorente de No', R. The Reflex Contractions of the Muscles of the Middle Ear as a Hearing Test in Experimental Animals. Trans. Amer. Laryng., Rhin, and Otol. Soc., 29, 26-42, (1933).

______. Harris, A. S. Experimental Studies in Hearing: II. The Threshold Curve of Reflexes of Muscles of Middle Ear: Hearing Loss After Extirpation of the Tympanic Membrane. Laryngoscope, 43, 324-326, (1933).

McArdle, F. and Tonndorf, J. Loss of Differential Pressure (SPL of Tympanic Cavity re SPL External Auditory Meatus) as a Factor in Eardrum Perforations. J.A.S.A., 41, (1967).

______. Perforations of the Tympanic Membrane and their Effects upon Middle Ear Transmission. Arch. Ohren-. Nasen-. u. Kehlk. Heilk., 192, 145-162, (1968).

McDonald, F. D.. Studebaker, G. A. Earmold Alteration Effects as Measured in the Human Auditory Meatus. J.A.S.A., 48, 1366-1372, (1970).

Markey, P. R. and Moshier, S. L. The Importance of the Pinna to Auditory Localization. J.A.S.A., 50, 91, (1971).

Miller, D J., Watson, C. S., and Covell, W. P. Deafening Effects of Noise on the Cat. Acta Otolaryng. Suppl., 176, 1-91, (1963).

Minton, J. P. The Dynamical Function of the Tympanic Membrane and Its Associated Ossicles. Proc. Nat. Acad. Sci., 11, 439-445, (1935).

Møller, A. R. Network Model of the Middle Ear. J.A.S.A., 33, 168-176, (1961b).

______. Transfer Function of the Middle Ear. J.A.S.A., 35, 1526-1534, (1963).

______. The Acoustic Impedance in Experimental Studies on the Middle Ear. Int. Audiol., 3, 123-135, (1964a).

______. Effect of Tympanic Muscle Activity on Movement of the Eardrum, Acoustic Impedance and Cochlear Microphonics. Acta Otolaryng., 58, 525-534, (1964b).

______. An Experimental Study of the Acoustic Impedance of the Middle Ear and Its Transmission Properties. Acta Otolaryng., 60, 129-149, (1965).

______. The Middle Ear. in Foundations of Modern Auditory Theory Vol. II, 133-194, J. V. Tobias, ed., Academic Press, New York, (1972).

Morton, J. Y., and Jones, R. A. The Acoustical Impedance Presented by Some Human Ears to Hearing-Aid Earphones of the Insert Type. Acustica, 6, 339-345, (1956).

Mundie, J. R. The Impedance of the Ear -- A Variable Quantity. Proc. Middle Ear Function Sem. Report No. 576, U. S. Army Med. Res. Lab., Ft. Knox, Ky., (1963).

Munson, A. W., and Wiener, F. M. In Search of the Missing 6 dB. J.A.S.A., 24, 498-501, (1952).

Olson, H. F. Elements of Acoustical Engineering. Van Nostrand, New York, (1947).

Onchi, Y. A Study of the Mechanism of the Middle Ear. J.A.S.A., 21, 404-410, (1949).

______. Mechanism of the Middle Ear. J.A.S.A., 33, 794-805, (1961).

Ostmann, P. *Lehrbuch der OhrenheilkUnde für Ärtzte und Studierende. F. C. W. Vogel, Leipzig, (1909).*

Payne, M. C., and Githler, F. J. Effects of Perforations of the Tympanic Membrane on Cochlear Potentials. *Archives of Otolaryng.*, 50, 666-674, (1951).

Peake, T. W., and Guinan, Jr., J. J. Middle-Ear Movement in Aneshtetized Cats. *J.A.S.A.*, 37, 1201, (1965).

Perlman, H.B. Some Physcial Problems in Condudtion Deafness. *Ann. Otol.*, 58, 86-110, (1949).

Pohlman, A. G. The Reactions in the Ear to Sound. *Ann. Otol.*, 50, 363-378, (1941).

Pong, W. and Maraccio, W. Nonlinearity of the Middle Ear as a Possible Source of Subharmonics. *J.A.S.A.*, 35, 679-681, (1963).

Price, G. R. Middle Ear Muscle Effects on Low Intensity Sounds (Cats). *J.A.R.*, 7, 119-127, (1967).

______. Correspondance between Cochlear Microphonic Sensitivity and Behavioral Threshold in the Cat. *J.A.S.A.*, 49, 1899-1901, (1971).

______. Influence of External Ear Acoustics on an Impulse Arriving at the Ear Drum. *J.A.S.A.*, 52, 129, (1972).

______. Transformation Function of the External Ear in Response to Impulsive Stimulation. *J.A.S.A.*, 56, 190-194, (1974a).

______. Upper Limit to Stapes Displacement: Implication for Hearing Loss. *J.A.S.A.*, 56, 195-197, (1974b).

Rubinstein, M., Feldman, B., Fischler, H., Frei, E. H., and Spira, D. Measurement of Stapedial-Footplate Displacements during Transmission of Sound through the Middle Ear. *J.A.S.A.*, 40, 1420-1426.

Shambaugh, G. *Surgery of the Ear.* Second Edition, Chapter 14, *Mechanisms of the Ear,* 369-400, W. B. Saunders, and Co., Philadelphia, (1967).

Shaw, E. A. G. Hearing Threshold and Ear Canal Pressure Levels with a Varying Acoustic Field. *J.A.S.A.*, 46, 1502-1514, (1969).

______. Transformation of Sound Pressure Level from the Free Field to the Eardrum in the Horizontal Plane. J.A.S.A., 56, 1848-1861, (1974).

______. and Teranishi, R. Sound Pressure Generated in an External-Ear Replica and Real Human Ears by a Nearby Point Source. J.A.S.A., 44, 240-249, (1968).

Sheehy, J. L., Gardner, Jr., G. and Hambley, W. M. Tuning Forks in Modern Otology. Archiv Otolaryng., 94, 132-138, (1971).

______. Reply. Archiv. Otolaryng., 95, 92, (1972).

Simmons, F. B. Middle Ear Muscle Activity of Moderate Sound Levels. Ann. Otol., 68, 1126-1144, (1959).

______. A Theory of Middle Ear Muscle Function at Moderate Sound Levels. Science, 138, 590-591, (1962).

______. Simultaneous Trans-Tympanic and Electrophysiological Indices of the Acoustic Reflex Activity in the Cat. Acta Otolaryng. 55, 309-314, (1962).

______. Middle Ear Muscle Acoustic Reflex as Index of Cochlear Sensitivity in Auditory Experiments: Some Technical Notes. J.A.R., 4, 255-260, (1964).

______. Binaural Summation of the Acoustic Reflex. J.A.S.A., 37, 834-836, (1965).

______. and Beatty, D. The Significance of Round-Window-Recorded Coclear Potentials in Hearing: an Autocorrelated Study in the Cat. Ann. Otol., 71, 767-800, (1962).

Sinyor, A. and Laszlo, C. A. The Role of the External Ear in the Hearing of the Guinea Pig. J.A.S.A., 50, 92, (1971).

______. The Acoustic Behavior of the Outer - Middle Ear Complex of Man and Guniea Pig. J.A.S.A., 52, 130, (1972).

Sivian, L J., and White, S. D. On Minimum Audible Sound Fields. J.A.S.A., 4, 288-321, (1933).

Stevens, S. S., and Davis, H. Hearing, Its Psychology and Physiology. John Wiley and Sons, Inc., New York, (1938).

Tasaki, I., Davis, H., and Eldredge, D. H. Exploration of Cochlear Potentials with a Microelectrode. *J.A.S.A.,* 26, 765-773, (1954).

______. and Legouix, J. P. The Space-Time Pattern of the Coclhear Microphonics (Guinea Pig), as Recorded by Differential Electrodes. *J.A.S.A.,* 24, 502-518, (1957).

Teranishi, R. and Shaw, E. A. G. External Ear Acoustic Model with Simple Geometry. *J.A.S.A.*, 44, 257-263, (1968).

Tonndorf, J. Surgical Approach of the Bulla Tympanica in the Guinea Pig, Rabbit, Cat, and Dog. Report No. 4, Randolph Field, Texas, 1-13, (1952).

______. *et. al.*, Bone Conduction: Studies in Experimental Animals. *Acta Otolaryng.Suppl.,* 213, 1-132, (1966).

______. and Brogan, F. A. Two Forms of Change in Cochlear Microphonics; Parallel Shift in Stimulus Intensity and Truncation of Gradient Curves. Proj. No. 21-27-001, Report No. 6, U S.A.F. Sch. Aviat. Med., 1-13, (1952).

______. and Khanna, S. M. Some Properties of Sound Transmission in the Middle and Outer Ears of Cats. *J.A.S.A.,* 41, 513-521, (1967).

______. The Quality of Impedance Matching by the Middle Ears of Cats. *Ann. Otol.,* 77, 154-163, (1968).

______. Submicroscopic Displacement Amplitudes of the Tympanic Membrane (Cat) Measured by a Laser Interferometer. *J.A.S.A.,* 44, 1546-1554, (1968).

______. The Role of the Tympanic Membrane in Middle Ear Transmission. *Ann. Otol.,* 79, 743-753, (1970).

______. The Tympanic Membrane as Part of the Middle Ear Transformer. *Acta Otolaryng.*, 71, 177-180, (1971).

______. Validation of Holographic Observations on the Displacement of the Tympanic Membrane in Cats. *J A.S.A.,* 50, 92, (1971).

______. Tympanic-Membrane Vibrations in Human Cadaver Ears Studied by Time-Averaged Holography. *J.A.S.A.,* 52, 1221-1233, (1972).

______. and Fingerhood, B. J. The Input Impedance of the Inner Ear in Cats. Ann. Otol., 75, 752-764, (1966).

______. and Greenfield, E. C. Total Myringoplasty: Functional Aspects. Acta Otolaryng., 73, 87-93, (1972).

Toynbee, J. The Diseases of the Ear: Their Nature, Diagnosis, and Treatment. Blanchard and Lea, Philadelphia, (1860).

Treitel. Recent Theories on Sound Conduction. translated by W. S. Bryant, Arch. Otolaryng., 32, 385-402, (1903).

Villchur, E. Audiometer-Earphone Mounting to Improve Intersubject and Cusion-Fit Reliability. J.A.S.A., 48, 1387-1396, (1970).

Wagemann, W. Arch. Ohr-usw. Heilk. u. Z. Hals-usw. Heilk., 164, 165-177, (1953).

Weiss, H. S., Mundie, Jr., J. R., Cushin, J. L., and Shinabarger, E. W. The Normal Human Intra-aural Muscle Reflex in Response to Sound. Acta Otolaryng., 55, 505-515, (1962).

Wever, E. G. Recent Investigations of Sound Conduction Part II. The Ear with Conductive Impairment. Ann. Otol., 59, 1037-1061, (1950).

______. The Cochlear Potential and their Relation to Hearing. Ann. Otol., 68, 975-989, (1959).

______. Hearing. Ann. Rev. Psych., 13, 225-250, (1962).

______. and Bray, C. W. The Nature of Acoustic Response: The Relation between Stimulus Intensity and the Magnitude of Cochlear Responses in the Cat. J. Exp. Psych., 22, 1-16, (1938).

______. and Lawrence, M. The Effects of Pressure in the Middle Ear. J. Exp. Psych., 30, 40-52, (1942).

Wever, E. G., and Lawrence, M. The Transmission Properties of the Middle Ear. Ann. Otol., 59, 5-18, (1950).

______. The Transmission Properties of the Stapes. Ann. Otol., 59, 322-330, (1950).

______. Physiological Acoustics. Princeton Univ. Press, Princeton, (1954).

______. and Rahm, Jr., W. E. The Phase Characteristics of the Ear. Proc. Nat. Acad. Sci., 40, 209-218, (1954).

______. and Smith, K. R. The Effects of Negative Air Pressure in the Middle Ear. Ann. Otol., 57, 418-428, (1948).

______. The Middle Ear in Sound Conduction. Arch. Otolaryng., 48, 19-35, (1948).

Wiener, M. F., and Ross., D. The Pressure Distribution in the Auditory Canal in a Progressive Sound Field. J.A.S.A., 18, 401-408, (1946).

Wiener, M. F., Pfeiffer, R. R., and Backus, A. S. N. On the Sound Pressure Transformation by the Head and Auditory Meatus of the Cat. Acta Otolaryng., 61, 255-269, (1966).

______. Analysis of the Middle-Ear Function. Part I: Input Impedance. J.A.S.A., 34, 1514-1523, (1962).

______. An Acoustic Coupler for Earphone Calibration LSC-S-7, Grant NGR-33-022-091, Nat. Aeron. Space Admin., Washington, D. C. 20546, (From the Laboratory of Sensory Communication, Syracuse University, Syracuse, N.Y. 13210), (1970).

Zwislocki, J. J. An Ear-like Coupler for Earphone Calibration, LSC-S-9, Grant NGR-33-022-091, Nat. Aeron. Space Admin., Washington, D.C. 20546, (From the Laboratory of Sensory Communication, Syracuse University, Syracuse, N.Y. 13210), (1971).