Calibration and Working Condition of 100 Audiometers

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ACCURACY in determining auditory thresholds is crucial for identifying persons with decreased hearing acuity, particularly in view of the ever-expanding growth of hearing conservation programs, diagnostic clinics, and the increased use of industrial and military audiometry. The results of hearing tests are important in determining the necessity for medical treatment, educational placement, acceptability for employment or military service, and the advisibility of a hearing aid.

The accuracy of hearing tests is directly related to a number of factors, such as the training and experience of the operator, environmental noise, and the cooperation and attention of the subject. Of equal importance is the state of calibration of the audiometer. Calibration is particularly relevant as the accuracy of an audiometer, like all electronic equipment, is subject to damage, aging, component malfunction, and change due to normal use.

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It is generally agreed that the calibration of audiometers should be checked periodically, although there is no agreement as to how frequently they should be checked.

Two sets of specifications, developed in the 1950's, describe the characteristics that are considered essential for audiometers. The specifications adopted by the Council on Physical Medicine and Rehabilitation of the American Medical Association (AMA) and the American Standards Association (ASA) were completed at approximately the same time, and several members of each association served concurrently on both committees. The two sets of specifications do not differ appreciably except that those of the ASA are slightly more detailed. The two organizations have adopted specifications for pure tone audiometers for screening purposes (*1*), audiometers for general diagnostic purposes (*2*), and speech audiometers (*3*). (Standards approved as ASA standards are now designated as USA standards; there is no change in the index identification or technical content.)

In December 1963 the committee on conservation of hearing of the American Academy of Ophthalmology and Otolaryngology voted to adopt the International Organization of Stand-

ardization (ISO) specifications (*4*) for pure tone audiometers (R–389), to become effective January 1, 1965. Davis and Kranz (*5*) explain in detail the differences between the international and the American specifications as well as the advantages and disadvantages of both sets of specifications.

An excellent review of the calibration procedures and some of the theoretical implications may be found in Corliss and Snyder (*6*). For additional information on specific standards, see Burkhard and Corliss (*7*), Cox and Bilger (*8*), and Wright (*9*). Martens (*10*) has outlined calibration techniques and described changes that may occur.

To date the few studies considering the actual state of calibration of audiometers have dealt primarily with new or stock audiometers. Morrical and co-workers (*11*) examined 10 stock audiometers manufactured by several firms in conjunction with the establishment of the acoustical and electrical requirements set forth by the AMA Council on Physical Medicine and Rehabilitation. They concluded that the overall performance of the 10 audiometers was satisfactory and that the requirements set forth by the AMA were not too stringent. There were, however, several instances in which the audiometers failed to meet standards, primarily in the intensity interval and intensity ranges for air conduction and in the sound pressure output of the air conduction receivers.

In another report (*12*), audiometers were evaluated in response to a request from the armed services. In citing the shortcomings of audiometers, the authors reported (*12a*):

> From inquiry among users of audiometers, both civilian and military . . . (we have) . . . found widespread complaints concerning many instruments. The complaints typically have to do with breakdown, difficulties of service and repair, inaccuracy of output (sound pressure levels), and difficulties of calibration and recalibration. From military users the chief complaint is simply that commercial audiometers are not rugged enough to stand up under the stresses of military transportation and use. Civilian users complain that service is slow and often inadequate when repair or recalibration is indicated.

Eagles and Doerfler (*13*) examined six audiometers to be used in a research study on hearing levels of children. Five audiometers were used initially and the sixth was purchased later as a spare. On the first calibration, all five audiometers failed to meet the ASA specifications in the following ways (*13a*):

> Interrupter click on termination of tone; acoustic radiation from audiometer chassis; intensity and frequency changes at onset and termination of signal tone; extraneous signals at certain frequencies; erratic earphone response; frequencies outside the 5% tolerance of the American Standard Specification; rms (root mean square) sound pressure errors of certain earphones greater than the tolerance limits of 4.0 dB at the test frequency of 2000 cps and lower, and 5.0 dB at the test frequencies above 2000 cps; variation in the sound pressure output greater than 2 dB as specified in the American Standard Specification when line voltage was varied from 105 to 125 volts; tone interrupter showing rise and decay times of tones outside of specifications; overshoot of tone outside specifications; attenuator linearity outside the tolerance limit of plus or minus 1.5 dB at 10 to 5, and 5 to 0 steps; and tests of purity of test tones showing the sound pressure levels of the fundamental to be less than 25 dB above any harmonic at certain frequencies.

The audiometers were sent back to the manufacturer for correction; upon return, only one met the specifications. On the third calibration, three audiometers met the specifications, but the fifth had to be returned for additional calibration.

The audiometers in the Eagles and Doerfler study (*13*) were continuously monitored by an acoustics laboratory—a facility not generally available to audiometer users. During the 21 months when the data were collected, only four audiometers remained within specifications for short continuous periods: one for 8 months, one for 4 months, one for 3 months, and one for only 2 months.

Referring to the same audiometric problems, Eagles and co-workers observed (*14*).

> The point to be made in this connection is that because an audiometer has just been received from the manufacturer, there is no guarantee that it meets the specified standards.
>
> The audiometers were of a type that has been widely used throughout the country and were produced by a company that cooperated fully in complying with its guarantee that the audiometers meet the American Standard Specification. It is emphasized that the experience with audiometer performance, as described here, is not unique to the make of audiometer used in the study.
>
> Experience gained in getting the audiometers to meet the specification demonstrated the need for compre-

hensive calibration and repair facilities which would be easily and quickly available.

Citing such studies, Catlin and Glackin (*15*) maintained: "The experiences . . . with contemporary audiometers in carefully controlled studies have shown that many of these instruments are inaccurate, unstable, or poorly constructed. Accordingly, a critical scrutiny of audiometer design principles appears to be in order."

Harris' procedure (*16*) for electroacoustical calibration of audiometers recommended initial calibration in the field, with the audiometers referred on a periodic basis to a secondary center serving a fairly large geographic area. The secondary centers would be under the supervision of a primary center, which would also disseminate information on current research, initiate research, and otherwise assist in bringing about improvements in current methods.

Our study was undertaken because of the scarcity of information on the calibration accuracy of audiometers in use. Previous projects had limited their scope primarily to new or stock audiometers. The purpose was to obtain specific information on the calibration and general operating conditions of a large number of audiometers used in various hearing programs and to determine the need for and frequency of routine checks of calibration accuracy and operating conditions of the instruments.

Procedure

Selection of Audiometers

The project sample consisted of 100 audiometers, selected at random from various sources in North Carolina, that we evaluated over a period of 3 years for accuracy of calibration and general operating condition. We tested 98 audiometers that were in general use and evaluated two as they arrived from the manufacturer. In an attempt to evaluate the units as they actually performed in the field and to reduce any damage that might be caused by shipment, we required the owners to insulate the units carefully and transport them to the laboratory by car.

After completing a pilot study to standardize procedures, we used the first 100 audiometers brought to the laboratory by 11 categories of agencies or operators. Most instruments were obtained from frequent users of audiometers, such as hearing and speech centers, public health departments, and public school systems. The units represented 30 models from eight manufacturers. The following list gives the distribution of audiometers among the various owners.

Owners	*Number of audiometers*
Health departments	28
Public school systems	26
Physicians	8
Hospitals	3
College or university teaching programs	6
Hearing and speech centers	17
Veterans' Administration	3
Military	1
Industry	1
Hearing aid dealers	4
Other diagnostic centers	3
Total	100

Equipment

All measurement equipment (fig. 1), including the audiometer being tested, was located on a laboratory bench outside an Eckel 9-cubic-foot anechoic chamber. The standard microphone, a Bruel and Kjaer (B. & K.) type 4132 with a No. 2613 cathode follower, and a National Bureau of Standards (NBS) 9A 6-cubic-centimeter coupler were suspended with elastic cord in the center of the anechoic chamber. The cathode follower was connected to the B. & K. type 2603 microphone amplifier that had a Spencer-Kennedy Laboratories (SKL) model 302 no-loss variable filter, which was used in the external filter switch position. The output of the microphone amplifier was bridged by the following monitoring instruments: Tektronix 502–A oscilloscope with C–12 camera, Beckman model 7361 electronic counter, Hewlett-Packard 302–A wave analyzer, and General Radio Co. type 1521–A graphic level recorder.

The graphic level recorder was mechanically coupled to a General Radio Co. model 1304–B beat frequency oscillator, which in conjunction with a United Transformer Corp. type LS–34 matching transformer (600 to 10 ohms) was used to plot the characteristics of the various earphones.

We checked the microphone calibration at regular time intervals with the B. & K. type 4142 microphone calibrator. The B. &. K. cathode follower was connected to the amplifier with an unmodified factory cable. All other wiring was installed free of ground loops and with an insignificant resistive loss. Weston model 433 alternating current voltmeter and General Radio Co. model W-5 Variac were used to measure and control line voltage.

Calibration Procedure—Nontechnical Data

When we received an audiometer for calibration, we recorded two sets of information, one technical and one nontechnical.

The nontechnical data consisted of informatio from the owners or users on purchase date, last calibration date, who calibrated the instrument, type of service involved, and the person who had major responsibility for operating the audiometer. All 100 units arrived with model and serial numbers intact. The earphones rarely had serial numbers, and we assigned these by inscribing the audiometer serial number and a notation of left or right on the back of the earphones. If the earphones were mounted in circumaural devices, we replaced these devices with type MX 41 A/R cushions before we made the measurements.

Calibration Procedure—Technical Data

We examined the audiometers individually to determine how well they met the standard specifications and the claims of the manufacturer. We recorded other data, not specified in either category, to clarify certain interactions revealed during the measurements.

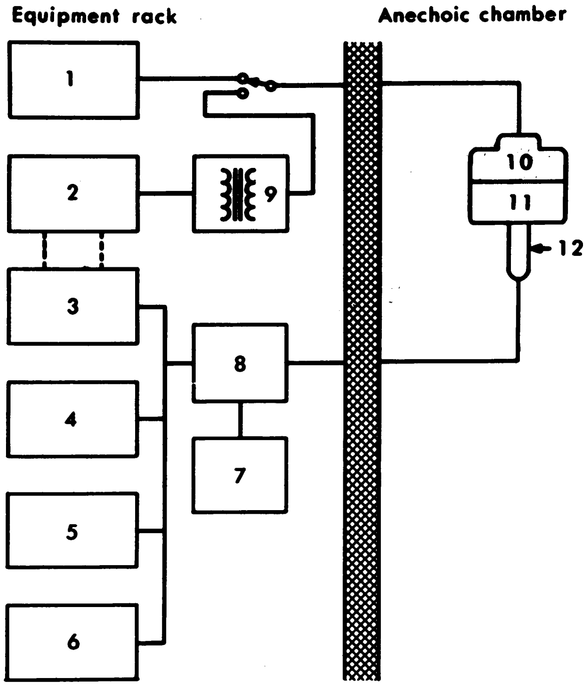
If possible, the measurements were made by using the sound pressure level output of the earphones rather than the audiometer terminal voltage reading.

We used the following routine procedures in the same sequence on each audiometer:

1. After a warmup of 30 minutes at the recommended line voltage, we checked the operating condition of the audiometer and made notations concerning its appearance and extent of wear.

2. Before any external connections were made that could cause a ground contact, we tested the unit for shock hazards.

Figure 1. Equipment interconnections used in calibration



1. Test audiometer.
2. General Radio 1304–B beat frequency oscillator.
3. General Radio 1521–A graphic level recorder.
4. Tektronix 502–A oscilloscope and C–12 camera.
5. Beckman 7361 electronic counter.
6. Hewlett-Packard 302–A wave analyzer.
7. Spencer-Kennedy Laboratories 302 variable filter.
8. Bruel & Kjaer 2603 microphone amplifier.
9. United Transformer Corp. LS–34 matching transformer.
10. Test earphone.
11. National Bureau of Standards 9A 6 cc. coupler.
12. Bruel & Kjaer 4132 microphone and 2613 cathode follower.

3. After serial identification numbers were assigned to the earphones, we removed them and placed them on the NBS–9A coupler. We dismantled the audiometer only to the extent that the plugs could be reached. Occasionally this necessitated removing several older models from their cabinets.

4. After we placed the earphones on the NBS–9A coupler, we positioned them so that a 125-Hertz tone produced the maximum output. If sufficient output could not be realized with proper positioning, we replaced the MX 41 A/R cushion. We used a 400-gram weight, insulated from earphone screw terminals, to maintain the proper phone coupler pressure.

After these four steps were completed, all tests requiring sound pressure level outputs

were performed. A description of each test and the equipment tested follows:

Earphone Cushions and Cords. The general condition of the cushion was determined by visual inspection. We judged consistency by feeling for resiliency and by observing sound leakage when the instrument was placed on the standard coupler. Damage from cleaning agents was noted.

We inspected the cords visually and aurally by feeding a 1000-Hertz tone to each earphone in separate tests. A listener seated in a quiet room performed average head and body movements; all extraneous noises were noted.

Dials. Each dial was checked to determine whether it functioned as indicated. Attenuators were checked between upper and lower limits for proper alinement. The maximum audiometer levels indicated by the manufacturers were compared with the maximum output, and any dial slippage was noted.

Speech. A speech channel in the audiometer was judged to be satifactory if a meter was furnished to produce, at the recommended deflection, a sound pressure level in the earphone coupler 6 decibels above the calibrated pure tone 1000-Hertz output at an attenuator setting of 75 decibels sensation level. A speech audiometer was classified as unsatisfactory if no meter was present to indicate speech input levels and, consequently, output levels.

Shock Hazard. Voltage was measured directly between an earth ground point and the front panel of the audiometer. Whenever a line isolation transformer was not provided in the audiometer, measurement was made between ground and earphone ground as well as the front panel. The alternating current voltmeter was used with an external shunting resistor of 1500 ohms.

Attenuator Noise. Wiper arm contact noise was noted by rotating the attenuator dial through its entire range while listening to the 250-Hertz tone from the earphones. Spurious noises or interruptions of tone were noted.

Rise and Fall Time. Using the measurement for sound pressure level output, the investigators observed the output of the condenser microphone on the oscilloscope while actuating the tone interrupter switch. The oscilloscope camera was adjusted to photograph a single sweep containing the interrupted tone. Rise and fall times were computed by multiplying the number of centimeters of deflection by the sweep rate over the interval being inspected. The overshoot was then measured by increasing the oscilloscope vertical gain and observing the interval's crestline when the interrupter switch was turned on.

Output Levels. The sound pressure level output was recorded from meter readings on the microphone amplifier referenced to 0.0002 dynes per square centimeter. Each audiometer was measured in 10-decibel intervals of the attenuator dial from 20 decibels sensation level to the recommended maximum at 125, 250, 500, 1000, 2000, 4000, and 8000 Hertz. We switched the Spencer-Kennedy Laboratories filter to a 200-Hertz highpass filter function when measuring 500 to 8000 Hertz, to 150-Hertz highpass when measuring 250 Hertz, and to 70-Hertz highpass when measuring 125 Hertz. The filter was used to eliminate low-frequency noise that was transmitted from the microphone mounted in the chamber. Accurate ASA levels were consistently recorded to 20 decibels sensation level.

We recorded sound pressure levels in a level vs. frequency matrix for the left earphone and made tracings on the graphic level recorder at several intensities before the earphone was removed from the coupler to confirm the proper power and frequency response. To accomplish this, the audiometer output was disconnected and the beat frequency oscillator was substituted and properly matched to the earphone impedance. We used an identical procedure on the right earphone. The chart was attached to the audiometer data. The audiometer levels were then entered in the level vs. frequency matrix for the right earphone.

Frequency Measurement. We measured each frequency of the audiometer with the attenuator set at 60 decibels hearing level and at maximum recommended output to check loading effects on the oscillator.

Frequency Stability. Line voltage was varied from 105 to 125 volts, and the frequency at 4000 Hertz was observed for instability. The 105-volt test was performed first, after the tube filaments were allowed to cool for 3 minutes.

Level Stability. We used the same test for

level stability as for frequency stability except that the sound pressure level output at 1000 Hertz was recorded for each line voltage setting.

HARMONICS. Harmonic content measurements were carried out at 125, 1000, and 4000 Hertz. The wave analyzer was connected to the condenser microphone amplifier output. We computed the harmonic content directly from meter readings while the audiometer attenuator was set at normal maximum output, which varied with the instrument. The microphone amplifier contributed negligible distortion when it was not overdriven.

NOISE. All noise measurements were made from sound pressure levels obtained with the audiometer tone interrupter switch in the off position. Meter readings were taken with the audiometer attenuator at 100 decibels sensation level and with the frequency dial set first at 1000 Hertz and then at 4000 Hertz. The microphone amplifier was weighted in accordance with figure 2 in section 3.7.1, ASA specification Z24.5–1951 (*2*). We observed maximum level readings with the interrupter switch on. After the switch was turned off, gain was advanced on the microphone amplifier to disclose the noise output from the earphone.

Sound pressure level signal-to-noise ratios were calculated from the difference between the two meter readings at both frequencies. Overall noise measurements, including the oscillator circuitry, were not performed. We did not test for compliance with noise requirements using the telephone influence factor because of the difficulties in establishing accurate factors from the many audiometers operating at distant points within North Carolina.

CROSS TALK. Both earphones were connected to the audiometer; one phone was on the NBS–9A coupler and the other was outside the anechoic chamber on the laboratory bench. We fed a 1000-Hertz tone to the exterior phone at 100 decibels sensation level and measured the sound pressure level from the contralateral phone on the coupler. We reversed the earphone selector switch and plugs and repeated the process. Two-channel audiometers were measured by interrupting the tone on the channel being examined while measuring the background tone of the alternate channel.

MASKING. We noted the type of masking (for example, white noise or sawtooth noise), if any, for each audiometer. Measurements were made under the standard setup, with sound pressure level being obtained from either earphone that was known to be satisfactory. We compared the readings with the standard, taking into account dial designations indicating either effective masking or actual sound pressure level output, over a range of 40 to 100 decibels. The microphone amplifier was switched to the flat response (20 to 20,000 Hertz) when measuring masking.

Comments were noted concerning the general condition of the audiometer. If the audiometer was inoperative when it was received because of a defective tube or capacitor, minimum repairs were made to place the audiometer in operation, and all measurements were made on that basis. Such conditions were noted under "general observations" because of their effect on the validity of the accumulated data.

Results

Age of Audiometers

The ownership of the audiometers and the year of purchase are listed in table 1. Fifty-two percent of the audiometers in use were purchased between 1960 and 1964. The median age of the 100 audiometers was 6 years.

Most Recent Calibration

The date of purchase and the date of the last calibration are listed in table 2. Forty-five percent of the units had never been calibrated even though 73 percent were 3 years old or older.

Fifty-eight percent of the audiometers used by hearing and speech centers, hospitals, private physicians, public school systems, and college and university teaching programs had never been calibrated, even though most of them had been purchased more than 3 years before the end of the study.

Fifty-five units had been calibrated at least once: 50 percent by the manufacturer, 41 percent by a local dealer, 2 percent by a local electrician, and 7 percent by the owner. Most of those calibrated by the owner belonged to the Veterans' Administration, where portable calibrating units are available. There is some doubt as to the actual disposition of the units cali-

Table 1. Ownership of audiometers, by year of purchase

Owner	Number purchased							
	Before 1950	1951–53	1954–56	1957–59	1960–62	1963–64	After 1964	Total
Total	12	5	19	8	28	24	4	100
Health departments	8	3	8	1	4	5		29
Public schools	2	1	3		11	5	2	24
Physicians	1		3	1		2	1	8
Hospitals						2		2
Colleges and universities			2	1	1	3		7
Hearing and speech agencies	1	1	2	3	5	4	1	17
Veterans' Administration					3			3
Military						1		1
Industry				1				1
Hearing aid dealers					3	1		4
Other diagnostic centers			1	1	1	1		4

Table 2. Number of audiometers calibrated, by year of last calibration

Year of purchase	Number calibrated						
	1954–56	1957–59	1960–62	1963–64	After 1964	Never	Total
Total	2	5	11	33	4	45	100
Before 1950	2	1	2	3		3	11
1951–53		1	1	1	1	1	5
1954–56		3	3	6	2	5	19
1957–59			1	4		5	10
1960–62			4	9	1	14	28
1963–64				10		13	23
After 1964						4	4

brated by local dealers. In some instances the audiometers may have been returned to the manufacturer through the local dealer, but many were calibrated locally by agreement between several dealers and a general electronics repair service that used one of the commercially available portable calibration units. In some calibrations done locally, excessive circuit tampering was evident, and incorrect wiring changes, cold-solder joints, and use of acid-core solder were noted. In several instances improper fuses had been used. In one audiometer the fuse had been bypassed entirely, which resulted in a burned-out transformer.

Audiometer Operators

The persons with major responsibility for operating the audiometers varied with the owner. Most operators were public health nurses (26) speech and hearing therapists (31) and audiologists (16). In college and university teaching programs, the operators were almost exclusively speech and hearing therapists. Audiologists were used exclusively at hearing and speech centers and the Veterans' Administration.

Earphones

Five types of earphones were used on the audiometers: 84 percent were the Telephonics TDH–39, 10 percent were government issue USN–H1, 3 percent were the Telephonics TDH–38, 2 percent were the Permaflux PDR–1, and 1 percent were the Permaflux PDR–8. Fourteen defective earphones were found; most had faulty power responses. The resistance measurements of several earphones showed an open coil, with the result that they were inoperative. In one instance an audiometer was delivered to the laboratory with two types of earphones from two manufacturers. Except for the de-

fective and unmatched earphones, the overall performance of the earphones was satisfactory. There was excellent agreement and consistency in the frequency and power-response characteristics of all earphones of the same type.

The condition of the earphone cushions was determined visually by judging their resiliency and the seal when they were mounted on the NBS–9A coupler. Normal aging and loss of resiliency, the most common faults, usually resulted in a poor seal. Thirty-one pairs of cushions were replaced on the 100 audiometers.

Apparently the excessive use of cleaning agents shortened the lifespan of some cushions. During the investigation, inconsistencies were noted in the size and shape of the MX 41 A/R cushions, especially in the diameter of the center hole and in the thickness around the hole. An increased thickness increases the cavity volume between earphone and microphone diaphragms.

Some types of audiometers lacked sufficient storage space to adequately house the earphones and the headband, and the cushions were badly distorted as a result of being pressed against the irregularly shaped accessories that were stored in the compartment.

The earphone cords were routinely checked to determine if they were broken, loose, spliced, or worn or if they produced extraneous noise with movement. Twenty-nine defective cords were replaced. The cords on most of the portable audiometers were badly twisted and sometimes they were knotted. Frequently, the broken cords had been mended with household tape, liquid solder, and various glues. In two instruments, extension cords had been made from spliced lamp-cord wire and produced only intermittent output from the earphones.

General Condition of Dials

We checked the hearing loss (intensity) dial, the frequency switch dial, and the tone interrupter switch for looseness, noisiness, alinement, and general condition. The hearing loss dial was poorly alined and loose in 19 percent of the audiometers. Either condition can affect accurate threshold measurements. Sixteen percent of the frequency selector dials also were poorly alined and loose, and 13 percent had a defective tone interrupter switch. The malfunctions in these categories were not related to the age or model of the audiometer. We also inspected the masking dial and masking levels.

Since there are no published specifications covering the condition of earphone cushions, earphone cords, and dials, the results of our investigation are the product of the foregoing subjective tests.

Speech Channel

ASA specification Z24.13–1953 (*3*) defines a speech audiometer as "having a source for speech, a transducer appropriate to the source, an amplifier, a meter or other device for monitoring the output of the amplifier to a known or predetermined level, an attenuator, and a calibrated earphone or earphones." A speech audiometer may be a pure tone audiometer provided with these additional elements. All but one of the discussed audiometers were live-voice instruments. Although the absolute value may be changed in time, the current pressure reference level is 6 decibels above the "normal" threshold for a pure tone of 1000 Hertz, as defined by the ASA specification covering audiometers for general diagnostic purposes (*2*).

Of the 100 audiometers tested, 82 were equipped with speech channels, which we automatically labeled as unsatisfactory if a meter or other monitoring device was missing. For audiometers with a metered speech channel, the output reference level was checked in compliance with the ASA specification (*3*). A speech channel was deemed unsatisfactory if it deviated from the specified output level by more than ±5 decibels. Since these speech channels were all incorporated in pure tone audiometers, the linearity and accuracy of the attenuator had previously been evaluated. Compliance with the noise requirement of at least 50 decibels signal-to-noise ratio was not checked for the speech function.

Of the 82 audiometers equipped with speech channels, 22 satisfactorily met the recommended specifications and 60 were unsatisfactory (table 3). Most of the audiometers with speech channels were supplied by health departments, public school systems, and hearing and speech centers. Twenty-five of the 26 audiometers belonging to health departments and 15 of the 16 belonging to public school systems were unsatis-

factory. The greatest single reason was the absence of a meter or monitoring device.

Speech audiometers seldom may be used by health departments or schools, but the large number judged to be unsatisfactory (8 of 15) in audiometers belonging to hearing and speech centers, where they are a valuable part of the testing procedure, is quite significant. Most speech channels of audiometers at these centers were metered but were judged to be unsatisfactory because they failed to meet the specified level of output.

Shock Hazard

ASA specification Z24.5–1951 (*2*), further referenced to ASA standard C65.1–1942, specifies that an open circuit of 25 volts or more that can be reduced to 7.5 volts or less when shunted by a 1500-ohm load is considered to be free of electric shock hazards. Two of the 100 audiometers that we tested by this procedure maintained the maximum 117 volts and clearly failed to meet the requirements. More than 25 audiometers, mostly from one manufacturer, were capable of producing a startling shock when shunted by human skin resistance. Many complaints were received concerning these small portable instruments, which were used most commonly by health departments and public school systems under varying conditions at changing locations. Several later models of the transformerless variety were equipped with polarized line cords and were also supplied with "cheater" adapters. One audiometer was capable of producing a dangerous shock because the insulation on its earphone cords was worn away in several places.

Table 3. Condition of speech channels in audiometers

Owner	Satisfactory	Unsatisfactory	Speech channel missing	Total
Total	22	60	18	100
Health departments	1	25	3	29
Public schools	1	15	8	24
Physicians	3	5	0	8
Hospitals	1	1	0	2
Colleges and universities	3	2	2	7
Hearing and speech agencies	7	8	2	17
Veterans' Administration	2	0	1	3
Military	0	1	0	1
Industry	0	0	1	1
Hearing aid dealers	3	1	0	4
Other diagnostic centers	1	2	1	4

Attenuator Noise

Although not specified in any standard set of requirements, the extraneous noise produced by the attenuator when the intensity settings were changed was included in the evaluation because some operators tended to change intensity settings without activating the interrupter switch. This tendency is particularly true of inexperienced operators in large screening programs. The extraneous noise produced by the attenuator could produce an erroneous response by the person being tested and thus be erroneously interpreted by the operator as a response to the test tone.

We checked extraneous noise through the entire attenuator range while listening to the earphone at a frequency of 250 Hertz. Seventy-seven audiometers clicked excessively when the attenuator settings were changed. The most troublesome design was the split step-type attenuator, with 50 decibels of the range attenuated at the output and the remainder with a high impedance interstage control. In this situation, the interstage blocking capacitor has a tendency to build up voltage between steps and discharge it with an audible click when contact is made again. We noted general improvement in most attenuators when silver, rather than brass, wiper arms were used.

Rise Time, Fall Time, and Overshoot

Differences exist in the specifications on rise time, fall time, and overshoot. ASA specification Z24.5–1951, sec. 3.11 (*2*), states: "It is recommended that after operation of the switch the time required for the test tone to rise to a value which is within ± 1 decibel of the required sound pressure shall not be less than 0.1 second and not more than 0.5 second." No reference is made to fall time or overshoot, and the specification could be interpreted as allowing any amount of overshoot as long as the test tone reached a level within ± 1 decibel of the required sound pressure in 0.5 second.

ASA specification Z24.12–1952, sec. 3.8 (*1*), states: "After operation of the interrupter switch for 'Tone on,' the time required for the acoustic output to reach a level within 1 dB of its final level shall be not less than 0.01 sec. or more than 0.5 sec. The output shall not overshoot its final level by more than 1 dB. After operation of the interrupter switch for 'Tone off,' the test tone shall decay at least 20 dB and preferably more within 0.5 sec." The specifications on rise and fall times and overshoot are specific for screening audiometers but lacking for general diagnostic audiometers.

The IEC recommendations agree on this aspect (*17,18*). Each publication states, in section 3.4:

> When the tone switch is moved to the 'ON' position, the time taken for the sound pressure level produced by the earphone to attain −1 dB relative to its final steady value shall not exceed 0.2 s from the instant of operating the switch. The rate of increase of the sound pressure level produced by the earphone shall not exceed 500 dB/s in region −20 dB to −1 dB relative to its final steady value.
>
> When the tone switch is moved to the 'OFF' position, the time taken for the sound pressure level produced by the earphone to decay from the level of −1 dB to the level of −60 dB relative to its steady value in the 'ON' position shall not exceed 0.2 s.
>
> The rate of decay of the sound pressure level produced by the earphone shall not exceed 500 dB/s in the region −1 to −20 dB relative to its steady value in the 'ON' position.
>
> At no time after operating the tone switch shall the sound pressure level produced by the earphone attain a value exceeding ±1 dB relative to its steady value in the 'ON' position.

Both recommendations stipulate fall times not exceeding 0.5 second from a switch-off position to a tone decay of 60 decibels, which is approximately the same as pertinent ASA screening recommendations. Since the study included screening and diagnostic audiometers and the newer audiometers, factory calibrated to ISO levels, it was necessary to consider all three specifications.

The older audiometers purchased before 1957 generally exceeded the tolerance limit for rise time. A failure rate of 84 percent (table 4) was recorded for rise and fall times when strict adherence to the audiometer's respective standard was observed. The 52 failing units of the 84 in the "diagnostic" category had rise times between 10 and 99 milliseconds, which were within the allowable range for "screening" audiometers. If screening requirements are applied to diagnostic audiometers, the number failing is reduced from 52 to 32. The 32 failed to meet any standard; four units had a rise time of less than 10 milliseconds, and 28 units had a rise time of 600 to 3200 milliseconds.

On the whole, fall time was good in all units. Overshoot did not present a problem since only two audiometers exceeded the stated limits. The results do not coincide with those of Eagles and Doerfler (*13*), which showed a high percentage of overshoot errors.

The variations in mean rise time, fall time, and overshoot in relation to the time when the audiometer was last calibrated are given in table 5. The same errors exist regardless of when the calibration was done, except for the period 1954–56. There were, however, only two audiometers in this category and one was excluded because of an inoperative interrupter switch.

Sound Pressure Output

The sound pressure levels of both earphones for each audiometer were recorded to form a matrix ranging in 10-decibel intervals from a dial (hearing level reading of +20 decibels to the upper hearing level reading fixed as a maximum by the manufacturer and printed on the frequency selection dial. Usually the measured intervals on ASA audiometers were as follows:

Hertz	*Decibels sensation level*
125	20 to 60.
250	20 to 80.
500	20 to 90.
1000, 2000, 4000	20 to 100.
8000	20 to 80.

Each matrix contains 54 separate level entries per earphone for the seven indicated frequencies, or a total of 108 entries per audiometer, except for several limited-frequency screening audiometers. The large number of audiometers used restricted practical measurement intervals to 10 decibels but attenuator linearity over the entire range was readily discernible. All manufacturers met or exceeded the maximum recommended output in design as outlined in ASA specification Z24.5–1951, sec. 3.4, table 1 (*2*).

In evaluating the sound pressure level output

Table 4. Rise time calibration status as compared with specifications

Type of audiometer	In	Out		Total
		Over	Under	
Total	16	28	56	100
Diagnostic [1]	12	28	55	95
Screening [2]	4	0	1	5

[1] ASA specification Z24.5–1951.
[2] ASA specification Z24.12–1952.

Table 5. Mean rise time, fall time, and overshoot, by year of last calibration

Year of last calibration	Number of audiometers	Mean tone		
		Rise time (msec.)	Fall time (msec.)	Overshoot (db)
1954–56	2	[1] 10.0	[1] 20.0	0
1957–59	5	1680.0	200.0	0
1960–62	11	503.6	78.6	.27
1963–64	33	629.4	93.4	.33
After 1964	4	511.2	112.5	0
Never	45	289.5	77.6	.25

[1] 1 audiometer excluded because interrupter switch was inoperative.

for earphones of different manufacturers and models, the coupler pressures were compared with a manufacturer's specifications, based on the NBS loudness-balance equivalent pressures described by Corliss and Snyder (*6*) and Cox and Bilger (*8*).

Graphic level recordings, displayed in a continuous sweep, were made of the power and frequency responses of each earphone. These recordings were invaluable in identifying the level discrepancies that occurred periodically. Whenever attenuator linearity was suspected, the power response curves of the accompanying earphones were carefully examined.

Based on an average 108 separate level measurements for each audiometer, only 11 audiometers of 100 met the appropriate standards. Seventeen percent had one to 10 errors, 55 percent had 11 to 50 errors, and, alarmingly, 16 percent had 51 to 100 errors (fig. 2). Gross error counts, in most instances, were due to an overall frequency shift downward of the oscillator because of faulty components in this circuit, which are common to all generated frequencies. Steep excursions in the higher frequency response of earphones accounted for many of the deviations in levels following a frequency shift, and often the smoother curve of the lower frequencies could produce levels within the standard but at an excessive frequency error. Other factors affecting the levels are storage and environmental conditions; approximately 25 percent of the instruments received indicated damage by heat, moisture, or rodents. One audiometer used by a county health department arrived with a mouse nest intact—resourcefully constructed from wire insulation and material from nearby components.

Attenuator Linearity

Attenuator linearity was judged by inspecting the level matrix. Linearity errors, computed on 10-decibel intervals, revealed that 27 audiometers had errors exceeding the specified tolerances, due exclusively to nonlinear attenuators. Inspection at 5-decibel intervals might have increased the figure. Direct and borderline errors occurred in the audiometers using attenuators of the split low- and high-impedence sections, described under "attenuator noise." These deviations usually occurred at the transition between the two sections. Continuously variable wire-wound attenuators were critical to wiper arm pressure, cleanliness, and composition of the wiper contact. In a critical state, these attenuators frequently produced fluctuations of ±2 decibels with slight finger pressure on the attenuator dial.

Frequency

Thirty-one of the 100 audiometers exceeded the 5 percent tolerance level for frequency. The IEC specifications set the tolerance limit at ±3 percent. The frequencies were checked at 60 decibels hearing level and at the maximum level specified by the manufacturer for each frequency. Of the 31 audiometers exceeding the tolerance limit for frequency, 26 were from one manufacturer and 16 represented one particular model. Ten of the 31 audiometers exceeded the tolerance limit at only one frequency. Ten exceeded the limit at all seven frequencies, and some errors were very large. In one instance, with the frequency dial set at 8000 Hertz, the

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audiometer produced 5866 Hertz, an output resulting in an error of 2134 Hertz. Many were off from 1500 to 2000 Hertz at the 8000-Hertz position, where these errors were most prevalent.

Of the 31 audiometers exceeding the tolerance limit, most were owned by health departments and public school systems. No audiometer passed the frequency specifications at the 60-decibel level and failed at the maximum level—a fact also noted in the "frequency stability" discussion. Mean frequencies at 60 decibels and at the maximum level, by date of last calibration, are given in table 6.

Stability

The ASA specifications for both diagnostic and screening audiometers state that the acoustic output level at the 60-decibel setting shall not depart by more than ±1 decibel from its value as the line voltage is varied from 105 to 125 volts. The IEC specifications simply state that the standards shall be met as the voltage is varied by ±10 percent.

Twelve of the 100 audiometers failed to meet level stability requirements. Errors existed in all audiometers except those purchased in 1957–59 and those purchased after 1964. The mean level variation is apparently unrelated to the last calibration (table 7).

Although not included in the specifications for audiometers, frequency stability at 4000 Hertz was checked at the 60-decibel level as the voltage was varied from 105 to 125 volts. The frequency was considered unstable if it exceeded the ±5 percent tolerance limit as the voltage was varied. Frequency stability was excellent. Only one audiometer exceeded the ±5 percent tolerance limit for frequency because of voltage variation.

Purity of Test Tone

The ASA specifications state that the sound pressure level of the fundamental frequency must be at least 25 decibels above that of any harmonic when measured with the earphone on the coupler. The IEC specifications state that the sound pressure level of each harmonic must be at least 30 decibels below that of the test tone at each attenuator setting and that the total harmonic disortion must not exceed 5 percent.

Six audiometers failed to meet these requirements. The sound pressure level of the harmonics at 125, 1000, and 4000 Hertz, measured in decibels relating to the sound pressure level of the fundamental, is shown in table 7. Most of the units that failed were battery operated. The 94 satisfactory units far exceeded the standards.

Noise

The ASA specifications state that the root mean square weighted sound pressure produced by the earphone on the coupler, at all frequencies except the test tone and its harmonics, must be

Figure 2. Distribution of sound pressure level errors by total number of audiometers affected

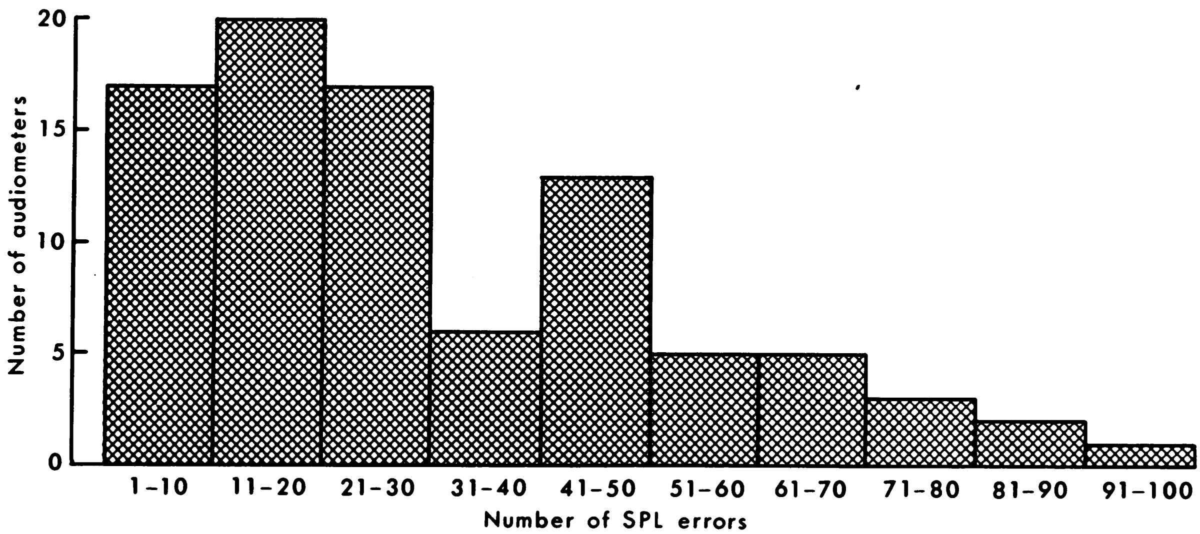

Table 6. Mean frequencies at 60 decibels and at maximum level, by year of last calibration

Frequency setting	Mean frequency, by year of last calibration					
	1954–56	1957–59	1960–62	1963–64	After 1964	Never
60-db level (Hz):						
125	114.5	116.0	121.2	122.8	122.7	117.2
250	231.5	232.6	239.7	244.5	251.8	239.9
500	494.0	449.8	479.4	490.1	501.0	478.1
1000	941.0	904.8	968.7	983.8	1006.8	961.8
2000	1935.5	1841.8	1946.7	1973.8	1987.2	1920.3
4000	3827.0	3687.0	3884.2	3975.8	3545.5	3864.2
8000	7354.0	7511.0	7711.8	7888.1	7907.2	7610.9
Maximum level (Hz):						
125	114.5	116.0	121.2	122.9	122.7	117.2
250	232.0	232.6	239.8	244.5	251.8	240.0
500	496.5	449.8	479.1	490.6	501.0	476.5
1000	944.0	904.8	969.0	1014.6	1006.8	962.6
2000	1943.0	1841.8	1948.0	1976.3	1987.2	2053.3
4000	3832.0	3687.0	3884.6	3977.3	3545.5	3859.6
8000	7381.5	7511.0	7412.2	7891.1	7907.2	7611.7

either less than 1×10^{-3} dynes per square centimeter or at least 60 decibels below the sound pressure, owing to the signal frequency and its harmonics, at all specifically designated frequencies and hearing loss dial settings. Since the IEC specifications were still under consideration, all audiometers were measured according to the ASA specifications.

Six audiometers failed to meet the noise requirements. Of these, four were received from county health departments and two from schools. Aging was a factor in five, and the sixth had alterations in the tone interrupter circuit to accommodate accessories for play audiometry.

The power supply filter capacitors of five older audiometers were failing. Four of these used limiting amplifiers in the tone interrupter circuit that were only partially working.

Cross Talk

Specifications for cross talk have not been published by any standard-setting organization, but each audiometer equipped with two earphones was examined for this defect as outlined. Instruments with a tone sound pressure level of −60 decibels or less in the contralateral "off" earphone when maximum levels were applied to the other earphone were judged to be satisfactory. Only two audiometers failed in this category, and understandably so because of numerous other defects in both units.

Many complaints by owners of dual channel audiometers indicated that cross talk might be prevalent but could not be verified under test conditions when the audiometers were operated in accordance with the manufacturers' instructions. However, nearly all of the dual channel units were capable of generating cross talk when improperly operated.

Several instances of cross talk were traced to the improper installation of extension wires from the audiometer to the headphone jack panel in soundproof rooms. Locally constructed devices for output switching, usually associated with play audiometry, were responsible for leakage in some audiometers.

Masking

In the absence of a standard, masking was evaluated with reference to the manufacturers' specifications. Complex, sawtooth, white noise, and narrow band white noise masking were all encountered. The unweighted sound pressure level masking output was compared with dial markings and related to either "effective masking," or "sound pressure level masking." Audiometers without dial calibration marks as well as slipped or loose dials were automatically termed unsatisfactory. Eighty-eight units had masking available in some form. Of these, 60 were at variance with any logical output pattern. Of the 28 in calibration, 13 were used in diagnostic centers and teaching programs, seven by physicians, six by health departments, and two by other organizations. Public school sys-

tems failed to have any in calibration. Eleven of 17 dual channel audiometers, all with masking available, were in calibration, while only 17 of 71 single channel units passed tests (table 8).

Discussion

Evaluation of 100 audiometers revealed that no screening audiometers passed the tests satisfactorily. Only the two new diagnostic audiometers could be judged in calibration when strict compliance with the standards was observed, and these were uncrated in the laboratory just before the calibration check. No audiometer in use was in completely satisfactory calibration for the testing for which it was manufactured.

Data were recorded on 11 audiometers that were in service but were not repaired and calibrated because of their age and generally poor condition. We recommended that eight of these be replaced with new units because complete rebuilding, in view of their age, was impractical. The other three units, with circuit board construction, were in better condition and were returned to the manufacturer by the owners.

The remaining 85 audiometers were repaired and calibrated to a standard of the owner's preference. Some of the repairs were minor, principally the replacement of components to bring the sound pressure levels and frequencies within limits. One audiometer was completely inoperative, and another had one defective channel that caused interference with the operative channel. Two audiometers were inoperative at selected frequencies.

One or more tubes were replaced in eight audiometers, and approximately 46 other repairs, some major, were effected. In 10 units the attenuator was rebuilt or replaced because of poor linearity or broken or worn wiper arms. Five oscillator sections were completely rebuilt, and the capacitors were changed in the oscillator circuitry of six units. Inoperative or potentially dangerous power cords were replaced in eight audiometers, and the tone interrupter switch was repaired or replaced in eight units. It was necesary to rebuild the power supply in two units, and cold-solder joints were detected in three units. Power transformers were replaced in two units and the components of two units failed because of excessive heat or moisture. The decision to undertake major repairs was based on the age of the audiometer, the years of service that could be expected from the

Table 8. Masking calibration of 88 audiometers having this feature, by owner and type of audiometer

Owner and type of audiometer	Total	Number in calibration	Number out of calibration
Total	88	28	60
Owner:			
Health departments	25	6	19
Physicians	8	7	1
Hearing aid dealers	4	1	3
Diagnostic and teaching centers	30	13	17
Other	21	1	20
Type of audiometer:			
Dual channel	17	11	6
Single channel	71	17	54

Table 7. Mean errors in audiometer measurements, by year of last calibration

Year of last calibration	Number of audiometers	Mean errors: 60 db, 105 volts	60 db, 125 volts	4000 Hz, 105 volts	4000 Hz, 125 volts	Harmonics (Hz): 125	1000	4000
1954–56	2	0.4	0.4	6.0	6.0	−42.0	−30.5	−37.8
1957–59	5	1.2	1.2	2.0	2.0	−33.7	−32.5	−44.4
1960–62	11	1.2	1.0	5.0	4.9	−34.2	−39.9	−44.7
1963–64	33	[1] 1.5	[1] 1.5	[1] 7.9	[1] 7.9	−32.4	−37.7	−45.0
After 1964	4	1.4	1.4	7.8	7.8	−25.8	−39.8	−47.0
Never	45	1.1	1.1	7.5	7.5	−27.9	−33.8	−43.6

[1] 1 audiometer excluded from means because it had no output at 105 volts.

repaired units, and the cost of repairs versus the replacement cost.

The most frequent earphone defect was incorrect sound pressure output; 89 of the 100 audiometers did not meet the specification. This problem was found most frequently by Morrical and co-workers (*11*) and Eagles and Doerfler (*13*). The specification is important and has many implications as it bears directly on the threshold measurement. The audiometers that were checked were removed from service for a brief period (averaging one a week). It is impossible to estimate the number of auditory thresholds measured during the time a unit was malfunctioning. A matter of concern, then, is the 89 audiometers that failed to meet the specifications for sound pressure output.

One audiometer, owned by a local health department, was used in group screening in the public schools. The operator estimated that 10,000 children had been screened with this machine over a period of 1 year, yet the attenuator had been incorrectly wired by the manufacturer and would not attenuate below 50 decibels hearing level. The soldered connection carried the factory inspection paint dot, which presumably verifies inspection and is used to detect alterations. The machine had been recalibrated by a local dealer, but the defect still had not been discovered.

The second most common defect involved excessive rise time. The deficiency could not be corrected without major design changes—beyond the scope of this study. In several older models from one manufacturer, a limiter circuit was used to interrupt the tone, and a change of values in the circuit effected an interaction with the output level and rise time. This circuit functioned properly in only two of 29 audiometers of this type.

The third most common deficiency was frequency outside the tolerance limit. Because of the frequency response characteristic of the earphones, the frequency shifts within the audiometer can produce erroneous sound pressure levels. When the dial in one audiometer in current use in a medical center's hearing clinic was set at the 8000-Hertz position, a tone of 5866 Hertz was transmitted to the patient. There are similar examples of errors of 1000 to 2000 Hertz at the 8000-Hertz setting, and proportional errors at other frequency settings.

Twenty-four audiometers failed to meet the specifications for the hearing loss interval and hearing loss range. Most audiometers, however, were out only in one or two positions. The major concern is the accumulation of errors, which over the range of the attenuator can become relatively large. Attenuator linearity was good except as noted.

Instability of sound pressure level output with variations in alternating current line voltage was found in 12 units. The instability was not great and did not substantially affect the threshold measurements.

Harmonic distortion beyond specifications was noted in six audiometers. Excessive harmonic distortion could possibly affect the hearing threshold measurements, depending on the audiometric configuration. In a sharply rising audiogram, it would be possible to respond to the harmonic rather than the fundamental should the sound pressure of the harmonic not be substantially below that of the test tone.

Two audiometers failed to meet ASA specifications for shock hazard. The voltage and current measured with a 1500-ohm load is different from that received by a person with a nominal skin resistance of as much as 30 times 1500 ohms. The shock could come from exposed or worn earphone cords, the chassis or front panel of the audiometer, or exposed screw terminals on the earphone. This is particularly true of the alternating current-direct current circuits that are constructed without the use of a power-line isolation transformer.

The 100 audiometers that we tested failed to meet specifications a total of 206 times; 162 deviations involved parameters affecting threshold measurements.

We initiated this study on the assumption that audiometers in current and general use might be in a state of discalibration sufficient to result in inaccurate threshold measurements. The data collected during the 3-year investigation supported this hypothesis and pointed out the need for adopting a more uniform standard. The need for improved design and quality control by the manufacturers, especially of low cost audiometers, is clearly indicated. While

solid state construction has saturated the field in devices marketed for domestic, industrial, and professional use, we received only a few such audiometers up to the close of this study in late 1966.

Based on our initial observations and supported by other studies, we suggest that audiometers be recalibrated every 6 months. To accomplish this the establishment of regional calibration centers may be necessary (*16*). Regional centers need not be equipped to make major repairs; these should be referred to the manufacturer. But the centers should be capable of effecting accurate calibrations in a short time and should recommend to the owners periodic replacement of the machines. The centers, along with continued investigation, could provide a needed service for the users and, consequently, for the persons being tested. Valuable data, made available to the manufacturers, should lead to the development of improved instrumentation.

The investigators of this study continued to monitor the previously calibrated audiometers for another 18 months. They will recommend followup calibration intervals based on the tests in a later publication.

Summary

The University of North Carolina Hearing and Speech Center, in cooperation with the Public Health Service, in 1966 investigated 100 audiometers, all but two of which were in current general use. The instruments were selected at random from various sources in North Carolina. The sample consisted of 30 models manufactured by eight companies and owned by 11 agencies or persons, such as health departments, public school systems, hearing and speech centers, and physicians.

Technical data were obtained on the extent to which each instrument met the specifications adopted by the American Medical Association and the American Standards Association and, when indicated, those of the International Organization of Standardization and the International Electrotechnical Commission. Additional information was obtained on date of purchase and last date of calibration.

The investigators found that none of the screening audiometers was in satisfactory condition. The two diagnostic audiometers not yet in use were in calibration. None of the audiometers in general use was in condition to do satisfactorily the testing for which it was manufactured.

The most frequent defect encountered was incorrect sound pressure output. The second most common defect was excessive rise time. The third ranking deficiency was frequency outside the 5 percent tolerance level. The 100 audiometers failed to meet standards a total of 206 times, with 162 deviations involving parameters affecting threshold measurements.

The investigators' assumption that audiometers in general use are in a state of discalibration, resulting in inaccurate test results, was supported by the study data.

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