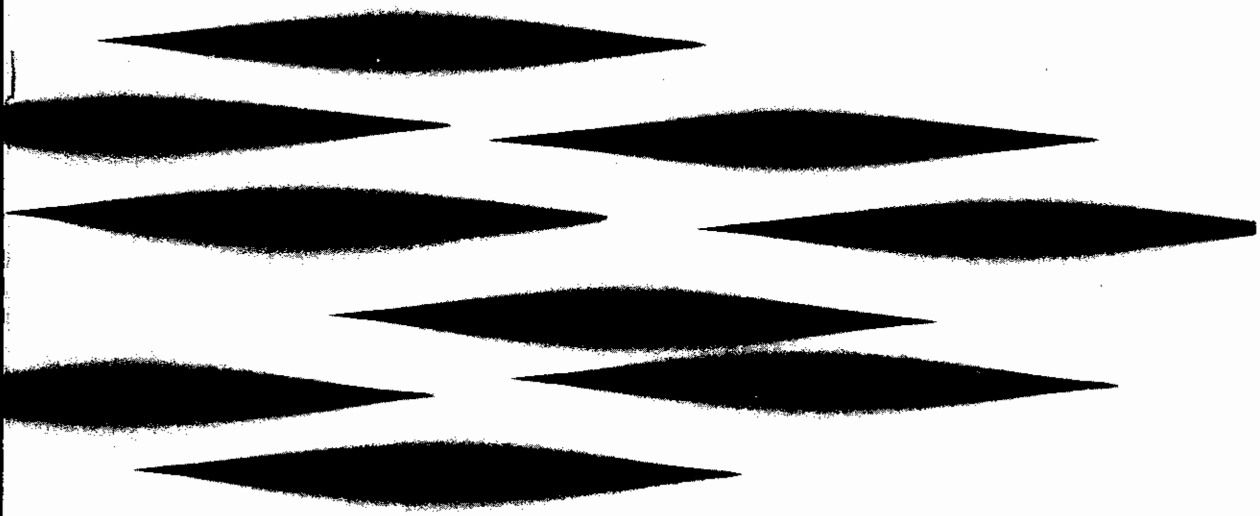
ACOUSTIC IMPEDANCE OF PATHOLOGICAL EARS



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Acoustic Impedance of Pathological Ears

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I

ABSTRACT

The report reviews the clinical usefulness of acoustic impedance measurements at the eardrum, as well as the currently used instrumentation and methods. The conclusion is reached that both absolute and relative impedance measurements can be made with the acoustic bridge as well as with appropriate probe-tube techniques. The absolute measurements and the measurements based on static pressure differences across the eardrum are the most generally applicable since they do not depend on the neural portions of the auditory system. However, tests based on the middle-ear reflexes provide valuable additional information. The reliability of measurements with the acoustic bridge is analyzed on the basis of three independent studies and is found to be high. The variability of intrasubject measurements is much smaller than intersubject differences. The absolute impedance measurements, when correctly executed, differentiate between otosclerotic and normal ears, or ears with sensori-neural hearing loss, in 90% of cases. In uncertain cases, corroborating evidence usually can be obtained from muscle reflex tests. Absolute impedance measurements are the only method that has been shown to discriminate between stapedial ankylosis and ossicular discontinuity. Furthermore, they make possible a differentiation between stapedial ankylosis and fixation of the larger ossicles. A number of cases are described in which impedance measurements were found to be of particular value. The acoustic symptomatology of the most frequent pathologies is summarized in a table.

II

INTRODUCTION

Metz's (1946) pioneering work on clinical measurements of acoustic impedance at the ear, and subsequent related investigations, have led to considerable discussion. Several controversial questions have arisen and the intensity of the arguments has increased with the number of investigations and competing claims. In the following parts of the introduction, we shall attempt to clarify the most outstanding issues. Then, in the subsequent sections, we shall review the acoustic-bridge method of impedance measurements, give normative data for normal and otosclerotic ears, discuss some special pathological cases, and, finally, suggest a tentative acoustic symptomatology.

USEFULNESS OF THE IMPEDANCE MEASUREMENTS

The first question concerns the usefulness of the impedance measurements. Do they contribute any essential information beyond that which results from case history, otoscopic examination, and audiometry? Although an affirmative answer has been given on several occasions, it may be worth restating in this review.

Currently, acoustic impedance measurements constitute the only means of direct examination of the middle-ear function. They are performed at physiological vibration amplitudes and, therefore, give a direct estimate of the efficiency of sound transmission. Except in acoustic reflex tests, the sensori-neural part of the auditory system is not involved.

The otoscopic examination is limited to directly visible anatomical changes and to a qualitative evaluation of the eardrum mobility at amplitudes that far exceed the normal physiological range. It is well known that the examination gives inconclusive results in all cases of conductive hearing loss, except those that are associated with gross changes in the eardrum anatomy, position, or mobility. Otosclerosis, ossicular interruptions, and even massive adhesions to the large ossicles usually remain undetected.

The audiometric examination provides only indirect nonspecific information about the state of the middle ear. The resulting diagnosis is limited to a differentiation between middle-ear disorders, on the one hand, and sensori-neural and cochlear disorders, on the other. No differentiation among the middle-ear malfunctions can be made solely on the basis of audiometric tests. The existence of a conductive component can be detected most of the time but not all of the time. Bone conduction depends to a certain extent on the middle-ear function, and the existence of the air-bone gap may not be clearly apparent unless the conductive loss is substantial. In pronounced hearing losses of a mixed type, it may not be possible to measure the bone conduction at all. What percentage of conductive hearing losses remain undetected as a result of these limitations is not known because the audiometric tests cannot be validated by any other independent method of examination. Surgery is not undertaken, unless evidence of a middle-ear malfunction is substantial.

With respect to middle-ear disorders, the diagnostic information from acoustic impedance measurements goes considerably beyond that which can be derived from otoscopic examination and audiometric tests. According to the already available experience, impedance measurements make it possible to detect pathological changes that cannot be detected either through otoscopy or audiometry. For instance, in cases of unilateral otosclerosis, the ear that appears normal in otoscopic and audiometric examinations frequently shows abnormal impedance values and a reduced or absent effect of stapedius contraction. Impedance measurements can be performed irrespective of hearing loss. As a consequence, disorders of the middle ear can be detected even when the hearing loss precludes bone-conduction testing. In addition, impedance measurements make it possible to differentiate among various middle-ear pathologies.

There should be little doubt that acoustic impedance measurements at the ear are clinically useful. The steadily increasing number of clinics in which they are used testifies to this conclusion. The fact that they have not yet reached the status of a generally accepted, routine method is due in part to the necessity of learning new concepts and new techniques, and in part to the still present shortcomings in methodology and instrumentation. Further progress will depend on the willingness of the clinicians to learn, and on the willingness of instrument makers to introduce improvements.

ABSOLUTE VERSUS RELATIVE IMPEDANCE MEASUREMENTS

While the usefulness of acoustic impedance measurements is increasingly apparent, the weight of the discussion is slowly shifting toward the methodological and technological aspects. Although both are related, they are not identical by any means and should be considered separately. We first shall discuss the basic methods.

Current clinical methods may be divided into three categories: measurements of absolute impedance, detection of impedance changes due to contractions of the middle-ear muscles, and detection of impedance changes due to a pressure differential across the eardrum. Somehow, probably because of historical accidents and misinterpretations, a disagreement arose concerning the suitability of absolute impedance measurements as compared to measurements of impedance changes. High individual differences that some investigators (Terkildsen and Nielsen, 1960) have found to obscure the pathological effects seem to constitute the main objection. Secondary objections stem from the need for more sophisticated instruments and measuring techniques, than are required for detection of impedance changes. For awhile, these objections completely eliminated the absolute impedance measurements from the clinical diagnostic armamentarium. However, a series of experiments that started in 1955 and led to a number of publications (Zwislocki, 1957a, 1957b, 1961, 1962, 1963, 1968; Feldman, 1963, 1964, 1967, 1969) showed that the individual differences could be reduced to a manageable level by eliminating the effect of the individually variable volume of the ear canal, and by performing the measurements with sufficient precision. Although precision still seems to be lacking in some experimental series (Bicknell and Morgan, 1968), absolute impedance measurements seem to be gaining ground. The best indication of this trend is that some instruments originally developed for the measurement of impedance changes have been modified to permit rough estimates of absolute impedance.

The return to absolute impedance measurements seems to be due not only to improvements in techniques and instrumentation but also to shortcomings of methods relying on impedance changes. Although the absence of impedance changes caused by the stapedius reflex is a good indicator of middle-ear malfunctions (Klockhoff, 1961), the reflex cannot always be elicited. When the reflex is elicited acoustically, the success depends on a sufficiently low hearing level; when it is elicited by noxious electrical stimulation of the ear canal, it is subject to attention and habituation. As a consequence, the absence of a detectable stapedius reflex is an unsafe indicator of middle-ear pathology. Although a detectable reflex constitutes a strong contraindication of such pathology, the reflex can be detected in some cases of ossicular separation and serous otitis media.

Detection of impedance changes that are due to a pressure differential across the eardrum are useful when the patient's Eustachian tube is malfunctioning (Thomsen, 1955, 1958). Tests for pressure differential across the eardrum also can indicate a pronounced fixation of the ossicular chain (Terkildsen and Thomsen, 1959). However, the method is likely to be a less sensitive indicator of such malfunctions as stapedial ankylosis and ossicular separation than are absolute impedance measurements. Although no statistical evaluation seems to be available, this is to be expected since the impedance changes cannot exceed the difference between an actual absolute impedance and a total fixation.

On the basis of our experience and that of others, we must conclude that none of the available impedance methods provides definitive diagnostic information in all instances. Absolute impedance measurements are the most generally applicable but do not always permit a distinction between normal and pathological ears. In uncertain cases, the patient should be tested to determine the presence of the stapedius reflex, if possible. Such tests are also useful in cases of suspected loudness recruitment (Metz, 1952), malingering (Jepsen, 1953), or facial nerve malfunction (Jepsen, 1955). Tests for detecting impedance changes due to a pressure differential across the eardrum provide useful data about patients with malfunctioning Eustachian tubes (Thomsen, 1955, 1958).

INSTRUMENTATION

There exists a considerable confusion with respect to impedance instrumentation. The belief seems to prevail that acoustic bridges are suitable for absolute impedance measurements while systems relying on sound delivery and pickup through narrow tubes, such as advocated by Terkildsen and Nielsen (1960) or Klockhoff (1961), are limited to the detection of impedance changes. Although the first clinical measurements of absolute impedance were performed by means of Schuster's acoustic bridge (Metz, 1946), one of us has introduced the probe-tube technique for absolute impedance measurements in order to overcome the technical difficulties inherent in Schuster's bridge (Zwislocki, 1957a,b). All early measurements of absolute impedance that led to a detailed analysis of the middle-ear function and to an impedance symptomatology of middle-ear malfunctions were performed with the help of probe tubes (Zwislocki, 1957a, b, 1961, 1962). In subsequent work, both Metz's bridge measurements and the probe-tube measurements became degraded to detecting impedance changes. Clearly, both techniques can be used for both kinds of measurements. Which method is selected depends on available instrumentation and convenience. The probe-tube technique was substituted for Schuster's bridge because the latter appeared too cumbersome and did not permit the elimination of the effects of the ear canal by convenient means (Zwislocki, 1957a,b). In turn, a modified acoustic bridge replaced the probe tubes when simple means were found for compensation of the ear-canal volume (Zwislocki, 1961, 1963). This happened because the bridge permitted a more direct and stable determination of impedance components. Currently, the probe-tube technique is more suitable for tests based on the pressure differential across the eardrum (Terkildsen and Thomsen, 1959), but there is no inherent reason why an acoustic bridge could not be adapted for such tests.

Future developments will depend to a large extent on the resourcefulness of instrument makers. For the present, we have the following suggestion. Clinical impedance measurements are still in their infancy and it is too early to decide which aspects will become the most useful. Therefore, as many aspects as possible should be included. If absolute impedance measurements are undertaken, they should include either both the reactance and resistance components, or parameters that permit their calculation. In dealing with impedance changes, quantitative methods should be chosen over simple detection (Lilly and Shepherd, 1964; Feldman and Zwislocki, 1965). Only when sufficient evidence has accumulated should the less useful aspects of impedance measurements be discarded and instrumentation developed that emphasizes the more useful ones.

III

METHOD

The data in this report have been obtained by means of an acoustic bridge manufactured by Grason-Stadler. Figure 1 shows the bridge in its place of operation. According to the current clinical method (Zwislocki, 1963; Feldman, 1963), the bridge is held by hand. Most data reported in this article have been obtained in this way. For more accurate measurements, the bridge may be secured by means of a holder especially designed for the purpose (Figure 2). The holder has two ball joints and one axial joint placed between the ball joints. It holds a speculum into which the bridge is inserted after the speculum has been positioned properly in the ear canal. Because of the joints, the positioning is almost as easy as if the speculum were not attached to the holder. When a satisfactory position is achieved, the joints are tightened by means of three small levers. This operation can be performed effortlessly by one hand, while the other hand holds the speculum. The lever system is so designed that, during the tightening operation, no resultant force that could disturb the position of the speculum is exerted on the arm of the holder. We found the holder to be easier to manipulate and more stable than commercially available flexible arms. With its help, measurements could be performed for time periods as long as one hour without causing any objectionable discomfort to the patients. During these experiments, the patients were lying on a simple examining table, with their heads supported by a cushion filled with ground cork. A substantial number of patients fell asleep. They had to be awakened since it was observed that the impedance may change during sleep. The cork-filled cushion was found to be an essential part of the equipment. It easily adapts to the shape of the side of the human head without producing pressure areas. At the same time, once adapted, it holds the head in a stable position. Cushions filled with highly resilient materials, especially foam rubber, are completely unsuitable. We use the cork-filled cushions even when the bridge is held by hand. Under these circumstances, the operating table is unnecessary. The patient can sit on an ordinary chair, in front of a table. The cushion is placed on the table, and the patient puts his head on it.

One of the most important prerequisites for accurate impedance measurements at the ear is a tight coupling between the measuring instrument and the ear canal. Any sound leakage either through air leaks or thin walls of the

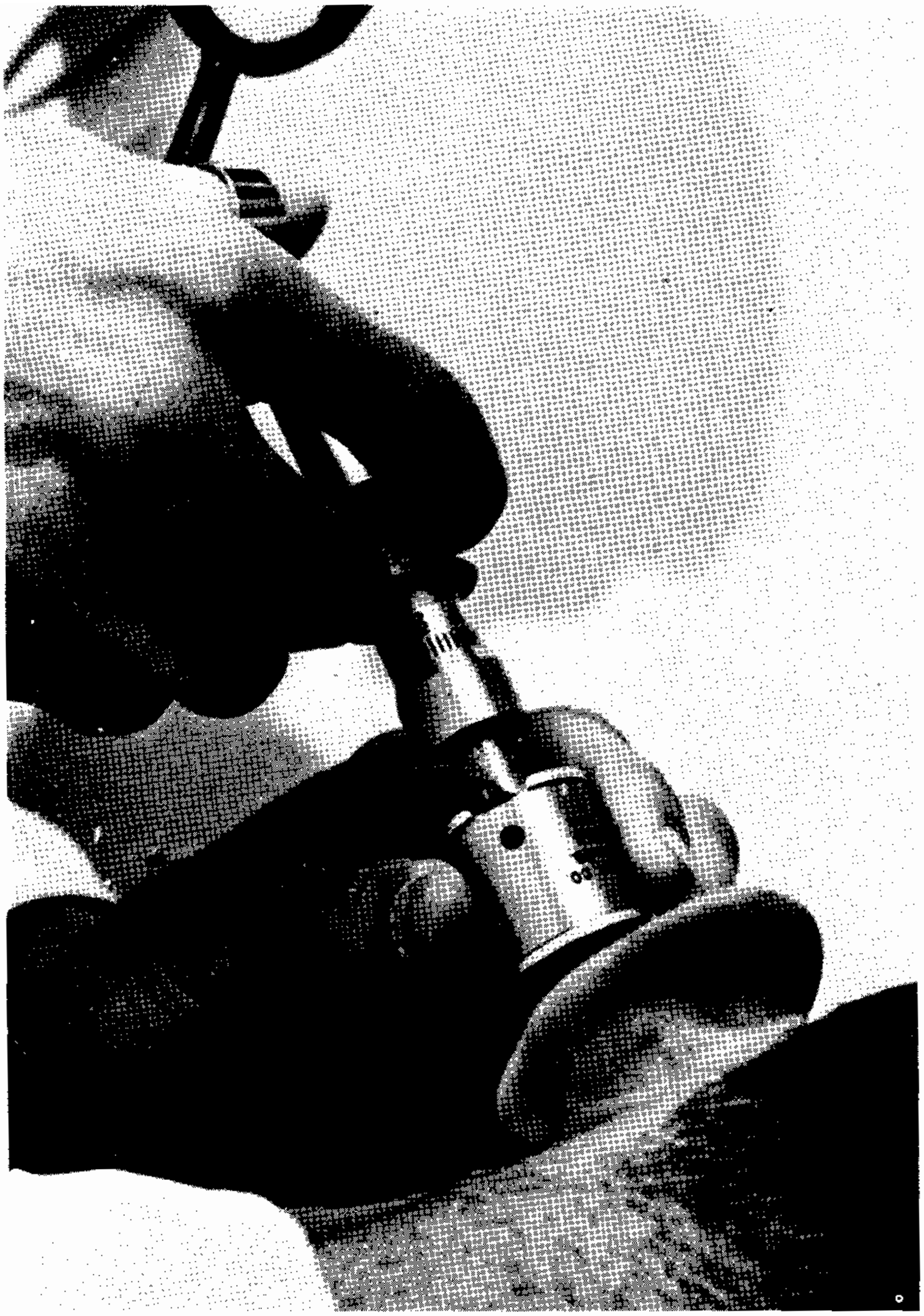


FIGURE 1. Acoustic bridge held in a patient's ear.

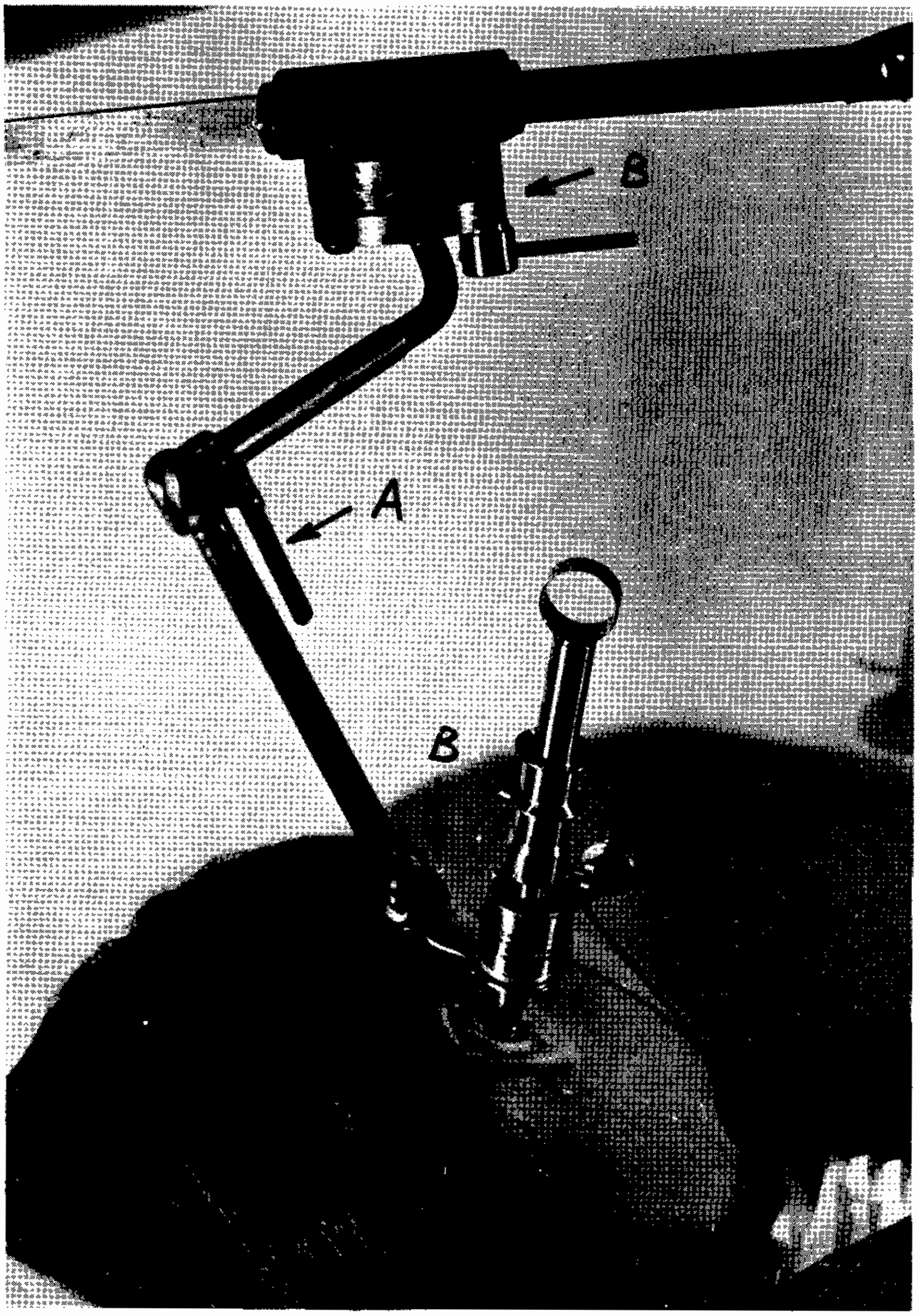


FIGURE 2. Acoustic bridge secured by means of a holder. Arrows marked B indicate the two ball joints, arrow A indicates the axial joint.

coupling devices may introduce serious errors. The tight coupling of the current models of the Grason-Stadler bridges is achieved by means of a rigid speculum and soft, plastic sealing tips which come in three sizes. The ear canal is inspected, and the appropriate tip selected. The tip is secured on the speculum and covered with petroleum jelly. Then the speculum is inserted into the ear canal. *Care must be taken to achieve a tight seal without closing the passage of the ear canal.* The speculum must be oriented toward the eardrum and held under a firm pressure without, however, causing any objectionable discomfort. The bridge is inserted into the speculum, where it fits snugly.

Prior to absolute impedance measurements, the cerumen must be removed from the ear canal and the volume of the ear canal measured. *No reliable measurements by any method can be achieved when the ear canal is completely or even only partially blocked by cerumen.* A partial blocking is often unstable and the free passage may increase or decrease in the course of measurements. *Accurate knowledge of the ear-canal volume between the eardrum and the tip of the measuring instrument is indispensable for absolute impedance measurements and also for quantitative measurements of impedance changes.* In a recent article, Bicknell and Morgan (1968) assert that the measured compliance of the eardrum is insensitive to the errors of volume measurement. This statement is most surprising, since the dependence of the impedance values on the ear-canal volume may be demonstrated experimentally as well as calculated theoretically. For instance, at low frequencies—100 or 200 Hz—the impedance at the eardrum is predominantly controlled by the compliance. The latter can be expressed in terms of an equivalent volume of air, and it is possible to show that the measured compliance values are equal to the actual values minus the error in the measured ear-canal volume. If the measured value amounts to 0.4 cc and the error in the measured ear-canal volume amounts to +0.2 cc, then the actual value is 0.6 cc, or 50% greater! The individual scatter of data published by Bicknell and Morgan is compatible with errors of this magnitude.

In measurements of impedance changes, the apparent change depends on the ear canal volume, unless an appropriate compensation is made. It has been shown that stapedius contractions decrease the compliance of the middle-ear mechanism at low frequencies (Møller, 1964; Dallos, 1964; Lilly and Shepherd, 1964; Feldman and Zwislocki, 1965). When the acoustic impedance is determined at the entrance to the ear canal, the measured compliance consists approximately of the sum of the compliances of the middle ear and of the ear-canal volume. Since the muscle reflex changes only the compliance of the middle ear, the percentage change of the measured compliance decreases as the compliance of the ear-canal volume increases. The percentage change controls the increment in sound pressure that usually serves as the index of the reflex. As a result, the same effect of the reflex appears smaller in a large ear canal than in a small one.

In all our impedance studies, the volume of the ear canal was measured by filling it with a calibrated amount of 70% alcohol. The method was introduced more than 10 years ago (Zwislocki, 1957a,b) and has been used by us and others with satisfactory results (for instance, Møller, 1960; Feldman, 1963, 1964, 1967; Nixon and Glorig, 1964; Tillman, Dallos, and Kuruvilla, 1964). Although other methods are possible, none appears more simple or reliable. In particular, filling the ear canal with alcohol to the tip of the speculum is equivalent to a pressure of less than 2 cm of water on the eardrum. Thus, excessive stresses on the middle-ear mechanism are avoided. We usually find it sufficient to fill the ear canal with alcohol at room temperature. This sometimes produces a mild caloric effect which can easily be avoided by prewarming the alcohol to body temperature. Our detailed procedure for the volume measurement is as follows. The patient is positioned on the examination table with his head sideways on the cork-filled cushion. The speculum with the appropriate sealing tip is properly inserted into the ear canal and held with the same pressure as during impedance measurements. This is essential, since position and pressure differences may cause changes in the ear-canal volume. The speculum is directed toward the meatus and not toward the canal wall. Alcohol is injected from a calibrated 2 cc syringe through a blunt hypodermic needle until its level reaches the tip of the speculum. At this point, the needle is withdrawn and the volume on the scale of the syringe is read. Then the ear is emptied and dried. This is achieved by taking the speculum out and replacing it with a wad of absorbent cotton. The head is turned 180°, and the alcohol allowed to flow into the cotton. After two or three minutes, the ear can be considered sufficiently dry for impedance measurements.

The measurements with the bridge begin with the setting of one of the bridge controls to the volume of the individual ear canal. This adjustment is important and should be made within 0.05 cc of the ear-canal volume. The examiner may perform it while waiting for the ear canal to dry. Subsequently, the sealing tip of the speculum is lightly coated with petroleum jelly, and the speculum is reinserted into the ear canal and held in the same position and at the same depth as during the volume measurement. Then the bridge is inserted into the speculum, and the measurement can begin.

The operation of the bridge, as it has been described repeatedly, consists of adjusting two independent controls until the intensity of a monitoring tone is minimized. The voltage producing the tone must be fed to the bridge from an oscillator or an audiometer and must be adjustable in both frequency and intensity. The monitoring may occur either by listening to the tone through a stethoscope or by means of a microphone. Practically all measurements reported in this article were obtained by means of the first procedure, which is the simpler and requires less equipment. However, in the most accurate, detailed measurements, a microphone with appropriate accessories was used. It consisted of a hearing-aid earphone connected to the bridge by means of a short rubber tube. The microphone was hooked up through a transformer to the General Radio Wave Analyzer, Type 1900-A, which also served as the oscillator. When a microphone is used, care must be taken not to increase the sound intensity in the bridge substantially above a comfortable level. Otherwise, muscle contractions may be produced. When the monitoring occurs by listening, the sound intensity should be adjusted so as to avoid disturbing harmonics and to produce the sharpest possible intensity minimum. From some criticisms voiced in the literature and from some inaccurate published results, it seems that the adjustment of the sound intensity is not always well understood. When the controls of the bridge are manipulated, the loudness of the monitoring sound repeatedly passes through a minimum. When the sound intensity is set too low, the sound vanishes altogether over a wide range of the control adjustments. As a consequence, the settings that correspond to an intensity minimum cannot be determined accurately. The minimum also appears subjectively flat when the sound is too loud. We have found that, for most accurate results, the sound intensity should be such as to make the sound barely audible when the minimum is reached. To achieve this, the examiner must readjust the sound intensity during the measurement.

We find it convenient to preset the bridge controls to normal average values before inserting the bridge into the speculum. Then we manipulate either the resistance or the compliance control, whichever seems to produce the greater change in sound intensity. With this control, we obtain a preliminary sound minimum. At this point, we begin adjusting the other control and the sound intensity on the oscillator. When a good minimum is achieved, we check the first control.

The bridge provides compliance and resistance values referred to the eardrum. The compliance values expressed in terms of the equivalent volume of air can be read directly on the bridge. Unfortunately, the resistance is still expressed in arbitrary units and the absolute resistance values must be derived from a calibration curve. For publication purposes, the latter should be used, otherwise interbridge comparisons are not accurate.

With respect to sound frequency, we find it convenient to begin with 500 Hz, then to test at 250 and 125 and, finally, at 750, 1000, and sometimes 1500 Hz. For further details of measurement techniques and instrument description, see earlier articles (Zwislocki, 1961, 1963, 1968; Feldman, 1963, 1964, 1967; and Feldman and Zwislocki, 1965).

IV

RESULTS

MEASUREMENTS ON NORMAL EARS

Measurements on populations with normal hearing were undertaken for two purposes: an additional evaluation of the reliability of the method, and a determination of the range and medians of the normal impedance parameters. One series of data was obtained by Feldman on a mixed group of 33 subjects. He used the standard clinical procedure, that is, the bridge was held by hand and the test sound was monitored by ear. The data have already been published (Feldman, 1967), but we reproduce them here in a different statistical form, which appears more suitable as a clinical reference. Zwislocki obtained another series on a different group of 10 males and 12 females. In these laboratory measurements, the bridge was secured by means of the holder described in the preceding section, and the test sound was monitored by means of a microphone and a voltmeter. Compliance and resistance values were determined on a large number of sound frequencies in order to obtain continuous impedance curves. A third series of data included in this section is derived from a study made by Hecker outside this project (Hecker and Kryter, 1964). Hecker learned the operation of the acoustic bridge in our laboratory while on a two-day visit, and was kind enough to send us his results. They were obtained on a population of 27 male subjects with normal hearing. The measurements were performed by means of the same standard clinical method as used by Feldman but under different field conditions.

Reliability

Figures 3 and 4 compare the median results of the first two series of measurements. The compliance values in Figure 3 agree very well. Note that the median compliance of the men's ears is somewhat higher than that of the women's ears. Some earlier observations indicated that such a difference may exist. More recently, it was noticed by Bicknell and Morgan (1968). The results obtained with the clinical method on a mixed group fit precisely between the male and female compliance values at low frequencies. At 750 and especially at 1000 Hz, the laboratory method produced somewhat higher compliance values than the clinical method. This does not reflect an inaccuracy of measurement but, rather,

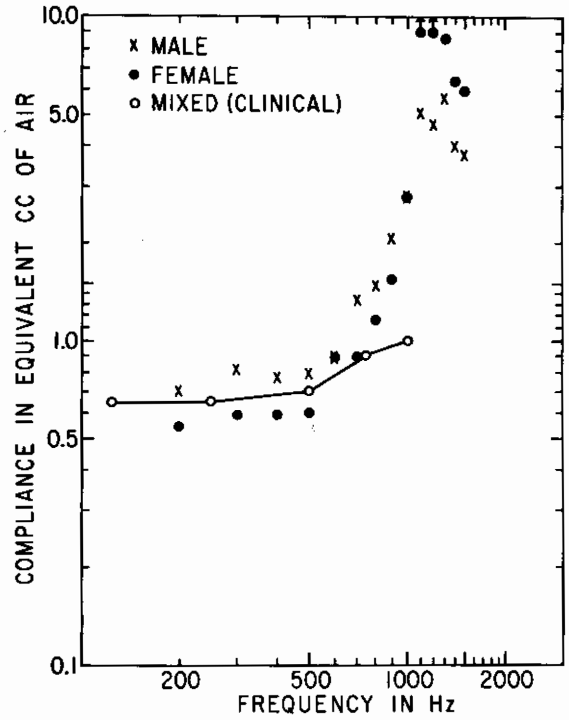


FIGURE 3. Median compliance of ears with normal hearing. Crosses and filled circles indicate the results of the laboratory method, unfilled circles, those of the clinical method.

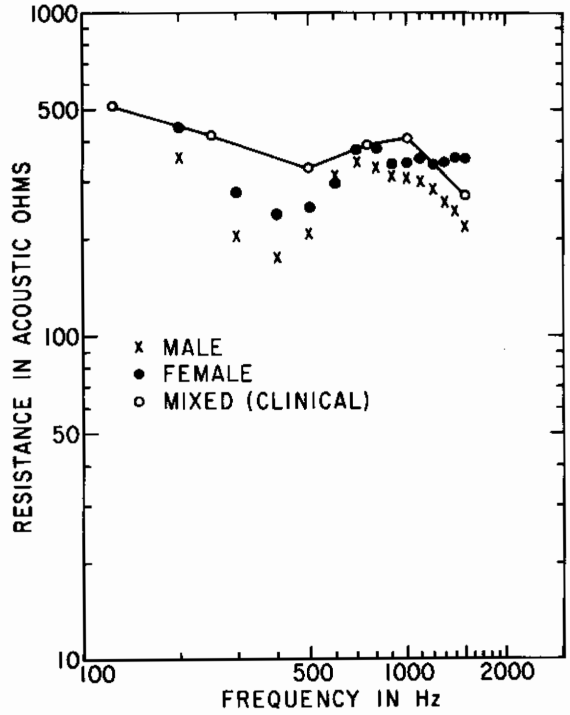


FIGURE 4. Median resistance of ears with normal hearing. Crosses and filled circles belong to the laboratory method, unfilled circles, to the clinical method.

an inherent property of the acoustic bridge. It stems from a residual effect of the resistance element, which can be minimized but not avoided. The effect increases with frequency. It can be determined quite accurately and eliminated in computations. This was done for the laboratory, but not for the clinical, measurements.

The resistance values obtained in the two series are plotted in Figure 4. Here the agreement is less good, especially in the vicinity of 500 Hz. Because no measurements were made between 250 and 500 Hz in the clinical study, and a straight line has been drawn between the two frequencies, the difference is exaggerated in the figure. Nevertheless, the clinical method produced consistently somewhat higher values than the laboratory method. We do not know the reasons for the discrepancy; they did not seem worth investigating. The intersubject variability is substantial, and the exact resistance values appear of less diagnostic importance than the compliance values. The laboratory data are noteworthy for the difference between the male and female groups and for the dip around 400 Hz. No clinical data have been obtained at this frequency and it is not known whether the dip is characteristically affected by middle-ear pathologies. It seems to be present in all normal ears.

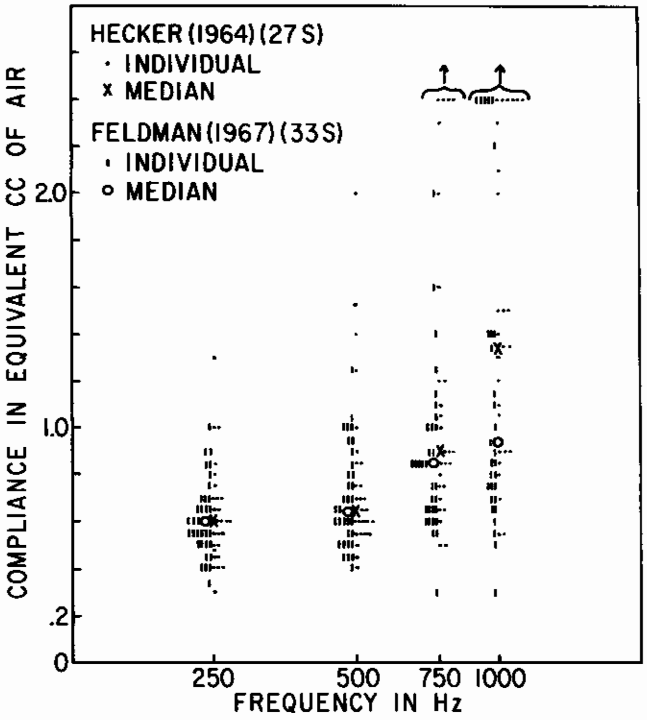


FIGURE 5. Compliance of ears with normal hearing. Individual data and medians resulting from two independent studies in which the clinical method was used.

Figure 5 compares the compliance results obtained by means of the clinical method in Feldman's and Hecker's studies. All the individual data are shown, as well as their medians. Up to 750 Hz, both series agree well with respect to the distributions of the individual values and their medians. At 1000 Hz, where large individual differences are encountered, the medians differ. As we shall discuss in later sections, 1000 Hz is of limited diagnostic usefulness. A similarly good agreement between the two series exists with respect to resistance values. However, Hecker's data are slightly closer to those obtained in the laboratory series.

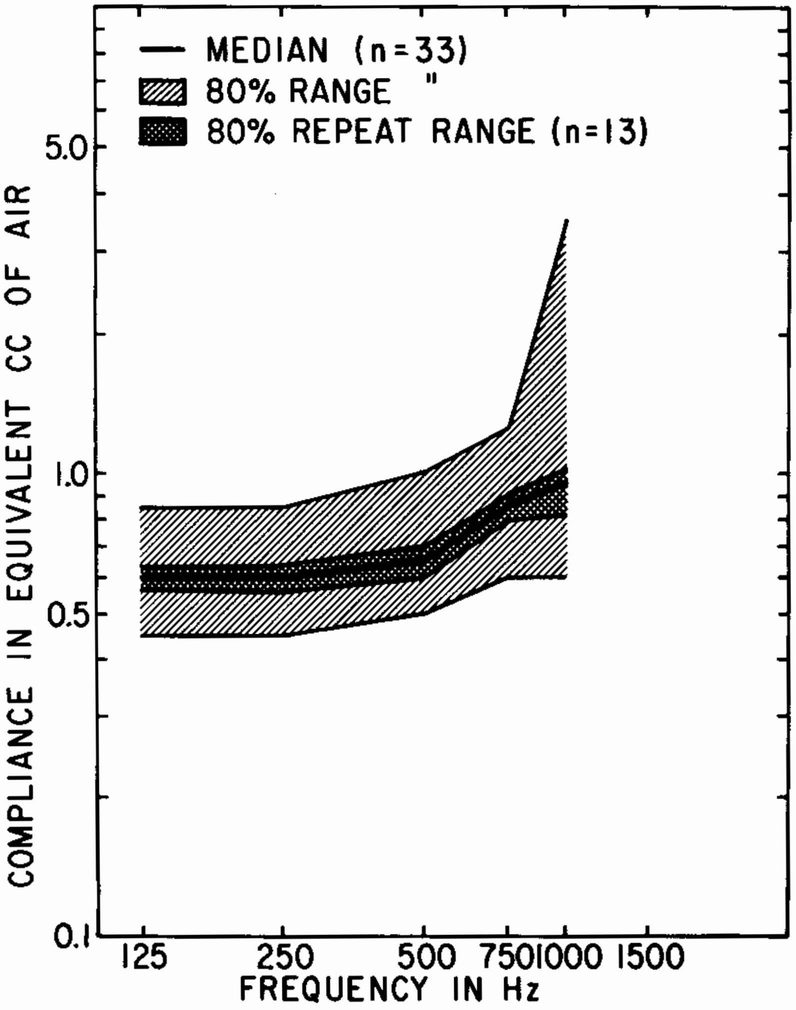


FIGURE 6. Compliance of ears with normal hearing. The heavy line indicates the medians, the wide band the 80% range of individual values, and the narrow band the 80% range of individual differences resulting from a repeat measurement.

To test the intrasubject consistency of bridge measurements, the compliance and resistance determinations were repeated on 13 subjects (Feldman, 1967). The crosshatched middle band in Figure 6 shows the 80% range of the compliance differences between the first and the second determinations. The range is much smaller than the corresponding range of individual values shown by

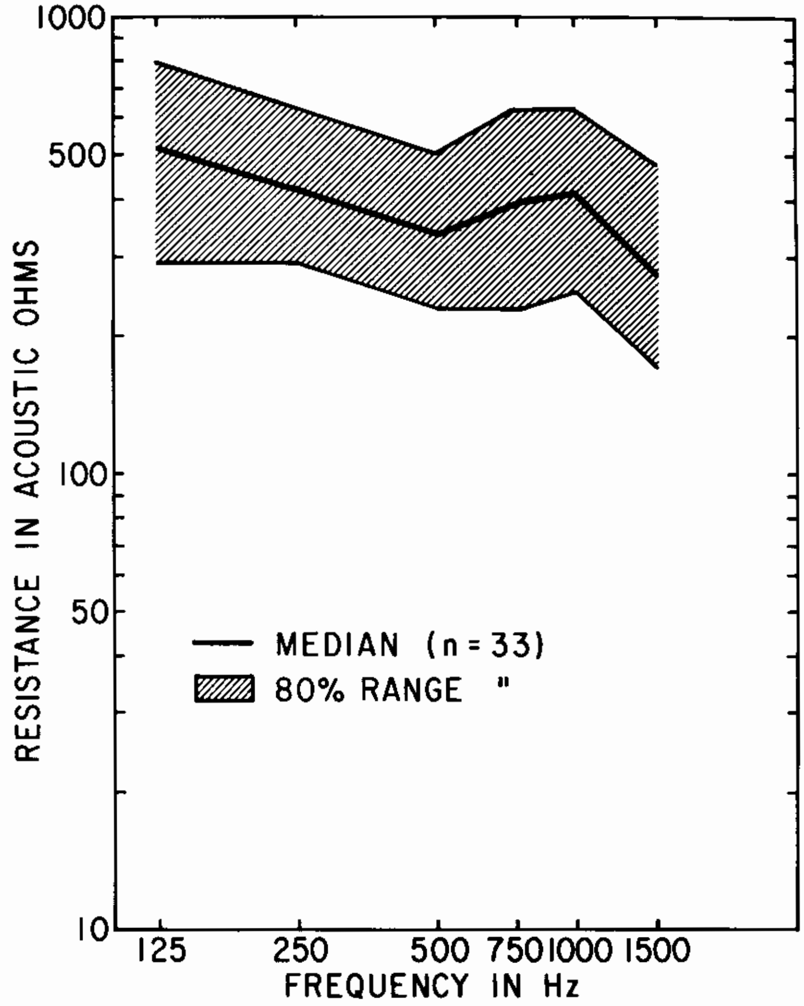


Figure 7. Median resistance and the 80% range of individual resistance values of ears with normal hearing.

the wide band. As a consequence, the compliance measurements are sufficiently precise. The intrasubject variability of resistance measurements is more considerable but remains small compared to intersubject differences (Feldman, 1967). Figure 7 shows only the 80% range of the individual values.

On the basis of the three studies just described, we conclude that the bridge measurements are quite reliable. The data obtained by different investigators with different instruments are comparable, and it makes little difference whether the bridge is held by hand or secured by means of a holder. The same data are obtained whether the test sound is monitored by ear or with the help of a microphone.

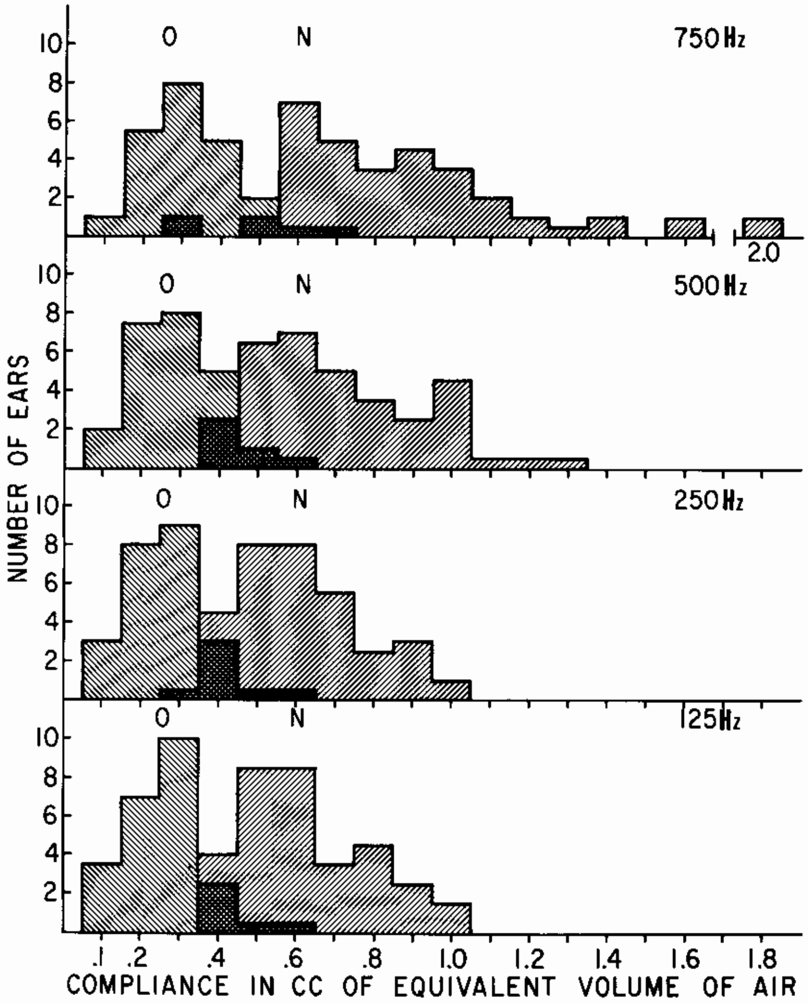


FIGURE 8. Compliance histograms of 33 ears with normal hearing and of 24 ears with otosclerosis. Letters *N* and *O* indicate the medians of the normal and otosclerotic populations, respectively.

Normal Impedance Values

The medians and 80% ranges of the normal compliance and resistance values are shown in Figures 6 and 7, respectively. The ranges have been obtained by leaving out 10% of the low values and 10% of the high ones. Since the distributions are skewed, parametric statistics may be misleading and should not be used in comparing normal to pathological values.

Some have voiced criticisms against evaluating the impedance of the ear in compliance terms, and have suggested that reactance, which is the imaginary part of the impedance expression, would be more appropriate. From a purist's point of view the criticism is justified, since the reactance together with the resistance are the actual impedance components. However, from the practical point of view, the compliance is a more convenient measure for diagnostic testing of the ear. First of all, it varies much less with sound frequency than does the reactance in the frequency range of diagnostic interest. Second, it can be measured with a directly calibrated instrument without the help of calibration curves or tables. Last, but not least, it more directly reflects the state of interossicular connections and of the ossicular attachments to the middle-ear walls. Consequently, for clinical purposes, we shall use the compliance rather than the reactance.

Taking another look at Figures 6 and 7, we note that the 80% ranges for both the compliance and resistance of ears with normal hearing are large. The compliance values defining the upper boundary are about twice the compliance values of the lower boundary. At 1000 Hz the ratio increases to more than five. For the resistance, the ratio is on the order to two and a half. The large individual differences encountered in ears with normal hearing have been known since Metz (1946). We have confirmed them repeatedly, and some of the statistical distributions have been published (Feldman, 1963, 1964, 1967). However, our intersubject variability is somewhat smaller than in Metz's study. This results from improvements in methodology, particularly from the compensation for the highly variable volume of the ear canal (Zwislocki, 1957a,b,

TABLE 1. Medians and 80% ranges of the normal compliance and resistance values.

	Compliance in cc of Equivalent Air Volume					
Frequency	*125*	*250*	*500*	*750*	*1000*	
Lower Bound	0.45	0.45	0.50	0.60	0.60	
Median	0.60	0.60	0.65	0.85	0.95	
Upper Bound	0.85	0.85	1.00	1.25	3.50	
	Resistance in Acoustic KOhms					
Frequency	*125*	*250*	*500*	*750*	*1000*	*1500*
Lower Bound	0.28	0.28	0.23	0.23	0.25	0.17
Median	0.51	0.42	0.33	0.39	0.41	0.27
Upper Bound	0.80	0.63	0.51	0.63	0.63	0.48

1961, 1963). We have found similar statistical distributions in several investigations, independent of the method, that is, whether a bridge or a probe-tube source was used. In particular, the 80% compliance range always approximated a ratio of two to one. A greater ratio obtained in a recent study by Bicknell and Morgan (1968) probably resulted from imprecise measurements. This assumption is confirmed by their statement that a ±0.2 cc error in the determination of the ear-canal volume does not appreciably affect the measured impedance values. Note that a ±0.2 cc error is approximately equal to the total range of compliance values at low frequencies (Figure 6).

Since the 80% ranges in Figures 6 and 7 have been obtained repeatedly under various conditions, we are confident that they are representative. Hence, we are specifying them in a numerical form in Table 1. We shall use them as a basis for discrimination between normal and pathological middle ears. This means that we shall consider 10% of ears with normal hearing but low compliance and 10% with normal hearing but high compliance as pathological. Since compliance changes appear to be more sensitive to middle-ear abnormalities than is hearing level, there is some justification in thinking that these ears may actually have minor defects. However, from the point of view of hearing, they must be considered normal and, from this point of view, the method will be in error 10% of the time on each side of the 80% range. The resistance changes are a less sensitive indicator of middle-ear pathologies, and we shall consider them only as an auxiliary indicator.

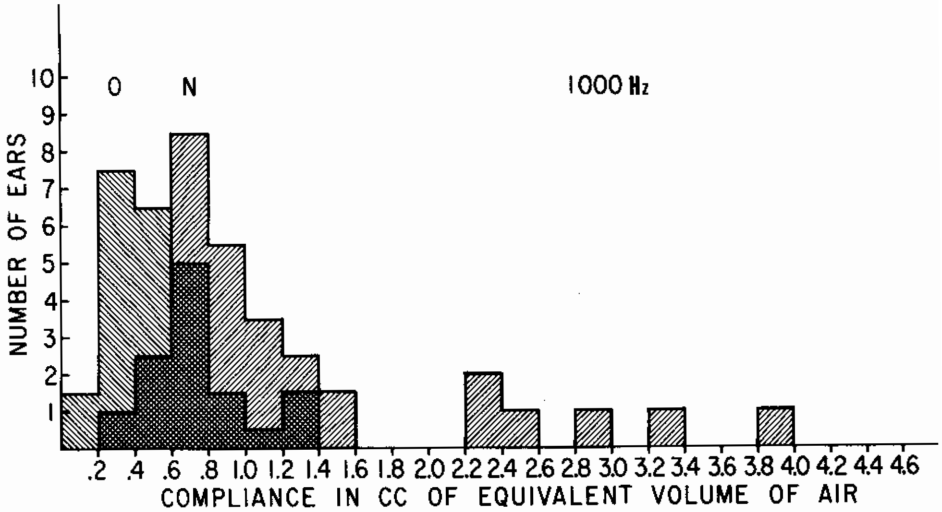


FIGURE 9. Compliance histograms at 1000 Hz of the same normal and otosclerotic populations as in Figure 8.

EARS WITH STAPEDIAL FIXATION

Because stapedial ankylosis occurs commonly in otosclerotic ears and is currently of great clinical interest, we investigated 24 patients with surgically confirmed stapedial ankylosis. The clinical bridge method was used throughout. Figures 8 and 9 show the compliance results in a histogram form. Figures 10 and 11 do the same for the resistance results. For comparison, the distribu-

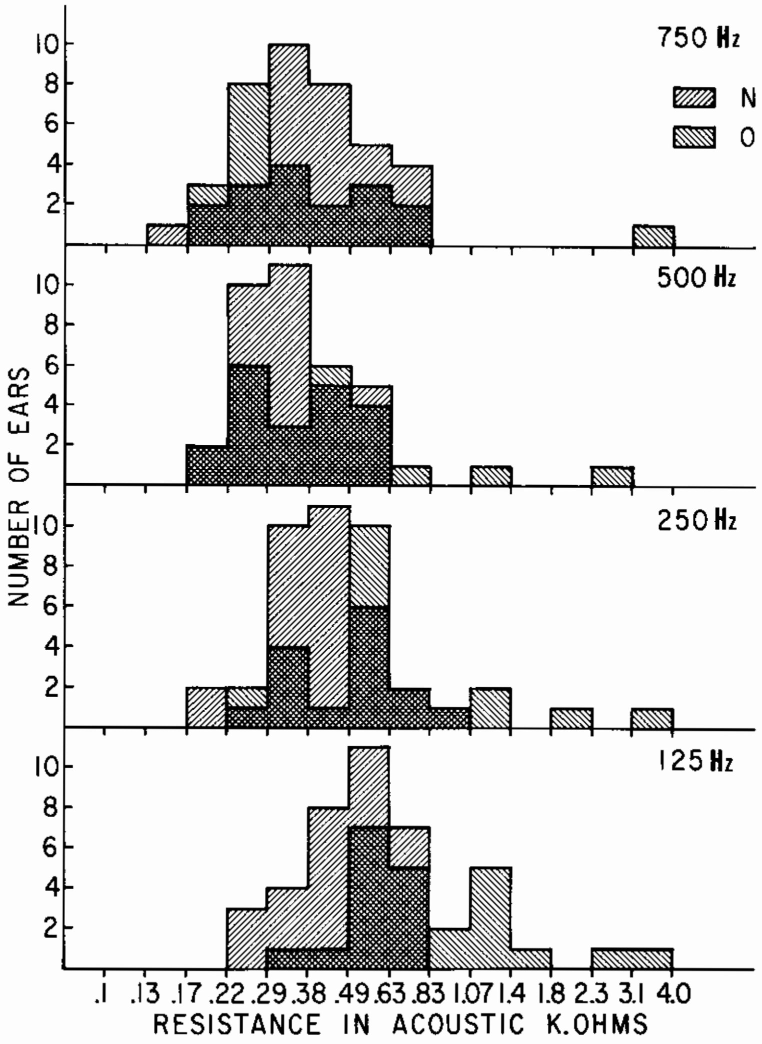


FIGURE 10. Resistance histograms of 33 ears with normal hearing, and of 24 otosclerotic ears.

tions obtained on the group with normal hearing also appear. It should be evident that the otosclerotic compliance population differs from that of the group with normal hearing at all tested frequencies. The overlap between the two populations is small except at 1000 Hz, in agreement with earlier results (Feldman, 1963, 1964). No such clear difference can be seen in resistance populations. Only at the lowest frequencies does the otosclerotic resistance tend to be somewhat higher than in normal ears. Note that the compliance is plotted on a linear scale. On this scale, the distributions are positively skewed, especially those belonging to the group with normal hearing. The resistance is plotted on a nonlinear scale resulting from the scale on the bridge dial. The distributions look almost normal. However, on a linear scale, they would be positively skewed.

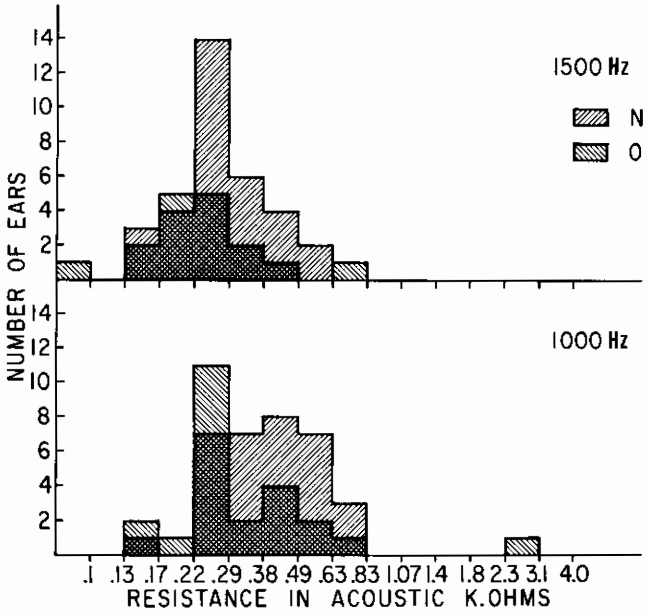


FIGURE 11. Resistance histograms of 33 ears with normal hearing, and of 24 otosclerotic ears, for higher frequencies.

The overlap between the compliance populations in Figures 8 and 9 is exaggerated by the choice of class intervals. When 80% ranges are drawn, as in Figure 12, they do not overlap, except at 1000 Hz. Consequently, fewer than 10% of ears with stapedial ankylosis would be mistaken for normal ears and vice versa. The same relationship may be expected to prevail between ears with stapedial ankylosis and sensori-neural hearing loss.

Because of the strong overlap in resistance values between the otosclerotic and normal populations, a plot of the 80% ranges would look rather obscure, therefore, we plotted only the medians in Figure 13. As we mentioned earlier,

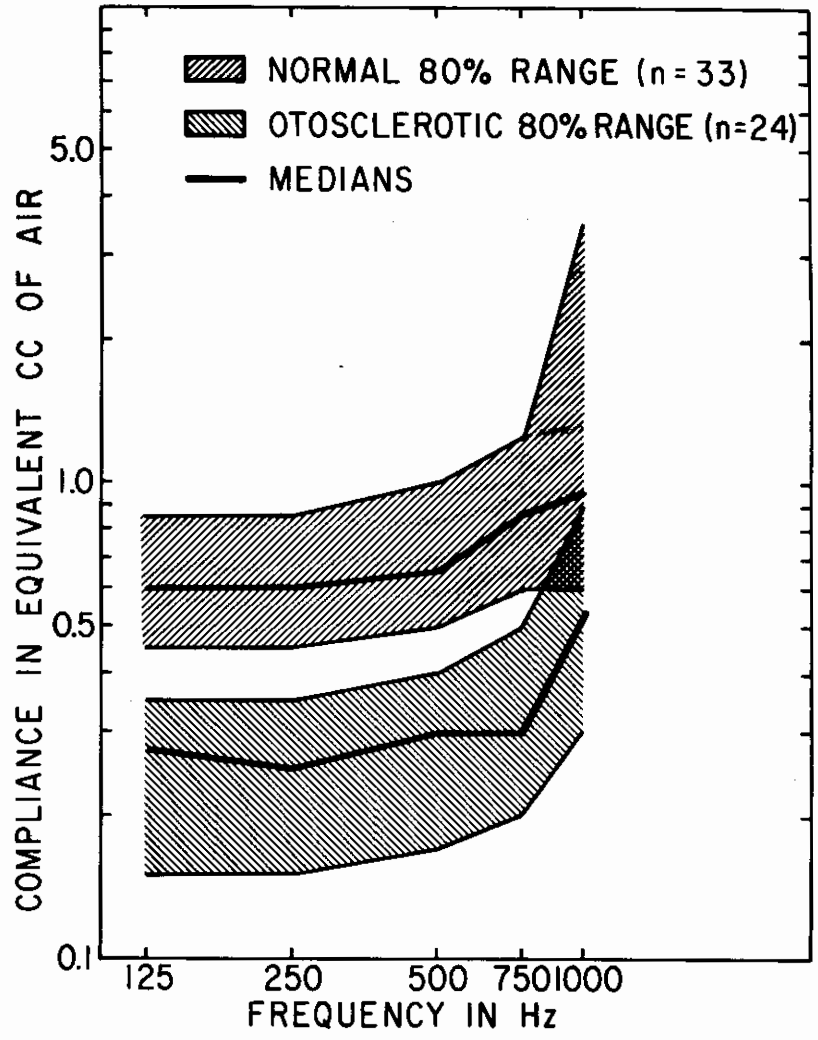


Figure 12. Median compliance values and 80% ranges of ears with normal hearing and with otosclerosis.

the otosclerotic resistance tends to be higher than the normal resistance at low frequencies. It decreases rapidly as the frequency increases. Whether this characteristic pattern has a diagnostic value remains questionable.

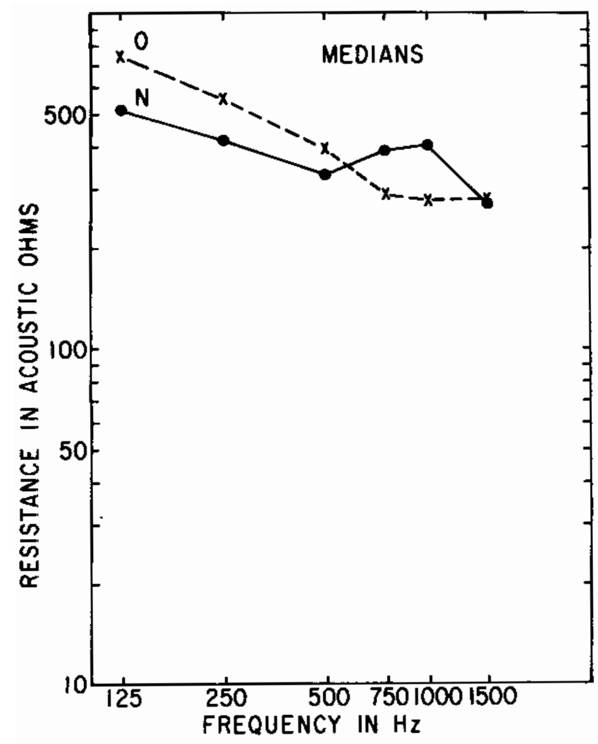
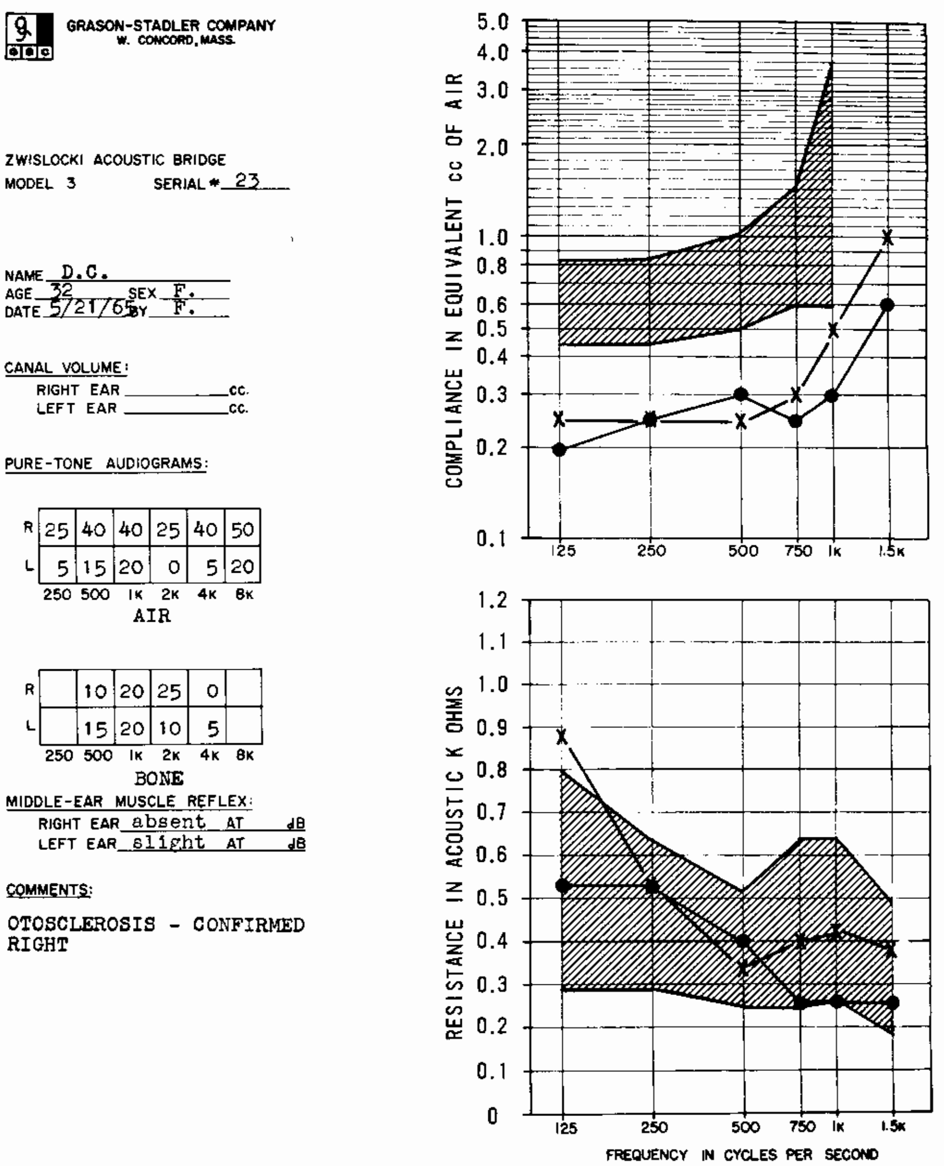


FIGURE 13. Median resistance values of 33 ears with normal hearing and of 24 ears with otosclerosis.

MISCELLANEOUS PATHOLOGIES

We did not have the opportunity of investigating sufficient numbers of patients with other middle-ear pathologies to warrant a statistical evaluation. Nevertheless, we could test enough of them to gain a clear impression of the associated impedance changes. A few examples we found particularly instructive are described in this section. Some of them, together with some additional ones, we have already mentioned in preceding articles (Zwislocki, 1957b, 1961, 1962, 1968; Feldman, 1963, 1964). The relevant audiometric and impedance data are plotted on standard clinical forms with indicated 80% ranges for normal compliance and resistance values.

The first two examples are of monaural hearing loss due to stapedial ankylosis. The audiometric and impedance data shown in Figure 14 belong to patient D.C. whose condition was initially diagnosed as unilateral otosclerosis in the right ear. The diagnosis was based mainly on audiometric results which showed a moderate hearing loss and an air-bone gap in the right ear but almost normal hearing with no air-bone gap in the left. The acoustic impedance examination revealed a bilaterally lowered compliance and a rapidly decreasing re-



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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME D.C.
AGE 32 SEX F.
DATE 5/21/65 BY F.

CANAL VOLUME:
RIGHT EAR ______ cc.
LEFT EAR ______ cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R	25	40	40	25	40	50
L	5	15	20	0	5	20

AIR

	250	500	1K	2K	4K	8K
R		10	20	25	0	
L		15	20	10	5	

BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR absent AT dB
LEFT EAR slight AT dB

COMMENTS:

OTOSCLEROSIS - CONFIRMED RIGHT

FIGURE 14. Compliance and resistance of a patient with "unilateral" otosclerosis. Shaded areas indicate 80% ranges of normal values.

sistance from low to high frequencies—characteristics compatible with stapedial ankylosis. A test of the acoustic middle-ear reflex showed no response in the right ear and a slight response in the left. Surgery confirmed the stapedial fixation in the right ear. The left ear has not been operated on, but a partial fixation must be suspected. A similar case of unilateral otosclerotic hearing loss is illus-

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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME C.A.
AGE 36 SEX M.
DATE 4/28/64 BY F.

CANAL VOLUME:
RIGHT EAR .60 cc.
LEFT EAR .60 cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R	10	10	25	5	15	15
L	50	55	60	45	55	55

AIR

	250	500	1K	2K	4K	8K
R		0	15	20	15	
L		-5	10	20	10	

BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR absent AT dB
LEFT EAR absent AT dB

COMMENTS:

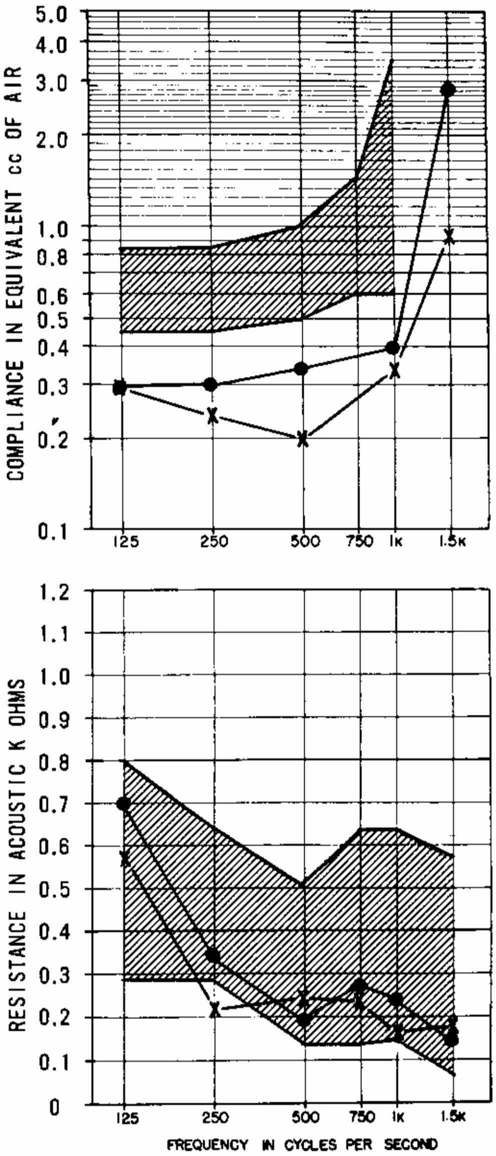

Figure 15. Compliance and resistance of a patient with "unilateral" otosclerosis.

trated in Figure 15. Patient C.A. was referred for a medicolegal consultation because of a suspected ossicular separation in the left ear, resulting from a blow to the head. Note the unilateral hearing loss with a pronounced air-bone gap. The impedance examination negated the initial diagnosis by showing a bilaterally lowered compliance and a rapidly decreasing resistance from low to high

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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME J.S.
AGE 50 SEX M.
DATE 5/9/66 BY F.

CANAL VOLUME:
RIGHT EAR .50 cc.
LEFT EAR .40 cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R	50	60	75	80	80	65
L	10	20	20	30	10	NR

AIR

	250	500	1K	2K	4K	8K
R		30	55	NR	50	
L		15	5	25	10	

BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR present AT dB
LEFT EAR present AT dB

COMMENTS:

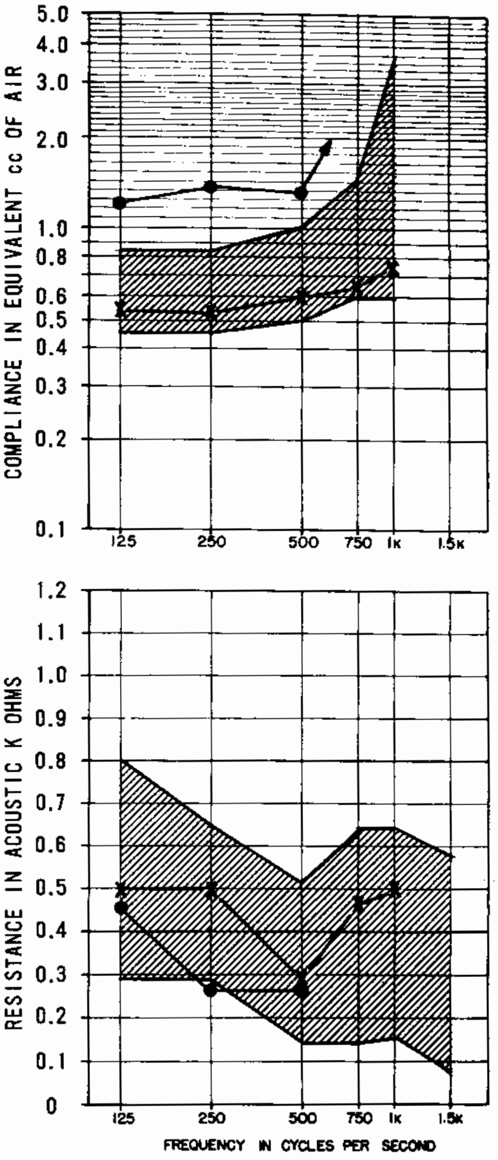
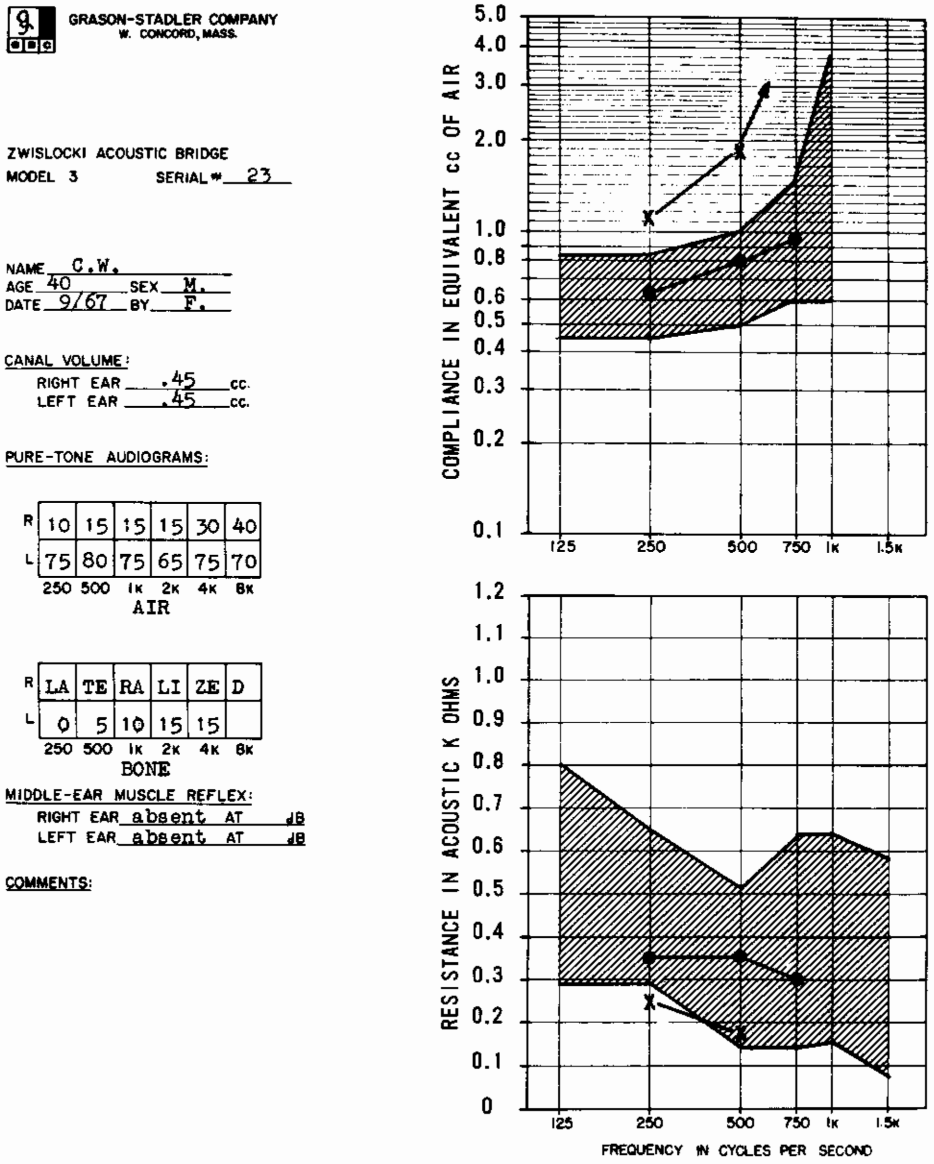


FIGURE 16. Patient with an incomplete ossicular separation in the right ear.

frequencies. Surgery revealed the presence of stapedial ankylosis in the left ear, in agreement with the results of impedance measurements.

From the two examples and other similar cases, we conclude that the acoustic compliance is a more sensitive indicator of stapedial fixation than are audiometric tests. Absence of a detectable muscle reflex in the middle ear provides



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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME C.W.
AGE 40 SEX M.
DATE 9/67 BY F.

CANAL VOLUME:
RIGHT EAR .45 CC.
LEFT EAR .45 CC.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R	10	15	15	15	30	40
L	75	80	75	65	75	70

AIR

	250	500	1K	2K	4K	8K
R	LA	TE	RA	LI	ZE	D
L	0	5	10	15	15	

BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR absent AT dB
LEFT EAR absent AT dB

COMMENTS:

Figure 17. Patient with a missing incus in the left ear.

corroborating evidence. Earlier, Klockhoff (1961) had noticed the sensitivity of the reflex to stapedial ankylosis. However, the reflex may still be present, although reduced in magnitude, when the compliance is substantially lowered.

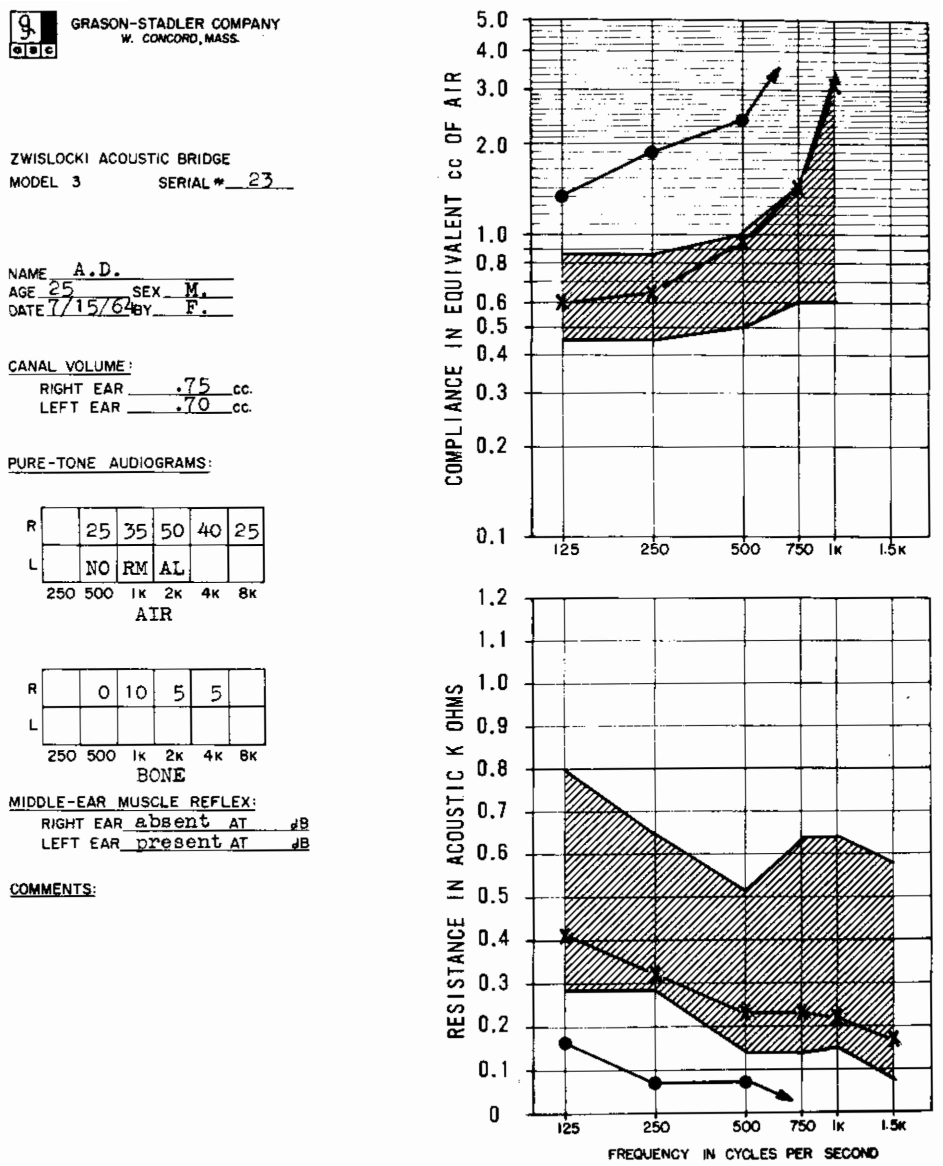
In addition to indicating stapedial fixation, the compliance determination provides a unique test for ossicular separation. This is illustrated by the following three examples. Patient J.S., whose audiometric and acoustic data are shown in Figure 16, incurred a skull fracture in 1941. The accident was followed by roaring tinnitus. He noticed no hearing loss until 10 years later. The audiometric results indicated a pronounced hearing loss of a mixed type in the right ear and a slight loss in the left ear. The acoustic tests revealed an increased compliance on the right side and normal on the left. The resistance was within the normal range in both ears, but was lower in the right ear. According to previous investigations (Zwislocki, 1957, 1961, 1962, 1968; Feldman, 1963, 1964), a high compliance and a low resistance are associated with ossicular separation. However, in the case at hand, two out of three resistance values were within normal bounds. Also, the muscle reflex could be detected in both ears. This speaks against ossicular discontinuity, except when it occurs at the level of the stapedial crura (Klockhoff, 1961; Feldman, 1963). Surgery of the right ear disclosed a fractured incus and a malleus pulled up in such a way that it made contact with the stapes through a remaining lenticular process. Apparently, the contact was not strong enough to provide a satisfactory sound transmission or keep the acoustic compliance within the normal range but was sufficient for a detectable stapedius reflex.

Patient C.W. (Figure 17) had a simple mastoidectomy of the left ear in his childhood. The eardrum appeared perfectly healed but hearing remained poor and appeared to become progressively worse. The audiometric examination showed a severe air-conduction loss with a practically normal bone conduction. The acoustic tests revealed a high compliance and a low resistance. There was no detectable muscle reflex. These results indicate ossicular separation. The operation disclosed a missing incus.

Patient A.D. (Figure 18) had a persistent bilateral secretory otitis as a child. There was a history of otosclerosis in his family. Audiometry showed a moderate air-conduction loss in the right ear with normal bone conduction. No muscle reflex could be detected on this side. It was present on the other. The absolute impedance tests disclosed a high compliance and a very low resistance in the right ear accompanied by normal values in the left ear. This clearly indicates an ossicular separation and militates against an ossicular fixation. Unfortunately, no operation was performed and the diagnosis remained unconfirmed.

Over the years we had the opportunity to test the acoustic impedance of more than a dozen ears with confirmed ossicular separation. They all showed a high compliance and a low resistance. At 750 Hz and above, the compliance values were usually beyond the range of the acoustic bridge. Earlier measurements with probe tubes (Zwislocki, 1957b, 1961, 1962) showed that, above 700 Hz, the reactance becomes positive. This means that the mass of the system predominates. We conclude that compliance values above the normal range indicate ossicular separation. Under these conditions, the resistance is low, usually below the 80% normal range.

The middle-ear muscle reflex is not detectable when the ossicular separation is complete and distal to the ossicular attachment of the stapedius muscle. How-



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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME A.D.
AGE 25 SEX M.
DATE 7/15/64 BY F.

CANAL VOLUME:
RIGHT EAR .75 cc.
LEFT EAR .70 cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R		25	35	50	40	25
L		NO	RM	AL		

AIR

	250	500	1K	2K	4K	8K
R		0	10	5	5	
L						

BONE

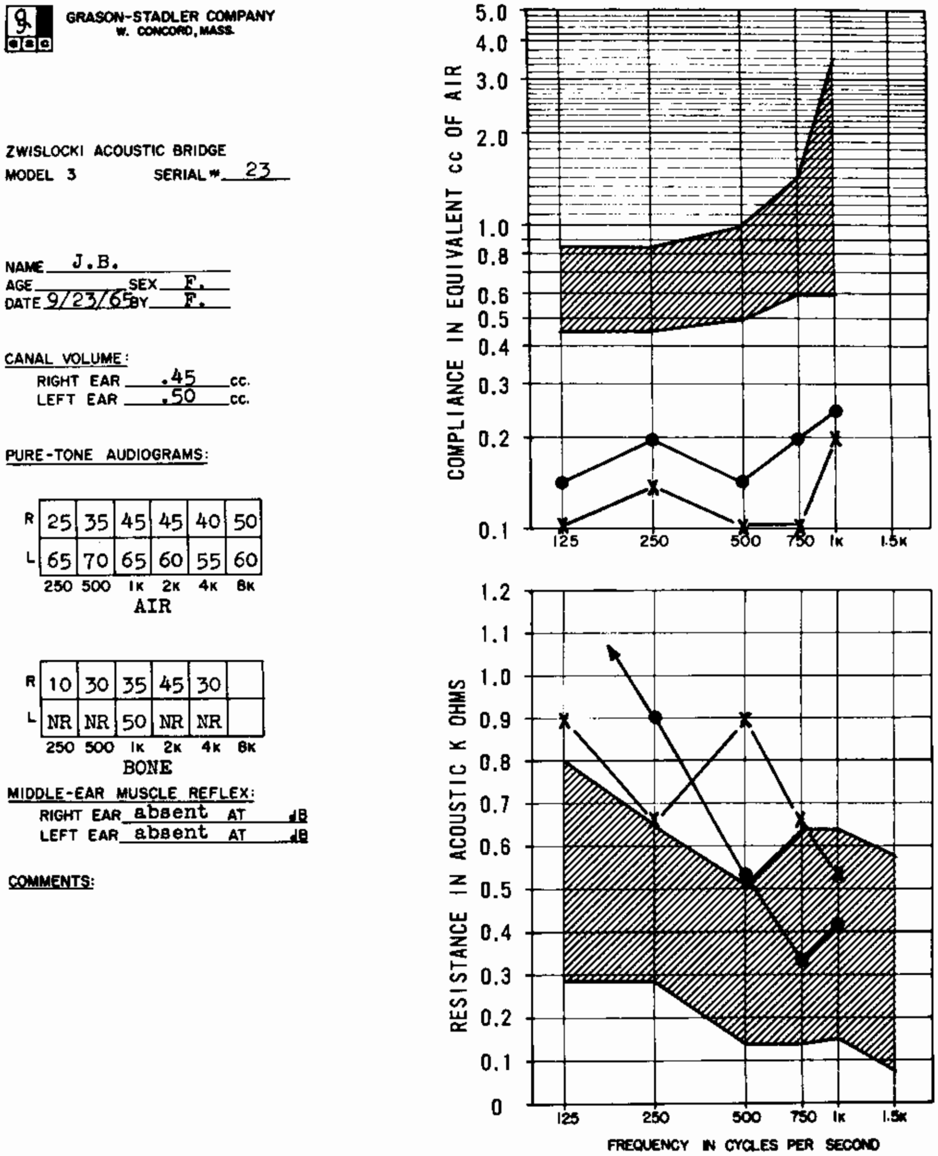
MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR absent AT dB
LEFT EAR present AT dB

COMMENTS:

Figure 18. Patient with a probable ossicular separation in the right ear.

ever, the reflex test does not discriminate between ossicular separation and fixation.

The following three examples deal with pathologies that produce extremely low compliances and extremely high resistances. Patient J.B. (Figure 19) was referred because of a possible otosclerotic involvement. The audiometric results



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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME J.B.
AGE ____ SEX F.
DATE 9/23/65 BY F.

CANAL VOLUME:
RIGHT EAR .45 cc.
LEFT EAR .50 cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R	25	35	45	45	40	50
L	65	70	65	60	55	60

AIR

	250	500	1K	2K	4K	8K
R	10	30	35	45	30	
L	NR	NR	50	NR	NR	

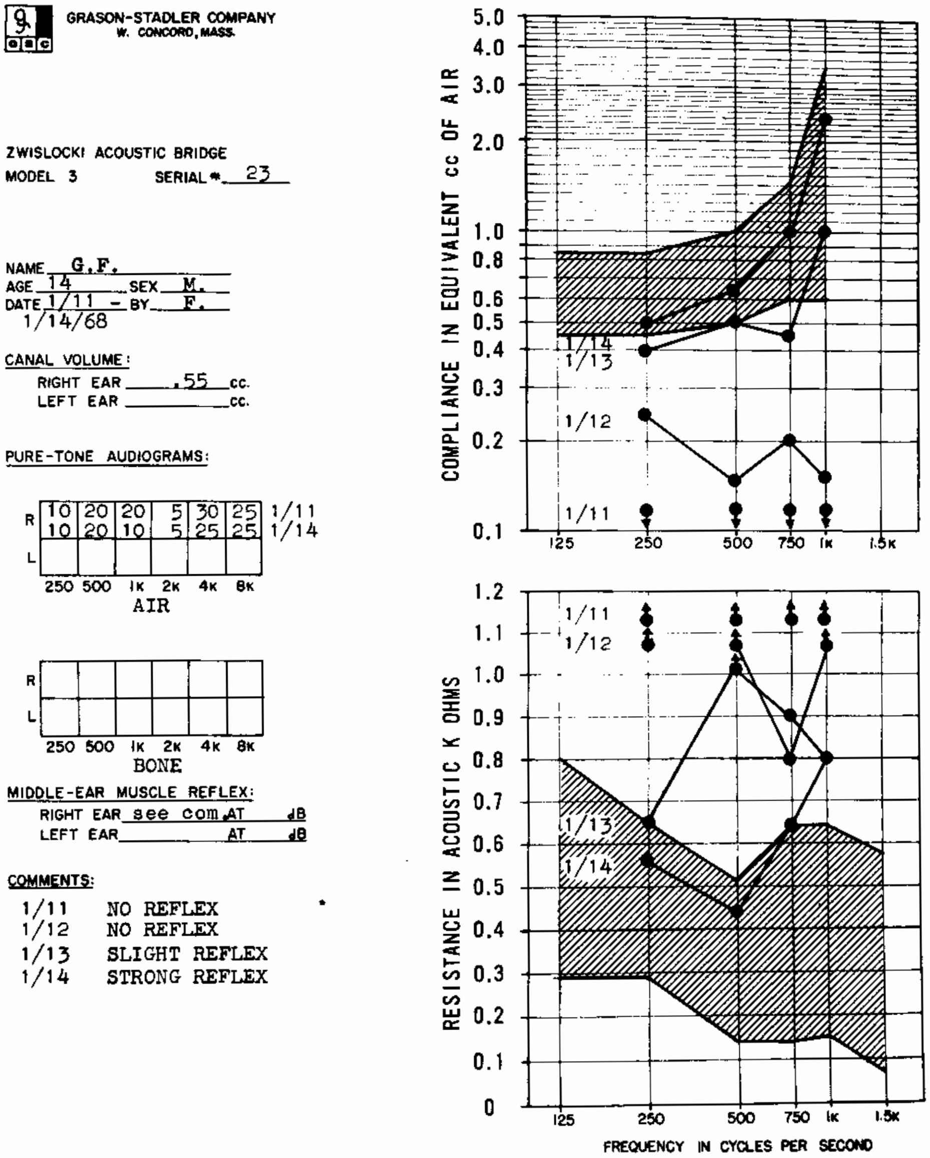
BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR absent AT ____ dB
LEFT EAR absent AT ____ dB

COMMENTS:

Figure 19. Patient with surgically confirmed massive middle-ear adhesions and mild stapedial ankylosis in the left ear and, probably, similar pathology in the right.

pointed to a sensori-neural hearing loss. No detectable acoustic reflex could be elicited, but this was not conclusive because of the pronounced hearing loss. However, the absolute impedance tests revealed a very low compliance, especially in the left ear, and a high resistance. On the basis of previous experience,



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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME G.F.
AGE 14 SEX M.
DATE 1/11 - BY F.
1/14/68

CANAL VOLUME:
RIGHT EAR .55 cc.
LEFT EAR ____ cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K	
R	10	20	20	5	30	25	1/11
	10	20	10	5	25	25	1/14
L							

AIR

	250	500	1K	2K	4K	8K
R						
L						

BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR see com. AT ___ dB
LEFT EAR ____ AT ___ dB

COMMENTS:

1/11	NO REFLEX
1/12	NO REFLEX
1/13	SLIGHT REFLEX
1/14	STRONG REFLEX

FIGURE 20. Course of compliance and resistance changes during an attack of acute otitis media.

it was suggested that massive adhesions to the large ossicles were present. Surgery on the left ear uncovered a mild stapedial ankylosis and massive middle-ear adhesions.

We were able to perform a sequence of acoustic tests on patient G.F. (Figure 20) during an acute attack of otitis media. On January 10, the patient be-

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ZWISLOCKI ACOUSTIC BRIDGE
MODEL 3 SERIAL # 23

NAME J.B.
AGE 20 SEX M.
DATE 6/12/67 BY F.

CANAL VOLUME:
RIGHT EAR .70 cc.
LEFT EAR .75 cc.

PURE-TONE AUDIOGRAMS:

	250	500	1K	2K	4K	8K
R	35	40	40	35	50	35
L	5	5	10	20	20	5

AIR

	250	500	1K	2K	4K	8K
R	NORMAL					
L	NORMAL					

BONE

MIDDLE-EAR MUSCLE REFLEX:
RIGHT EAR absent AT dB
LEFT EAR absent AT dB

COMMENTS:

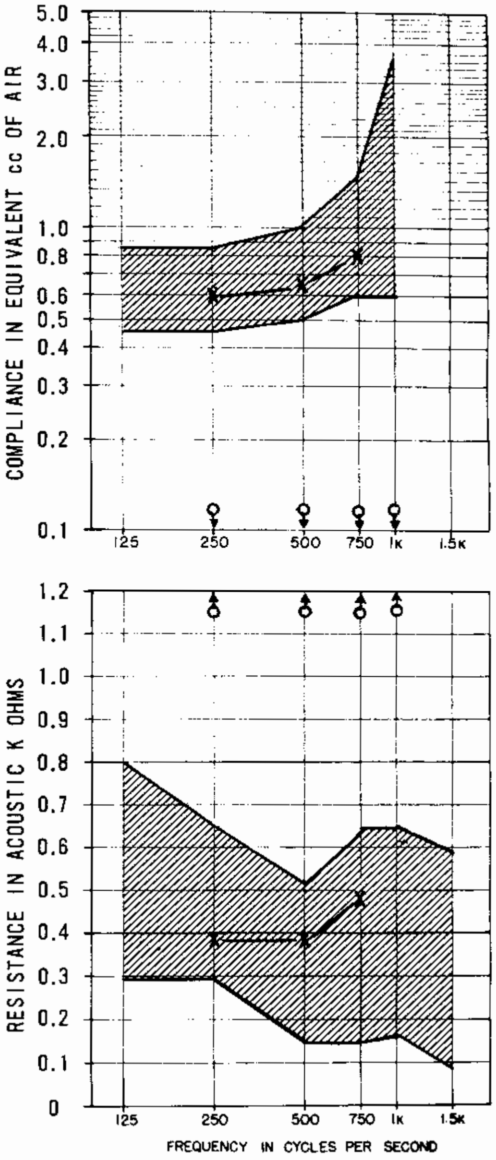

Figure 21. Patient with a severely retracted eardrum in the right ear.

gan to suffer from earache on the right side, and otoscopic examination revealed inflammation of the superior-posterior portion of the tympanic membrane. On the second day, otoscopic examination revealed middle-ear fluid, and acoustic examination showed an extremely low compliance, an extremely high resistance, and no detectable muscle reflex. The patient was put under medication. Acoustic measurements on January 12 showed a somewhat higher but still very low compliance and a somewhat lower but still very high resistance. No muscle reflex could be detected. On the following day, the subjective symptoms began to recede and, simultaneously, the compliance became almost normal. The resistance was still high. A small but detectable muscle reflex appeared. On the fourth day after medication had started, the compliance became normal, although the resistance remained somewhat high. The muscle reflex was easily detectable.

From this and other cases of acute and serous otitis media (Feldman, 1964), we have concluded that they are associated either with a very low compliance, a very high resistance, and no detectable muscle reflex, or with a moderately low compliance, high resistance, and a weakly detectable reflex. Which set of symptoms is encountered depends on the phase and gravity of the disorder.

The last example refers to patient J.B. (Figure 21), who sustained a severe head injury with an ensuing moderate hearing loss in the right ear. The hearing level in the left ear remained almost normal, and the bone conduction was found to be normal bilaterally. The otoscopic examination revealed a strongly retracted right eardrum. The acoustic examination showed an extremely low compliance and an extremely high resistance on the right side with normal values on the left. No acoustic reflex could be detected in the right ear, while it was normal in the left. These acoustic symptoms confirm our earlier observation that severe eardrum retractions are associated with extremely low compliance and extremely high resistance values and absence of a detectable middle-ear reflex.

V

ACOUSTIC SYMPTOMATOLOGY

The diagnostic experience with acoustic impedance measurements is still limited and many more studies will be necessary for the evaluation of its full potential. Nevertheless, definite conclusions are possible with respect to certain middle-ear pathologies. This is particularly true with respect to stapedial ankylosis and ossicular separation. Figure 22 shows the compliance values of all the ears with normal hearing, stapedial ankylosis, and ossicular separation that we tested in this study by means of the clinical method. Clearly, there is little overlap between the normal and otosclerotic populations on the one side, and no overlap between the normal population and that with ossicular separation on the other. In this study, we investigated only four cases of surgically confirmed ossicular separation, but similar results have been obtained previously. It is noteworthy that the lowest compliance of an ear with ossicular separation is twice the highest compliance of an ear with stapedial ankylosis. As a consequence, the method permits a good discrimination between the two pathologies. Insofar as the discrimination between normal ears and ears with ossicular separation is concerned, note the very large compliance of the latter at 750 Hz. At this frequency, it is more than twice the highest compliance encountered in a normal ear.

As mentioned before, the discrimination between normal ears and ears with stapedial fixation cannot always be achieved by means of absolute impedance measurements. A 10% error in either direction appears unavoidable. However, the problem may be almost completely resolved with the help of the middle-ear muscle reflex. We used the reflex routinely on pathological ears. Because of the limitations of the test, the absence of the reflex is often inconclusive, but its presence practically excludes the possibility of a stapedial fixation. Our experience has been that, using both the absolute impedance and the reflex, the discrimination between a normal middle ear and an ear with stapedial fixation is nearly always possible.

Our general experience with the clinical impedance measurements is summarized in Table 2. Except in the case of sensori-neural hearing loss, the table refers to mechanical changes in the middle ear, which directly control the magnitude of the impedance components. Each of these changes may be produced by more than one disease process. In order to decide which has caused the par-

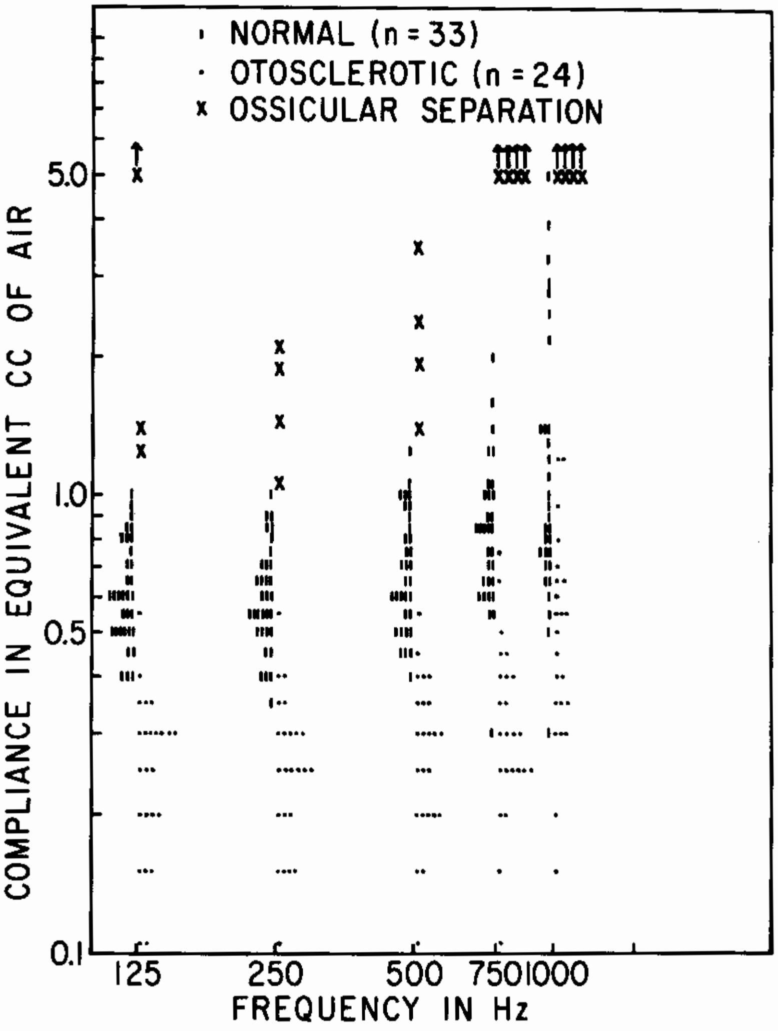

FIGURE 22. Individual compliance values of ears with normal hearing, otosclerosis, and ossicular separation.

ticular malfunction, additional sources of information are necessary. The acoustic method used by us provides only one part of the evidence. In that, it is not unique. A full medical diagnosis is almost always based on several kinds of information.

Scrutiny of Table 2 shows that the acoustic reflex is undetectable in almost all middle-ear disorders that lead to hearing loss. Consequently, it does not discriminate among these disorders. Fracture of the stapedial crura is one exception. On the other hand, the absolute impedance, as expressed in terms of compliance and resistance, discriminates among three categories of middle-ear malfunctions: ossicular separation, stapedial ankylosis, and fixation of the large ossicles. Whether the latter occurs because of adhesions, eardrum retraction, or

TABLE 2. Partial acoustic symptomatology.

	Compliance				Resistance			Reflex		
Pathology	*Very Low*	*Low*	*Normal*	*High*	*Low*	*Normal*	*High*	*Absent*	*Weak*	*Normal*
Ossicular Separation										
Distal to Stapedius				×	×			×	(×)	
Proximal to Stapedius				×	×					×
Stapes Ankylosis										
Complete		×				×	(×)	×		
Partial		×				×		×	(×)	
Massive Adhesions	×						×	×		
Retracted Eardrum	×						×	×		
Middle-Ear Fluid	×	(×)				(×)	×	×	(×)	
Sensori-Neural Hearing Loss			×			×				×

fluid, cannot be decided on the basis of acoustic measurements. However, eardrum retraction and fluid can usually be detected in otoscopic examination.

Another limitation of the acoustic method, which includes both absolute and relative impedance measurements, is not apparent in Table 2 but must be strongly emphasized. In cases of compounded disorders, the method only indicates the pathology closest to the eardrum. For instance, when ossicular separation occurs together with stapedial ankylosis, the latter cannot be detected. Furthermore, stapedial ankylosis is masked effectively by massive adhesions to the large ossicles.

In general, the acoustic measurements are more sensitive to changes that occur near the eardrum than to changes that occur proximally to the incudostapedial joint. On the other hand, the former tend to produce less hearing loss than the latter. The combination of the two trends may be diagnostically useful. For instance, a small hearing loss accompanied by a very low compliance is indicative of middle-ear fluid or eardrum retraction. A substantial hearing loss accompanied by a very low compliance may be indicative of a combination of stapedial ankylosis and middle-ear adhesions.

The acoustic impedance measurements do not solve all the problems of middle-ear diagnostics but they appear helpful in several respects. They provide corroborating evidence for the often uncertain results of bone-conduction tests, and they discriminate among middle-ear malfunctions better than any other known method. In addition, they have yielded some unexpected dividends. Abnormally patent Eustachian tubes could be detected by observing the test tone of the bridge. When the latter is balanced, the tone intensity changes rhythmically with breathing. Of course, the state of the Eustachian tube can be tested more directly by executing the Valsalva maneuver during impedance measurements. In one case, the impedance examination led to the discovery of a glomus jugulare. It produced an oscillation of the test tone in synchrony with the arterial pulse. Finally, numerous instances of collapse of the ear canal under the earphone in pure tone audiometry became evident when the ear was undergoing impedance measurement for an unexplained conductive component of a hearing loss.

VI

SUMMARY

The first part of this report reviews the clinical usefulness and the methods of acoustic impedance measurements at the ear. It describes two basically different kinds of instrumentation that may be used for measurement of absolute impedance parameters as well as of impedance changes. Advantages and limitations of the methods now in use are pointed out. The conclusion is reached that measurements of absolute impedance are more generally applicable than measurements of impedance changes, especially when the changes are produced by the acoustic middle-ear reflex. However, in a small percentage of cases, absolute impedance determinations are not sufficient for differentiating between normal and pathological middle ears. In these cases, testing the stapedius reflex usually provides a sufficient corroborating evidence. An easily detectable reflex is a reliable index of a normal middle-ear function, except when the ossicular chain is separated at the level of the stapedial crura. Conversely, absence of a detectable reflex does not necessarily indicate a middle-ear pathology. The absence can be due to factors outside the middle ear. Tests relying on pressure changes in the ear canal are useful in the presence of a malfunctioning Eustachian tube, but otherwise cannot provide more information than can measurements of absolute impedance.

A subsequent section describes two technical variants of acoustic bridge measurements. In one, called the clinical method, the bridge is held in the ear canal by hand, and the test tone is monitored by ear; in the other, called the laboratory method, the bridge is held by means of an adjustable holder, and the test tone is monitored with the help of a microphone and voltmeter assembly. Both methods yield comparable results.

Comparison of three series of measurements performed by different investigators under different conditions leads to the conclusion that the bridge measurements are highly reliable. This conclusion is strengthened by repeat measurements on one group of subjects. The error of measurement is considerably smaller than the intersubject variability. This is particularly true for the acoustic compliance.

Absolute impedance measurements at the eardrum depend on an accurate knowledge of the volume of air enclosed in the ear canal. Inaccurate volume measurements can considerably increase the scatter of individual data and decrease the diagnostic value of the method.

Median compliance and resistance values and 80% ranges are given for a population of 33 ears with normal hearing. The ratio of the highest and lowest values within these ranges is on the order of 2 for the compliance and on the order of 2.5 for the resistance, in agreement with the results of earlier studies. For practical purposes, values below and above the 80% ranges are considered abnormal.

Corresponding statistical measures for the compliance and resistance of 24 ears with stapedial ankylosis show that the median compliance is approximately half the median normal compliance and that there is little difference in resistances. The 80% compliance range for otosclerotic ears does not overlap with the corresponding range of normal ears. We conclude, therefore, that compliance measurements are useful in discriminating between normal and otosclerotic ears. On the basis of these measurements alone, less than 10% of normal ears would be mistaken for otosclerotic ears and vice versa. The same conclusions hold for the diagnostic differentiation between sensori-neural disorders and otosclerosis, since the former do not affect the middle ear. We suggest that, in uncertain cases, corroborating evidence may be obtained from the middle-ear reflex. On the basis of our experience, the absolute impedance measurements in conjunction with reflex tests permit a clear differentiation between otosclerotic and normal middle ears in practically all instances.

Impedance and audiometric data are given for individual ears with various middle-ear pathologies. The compliance in ears with ossicular separation is considerably higher than in normal ears, and the resistance is below the normal 80% range. These ears can be differentiated clearly from otosclerotic ears on the basis of absolute impedance measurements.

Ears that have massive adhesion to the two large ossicles, fluid, or a retracted eardrum exhibit extremely low compliance and high resistance. They constitute a separate population from the point of view of absolute impedance measurements. In general, middle-ear changes that directly affect the mobility of the eardrum or of the two larger ossicles have a pronounced effect on the impedance values but produce only small or moderate degrees of hearing loss. On the contrary, fixation of the stapes has only a moderate effect on the impedance but a more substantial effect on the hearing level. These relationships could prove to be diagnostically useful.

Our study of cases of "unilateral otosclerosis" indicates that the acoustic compliance is more sensitive to partial stapedial fixation than is the hearing level. Because of this, impedance measurements may have a prognostic value.

The results of absolute impedance measurements and of reflex tests are summarized in a table of acoustic symptomatology. The table indicates that, on the basis of the acoustic impedance measurements alone, it is possible to distinguish among four kinds of auditory malfunctions: ossicular separation, stapedial fixation, fixation of the two larger ossicles, and sensori-neural disorders. Ossicular separation can be localized to a distal or proximal portion of the ossicular chain relative to the stapedius attachment.

Not included in the table are patients in whom impedance examinations helped to discover abnormally functioning Eustachian tubes or a glomus jugulare. In the latter instance, the test tone in the impedance bridge was found to change rhythmically with the arterial pulse. We have also omitted cases in which impedance examinations helped discover a collapsed ear canal during air-conduction testing.

VII

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