CHAPTER 24

PHYSIOLOGY OF HEARING

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INTRODUCTION

The basic function of the hearing mechanism is to gather, conduct and perceive sounds from the environment. Sound waves, propagated through an elastic medium, liberate energy in a characteristic pattern which varies in frequency and intensity.

The human voice and other ordinary sounds are composed of fundamental tones modified by harmonic overtones (refer to Chapter 23). Our hearing sensitivity is greatest in childhood, but as we get older, our perception of high tones worsens, a condition labelled "presbycusis." The frequency range of the human ear extends from as low as 16 Hz to as high as 30,000 Hz. From a practical standpoint, however, few adults can perceive sounds above 11,000 Hz.

The ear responds to alterations in the pressure level of sound. The amplitude of these sound pressure alterations determines the intensity of the sound. So great is the range of intensities to which the ear responds that a logarithmic unit, the decibel (dB), is commonly used to express the pressure level of sound. The subjective correlates of frequency and intensity are pitch and loudness.

The translation of acoustical energy into perceptions involves the conversion of sound pressure waves into electrochemical activity in the inner ear. This activity is transmitted by the auditory nerves to the brain for interpretation. Although there are many gaps in our understanding of the precise mechanism of hearing, the following presentation will emphasize the peripheral processes involved in hearing.

PERIPHERAL MECHANISM OF HEARING

Sound reaches the ear by three routes: air conduction through the ossicular chain to the oval window; bone conduction directly to the inner ear; and conduction through the round window. Under ordinary conditions, bone conduction and the transmission of sound through the round window are less significant than air conduction in the hearing process. An example of bone conduction occurs when you tap your jaw. The sound you perceive is not coming through your ears but through your skull. Sound perception via air conduction is the most efficient route and it encompasses the external and middle ear conducting system which will be discussed in more detail.

Conduction of Sound

External Ear. Anatomically, the ear can be divided into an external portion (outer ear), an "air-filled" middle ear, and a "fluid-filled" inner ear (Fig. 24-1). The outer ear consists of the auricle and the external auditory meatus, or canal. The auricle is an ornamental structure in man. Neither does it concentrate sound pressure waves significantly, nor does it function in keeping foreign bodies out of the ear canal. The two ears give us "auditory localization" or "stereophonic hearing," namely, the ability to judge the direction of sound. One explanation is that sound waves arriving at the two auricles have a slight time lag, differing in intensity and timbre since in the far ear the sound must travel a greater distance.

The external auditory canal is a little more than an inch in length and extends from the concha to the tympanic membrane. The skin of the cartilaginous portion of the ear canal secretes wax, which helps maintain relatively stable conditions of humidity and temperature in the ear canal. The ear canal protects the tympanic membrane and acts as a tubal resonator so that the intensity of sound pressure waves are amplified when they strike the tympanic membrane.

The tympanic membrane (TM, eardrum) separates the external ear from the middle ear. This almost cone-shaped, pearl-gray membrane is about a half-inch in diameter. The distance the eardrum moves in response to the sound pressure waves is incredibly small, as little as one billionth of a centimeter.[1] Besides vibrating in response to sound waves, the eardrum protects the contents of the middle ear and provides an acoustical dead space so that vibrations in the middle ear will not exert pressure against the round window.

Middle Ear. Medial to the eardrum is the special air-filled space called the middle ear. It houses three of the tiniest bones in the body: the malleus (hammer); the incus (anvil); and the stapes (stirrup). The handle of the malleus attaches to the eardrum and articulates with the incus which is connected to the stapes. The malleus and the incus vibrate as a unit, transmitting the sound waves preferentially to the stapedial footplate, which moves in and out of the oval window. Below and posterior to the oval window is the round window whose mobility is essential to normal hearing.

Fig. 24-2 shows the two intratympanic muscles, the tensor tympani and the stapedius. The tensor tympani extends from the canal above the eustachian tube to the handle of the malleus. It moves the malleus inward and anteriorly, and helps maintain tension on the eardrum. The stapedius muscle inserts on the posterior aspect of the neck of the stapes. It pulls the stapes outward and posteriorly.

The two muscles are antagonistic in their action, but contract only when stimulated by rela-

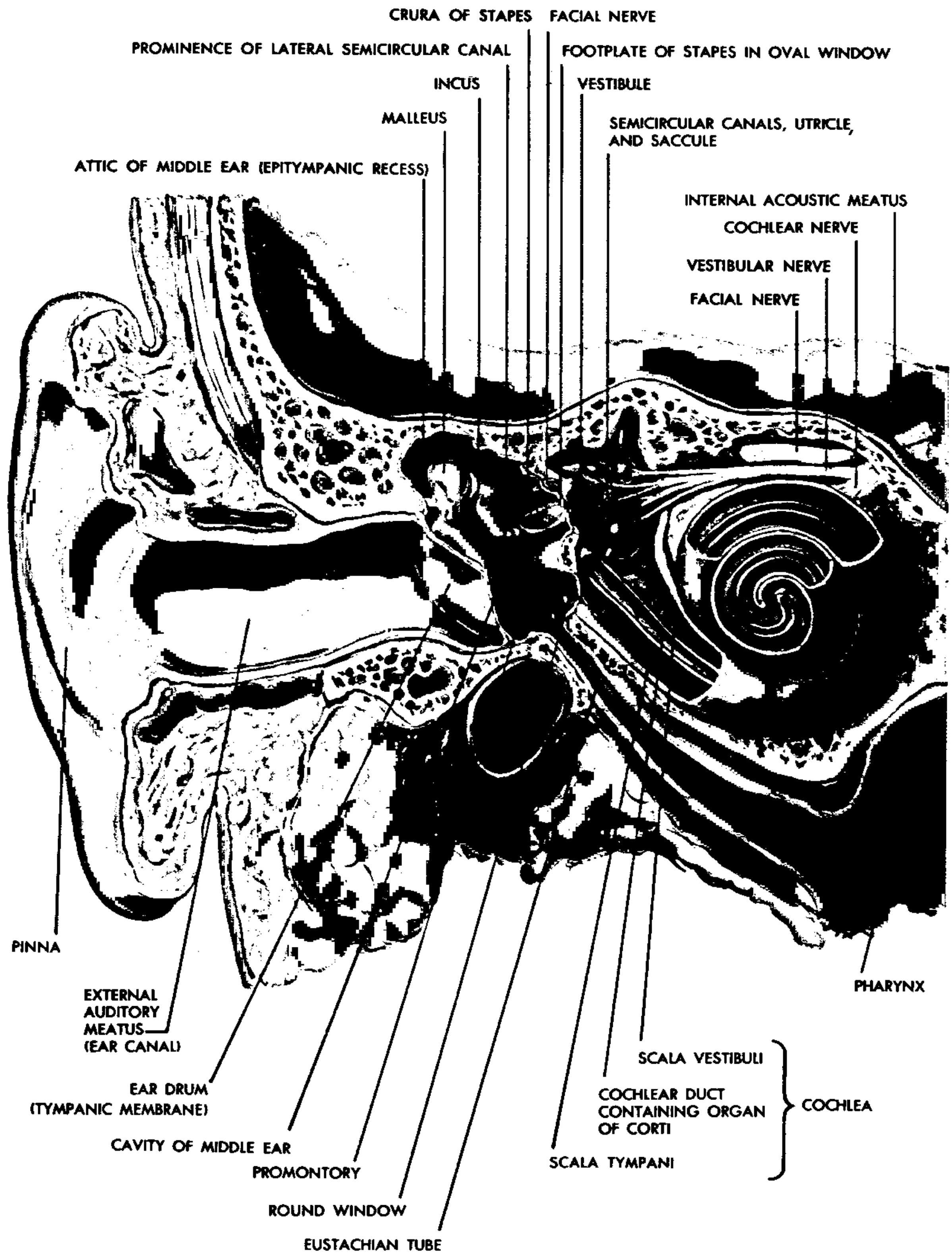
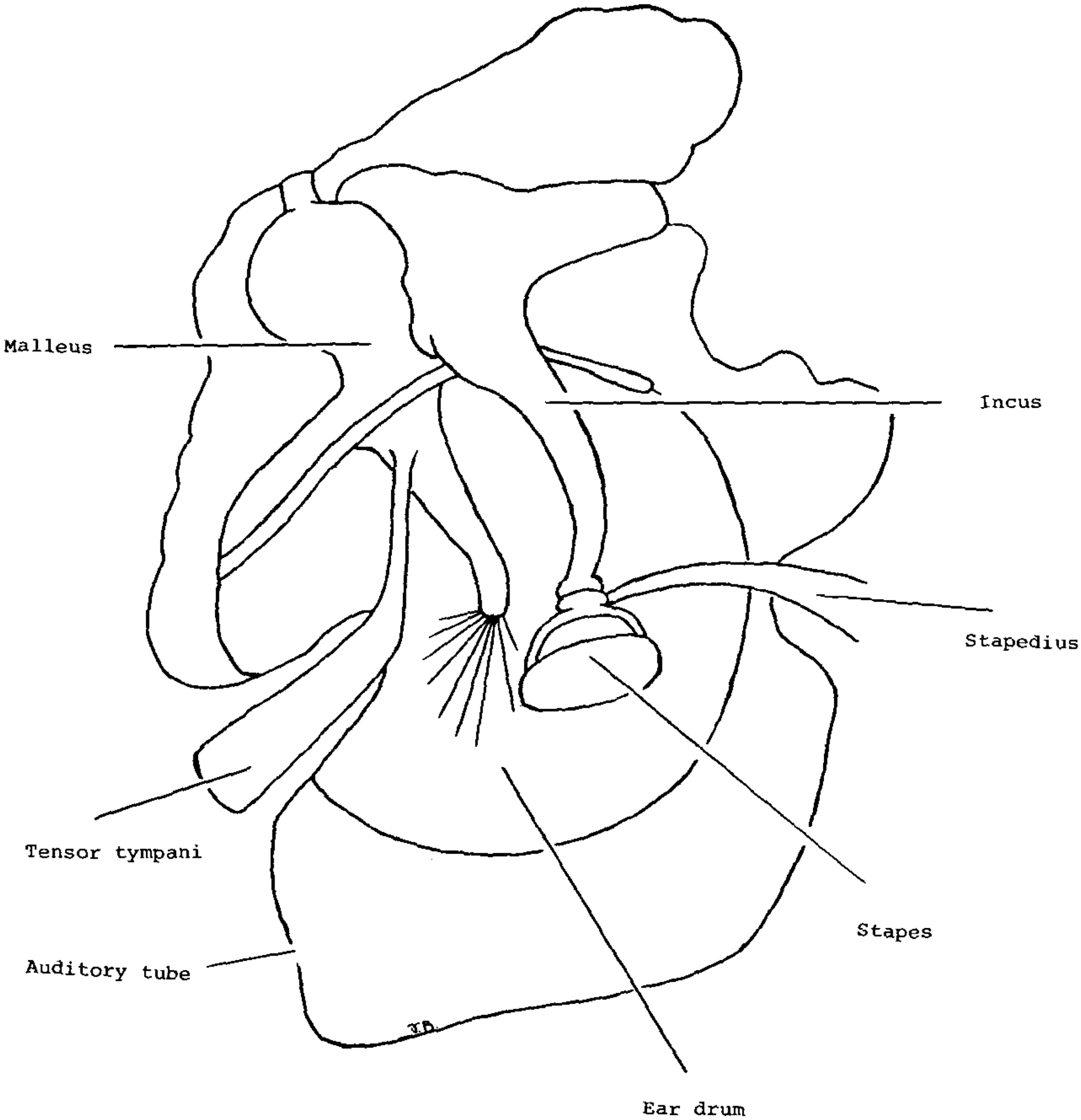


Figure 24-1. Pathway of Sound Conduction Showing Anatomic Relationships.



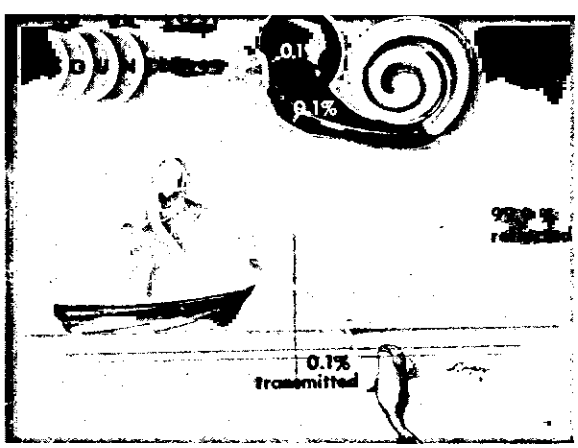
Lockart R., Hamilton G., Fyfe F.: Anatomy of the Human Body. London, Faber & Faber, 1959, p. 463.

Figure 24-2. Intratympanic Muscles Viewed from the Medial Wall. Faber & Faber, London.

tively loud sounds. Contraction of the muscles causes rigidity of the ossicular chain with a resultant decrease in the conduction of sound energy to the oval window. A limited protective function has been ascribed to this reflex contraction of the muscles although the aural reflex does not react fast enough to provide complete protection against sudden and explosive sounds. Also, exposure to steady state noise for long periods of time would cause the muscles to adapt or fatigue to the auditory stimulus.[2]

The "eustachian or auditory" tube connects the anterior wall of the middle ear with the nasopharynx. It is about an inch and a half in length and consists of an outer bony portion (one third of the tube which opens into the middle ear) and an inner cartilaginous part (two thirds of the tube which opens into the throat). The lumen of the bony part is permanently opened while that of the cartilaginous portion is closed except during certain periods such as swallowing, yawning, or blowing the nose. To hear optimally, the atmospheric pressure on both sides of the eardrum should be equal. The act of swallowing, for example, forces air up the middle ear and thus equalizes the atmospheric pressure on either side of the tympanic membrane.

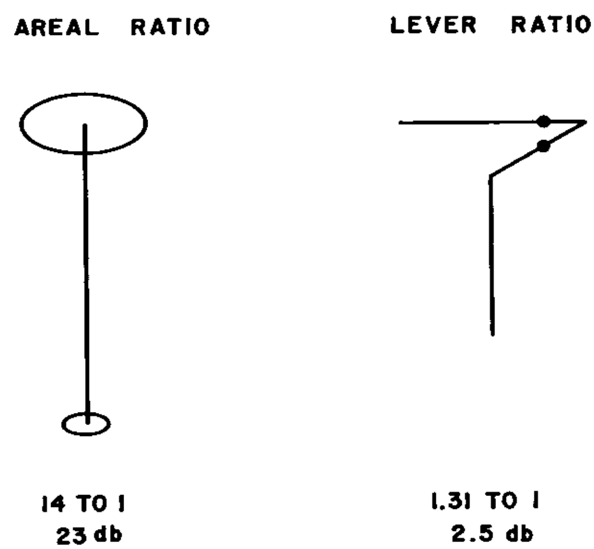
Yet, the fundamental problem that the middle ear must resolve is that of "impedance matching." In other words, the ear must devise a mechanism of converting the sound pressure waves from an air to a fluid medium, without a significant loss of energy. This is a noteworthy accomplishment since only 0.1% of airborne sound enters a liquid medium whereas the other 99.9% is reflected away from its surface. Stated differently, the intensity of vibration in the fluid of the inner ear is 30 decibels less than the intensity present at the eardrum (Fig. 24-3). The middle ear has two arrangements to narrow this potential energy loss.



Lawrence M., cited by De Wéese D., Saunders W.: Textbook of Otolaryngology. St. Louis, C. V. Mosby Company, 1968, p. 270, ed. 3; Courtesy of Dr. Merle Lawrence, Ann Arbor, Michigan.

Figure 24-3. Loss of Sound Energy at the Air-Water Interface.

First is the "size differential" between the comparatively large eardrum and the relatively small footplate of the stapes. The eardrum has an effective areal ratio which is 14 times greater than that of the stapedial footplate. This hydraulic effect increases the force of pressure from the eardrum onto the footplate of the stapes so that there is approximately a 23 dB increase of sound intensity on the fluid of the inner ear. The "lever action" of the ossicles amplifies the intensity of sound as it traverses the middle ear by about 2.5 dB. Thus, the impedance matching mechanism of the middle ear is not perfect, but accounts for a 25.5 dB increase in the intensity of sound pressure at the air-liquid interface (Fig. 24-4).



Lawrence M.: How we hear. JAMA 196:83, Copyright 1966, American Medical Association, Chicago, Ill.

Figure 24-4. Impedance Matching Mechanism of the Middle Ear which Minimizes Energy Loss as Sound Is Transferred from Air to Fluid Medium. Journal of the American Medical Association.

Perception of Sound

Inner Ear. The labyrinth or inner ear is a complex system of ducts and sacs which houses the end organs for hearing and balance. It consists of an outer bony and an inner membranous labyrinth. The center of the labyrinth, the vestibule, connects the three semicircular canals and the cochlea. A watery fluid, perilymph, separates the bony from the membranous labyrinth while inside the membranous labyrinth are fluids called endolymph and cortilymph.

The cochlea resembles a snail shell which spirals for about two and three-quarter turns around the bony column called the "modiolus" (Fig. 24-5). There are three stairways or canals within the membranous cochlea: the "scala vestibuli;" the "scala tympani;" and the "scala media

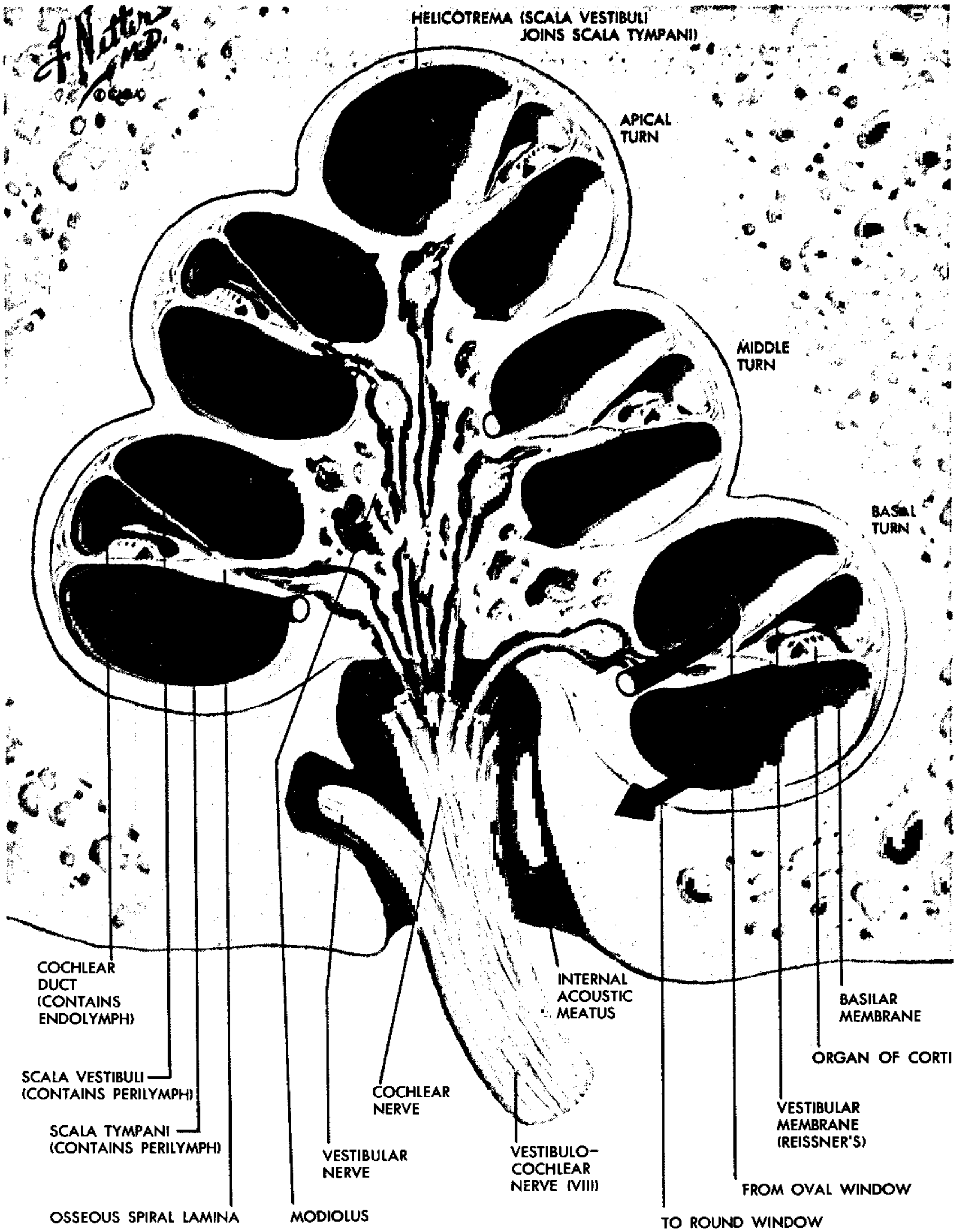


Figure 24-5. Cross Section of Cochlea.

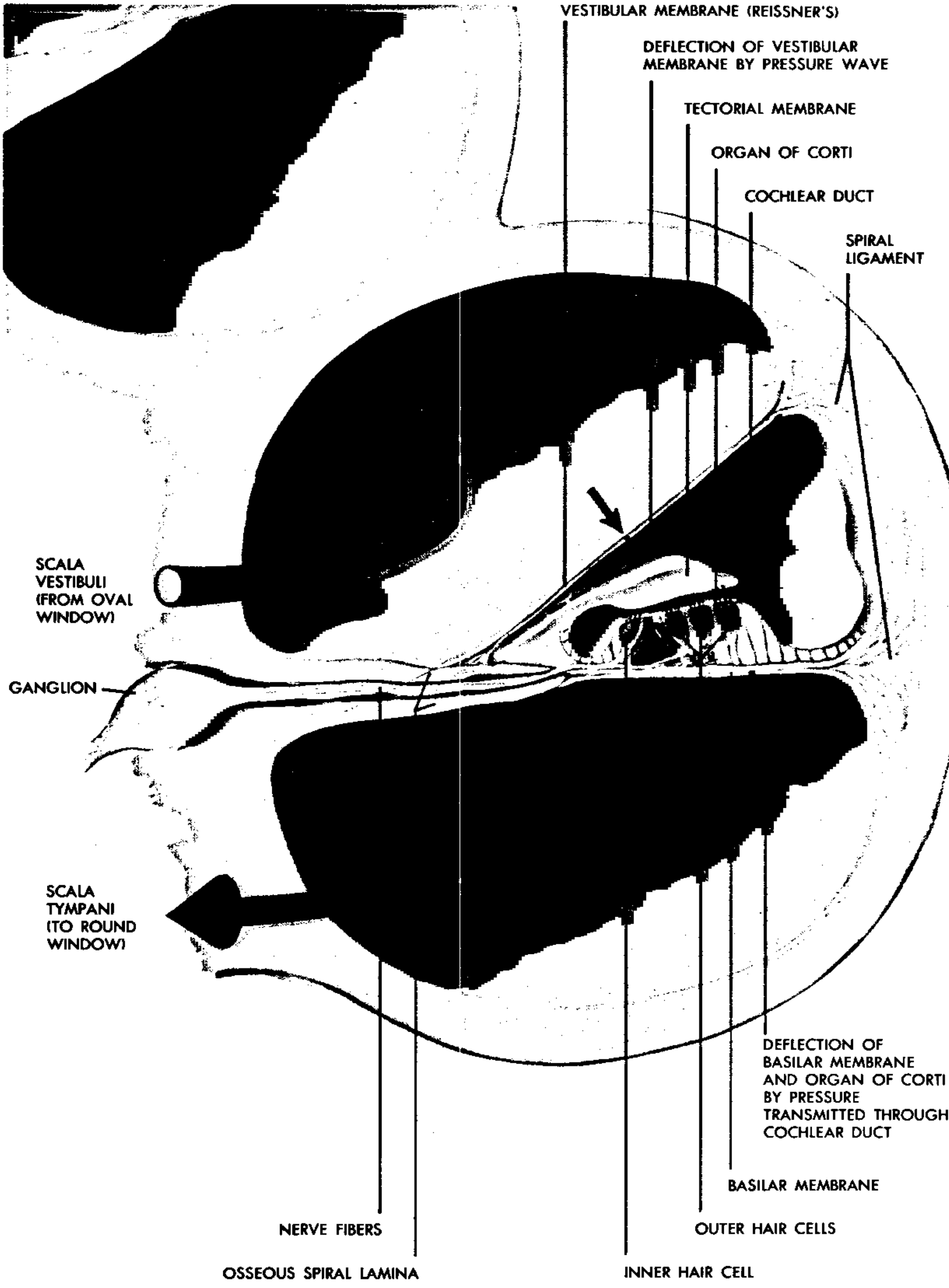


Figure 24-6. Transmission of Sound across the Cochlear Duct Stimulating the Hair Cells.

or cochlea duct." A bony shelf, the "spiral lamina," together with the basilar membrane and the spiral ligament, separate the upper scala vestibuli from the lower scala tympani. The third canal, the scala media, is cut off from the scala vestibuli by Reissner's vestibular membrane.

The scala media is a triangular-shaped duct within which is found the organ of hearing, namely, the "organ of Corti." The basilar membrane, narrowest and stiffest near the oval window, widest at the apex of the cochlea, helps form the floor of the cochlear duct. On the surface of the basilar membrane are found phalangeal cells which support the critical "hair cells" of the organs of Corti. The hair cells are arranged in a definite pattern with an inner row of about 3,500 hair cells and three to five rows of outer hair cells numbering about 12,000. The cilia of the hair cells extend along the entire length of the cochlear duct and are imbedded in the undersurface of the gelatinous overhanging tectorial membrane (Fig. 24-6).

Inner Ear Fluids. The vestibular and tympanic canals contain perilymph and communicate with each other through a tiny opening at the uppermost part of the cochlea, the "helicotrema." The perilymph has a high sodium concentration and a low potassium content whereas the opposite is true of endolymph. Since the transmission of neural impulses should be impossible in the high concentration of potassium found in endolymph, it has been shown that the fluid which bathes the organ of Corti — Cortilymph — has a different ionic content than that of endolymph, and furnishes a suitable medium for the normal functioning of the hair cells and neural endings of the organ of Corti.[3, 4]

The tectorial membrane appears to maintain a zero potential compared to the scala tympani while the endolymph has a positive potential and the organ of Corti, a negative potential. The positive resting potential of the endolymph has been labelled the "endocochlear or DC potential." A change in the resting potential of the endolymph results from acoustical stimulation so that the scala media is negative relative to the scala tympani, "summating potential."

In short, the fluids of the cochlear duct supply nourishment to Corti's organ, a system of removing waste products, an appropriate medium for the transmission of neural impulses, and a means of eliminating noise that its own blood supply would produce.

Transmission of Sound Waves in the Inner Ear. The two openings afforded by the oval and round windows are essential for sound pressure waves to pass through the cochlear fluids. The movement of the stapedial footplate in and out of the oval window moves the perilymph of the scala vestibuli (Fig. 24-7). This vibratory activity travels up the scala vestibuli, but causes a downward shift of the cochlear duct with distortion of Reissner's membrane and displacement of endolymph and Corti's organ. The activity is then transmitted through the basilar membrane to the scala tympani. When the oval window is pushed inward, the round window acts as a relief point and bulges outward.

Transduction. The conversion of mechanical energy of sound into electrochemical activity is called transduction. The vibration of the basilar membrane causes a pull, or shearing force of the hair cells against the tectorial membrane. This "to and fro" bending of the hair cells activates the neural endings so that sound is transformed into an electrochemical response. It remains to be clarified whether an electrical and/or chemical process stimulates the neural endings.

Travelling Waves. In general, the hair cells at the base of the cochlea transmit high frequency sounds while those at the apex especially respond to low frequency tones. This results in the travelling wave phenomena in which there is a specific point of maximum displacement of the basilar membrane beyond which the wavelength and the amplitude become progressively smaller in character. High pitched sounds travel a short distance along the basilar membrane before they die out; the opposite occurs with low pitched sounds.

Nerve Conduction. Each nerve fiber connects with several hair cells, and each hair cell with several nerve fibers. The hair cells stimulate auditory neural endings and nerve fibers which stream out through small openings in the spiral lamina into the hollow modiolus (Fig. 24-5). The cell bodies of the nerve fibers form the spiral ganglia whose axons make up the cochlear (auditory) division of the eighth cranial nerve. The movement of the hair cells sets up action potentials, and coded information from both ears are sent to the cochlear nuclei and thereafter to the temporal lobe of the brain where cognition and association takes place. Fig. 24-7 summarizes the peripheral mechanism of hearing.

CLASSIFICATION OF HEARING LOSS

Loss of hearing can be classified into the following categories: 1. Conductive impairment; 2. Sensorineural impairment; 3. Mixed (both conductive and sensorineural); 4. Central impairment; 5. Psychogenic impairment.

Conductive Hearing Loss

Any condition which interferes with the transmission of sound to the cochlea is classified as a conductive hearing loss. Pure conductive losses do not damage the organ of Corti nor the neural pathways.

A conductive loss can be due to wax in the external auditory canal, a large perforation in the eardrum, blockage of the eustachian tube, interruption of the ossicular chain due to trauma or disease, fluid in the middle ear secondary to infection, or otosclerosis, that is, fixation of the stapedial footplate. A significant number of conductive hearing losses are amenable to medical or surgical treatment.

Sensorineural Hearing Loss

A sensorineural hearing loss is almost always irreversible. The sensory component of the loss involves the organ of Corti and the neural component implies degeneration of the neural elements of the auditory nerve.

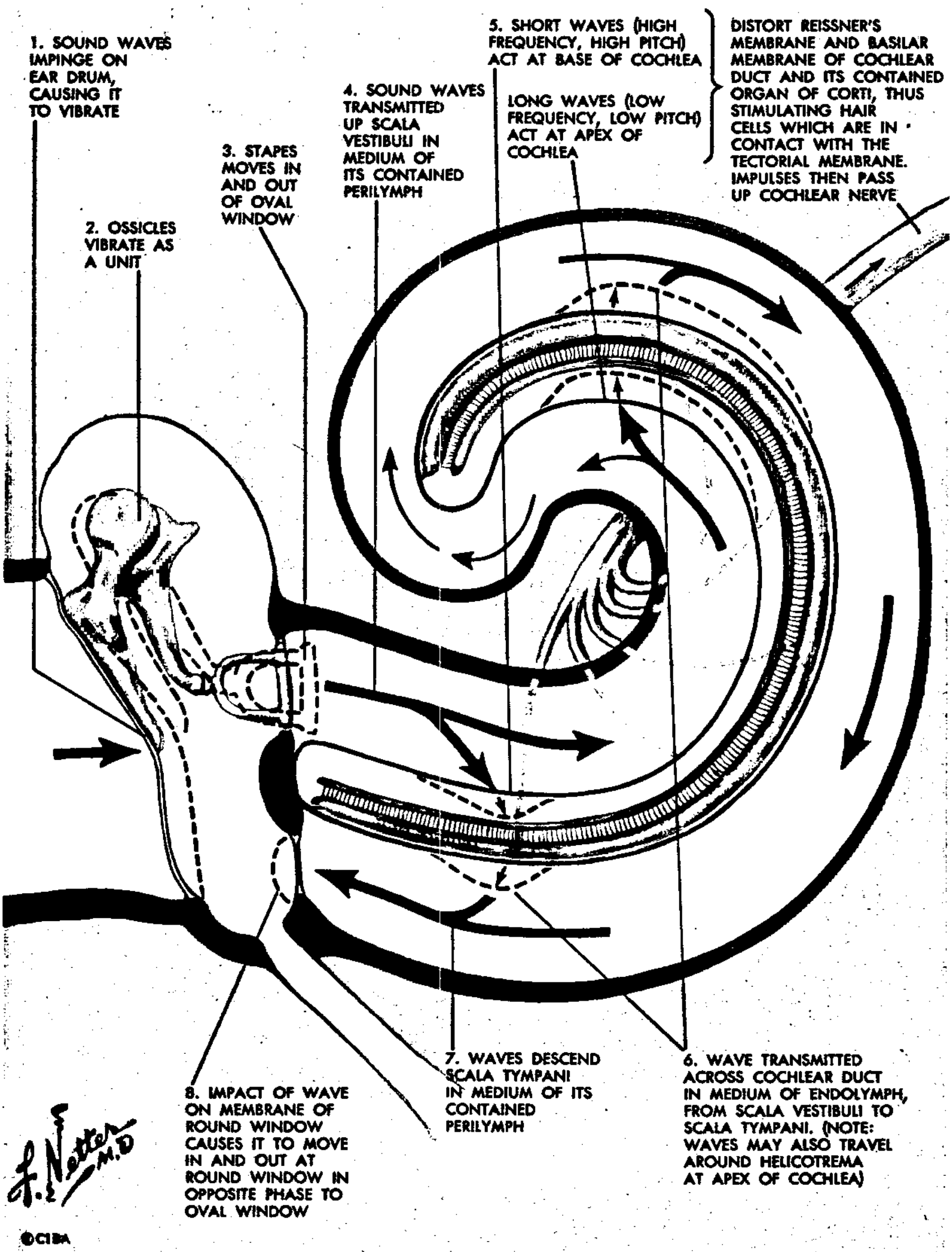


Figure 24-7. Transmission of Vibrations from Drums through Cochlea.

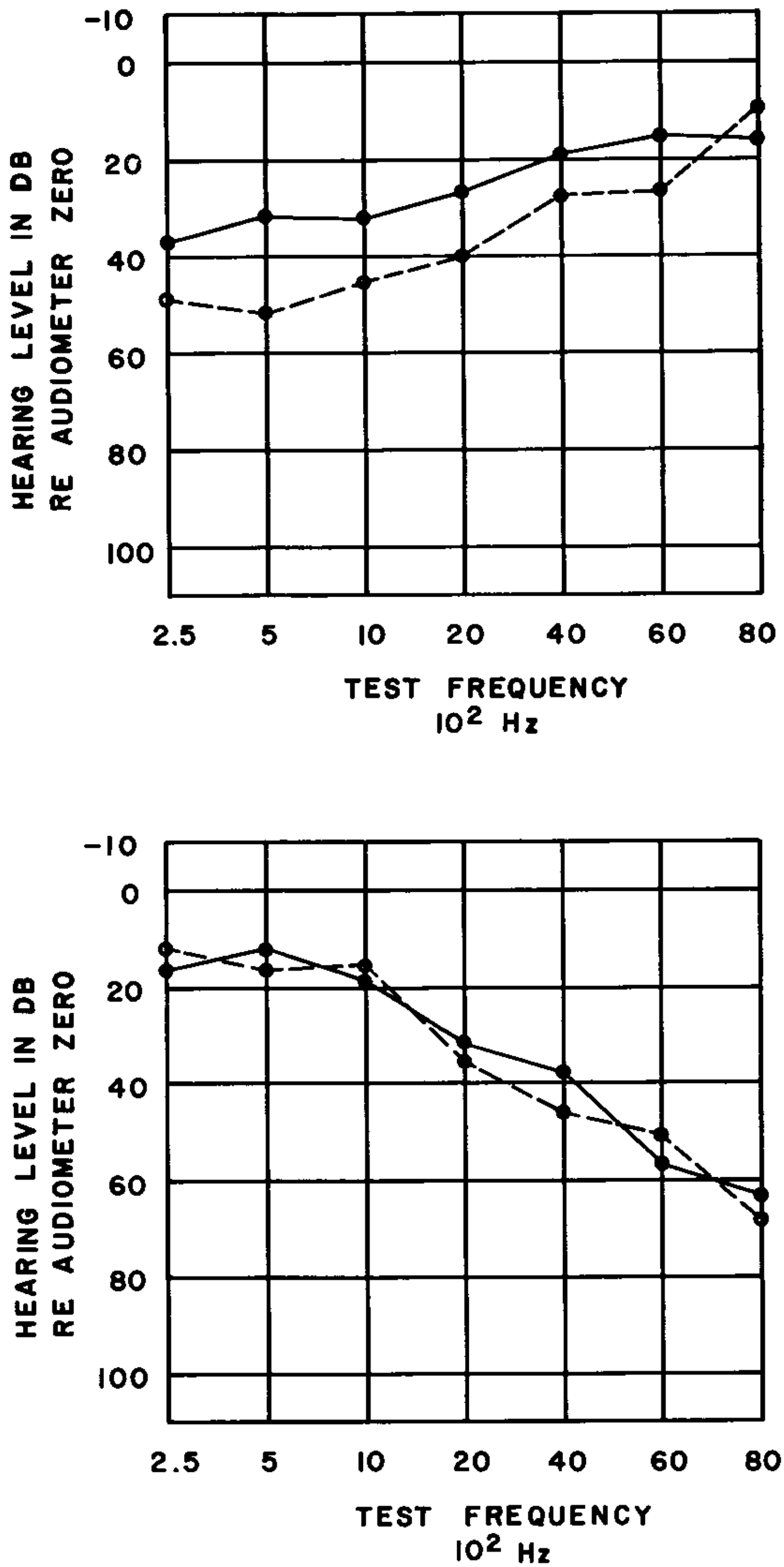


Figure 24-8. Audiograms Showing A) Conductive and B) Sensorineural Types of Hearing Loss.

Exposure to excessive noise causes an irreversible sensorineural hearing loss. Damage to the hair cells is of critical importance in the pathophysiology of noise-induced hearing loss. Invariably, degeneration of the spiral ganglion cells and the peripheral nerve fibers accompany severe injury to the hair cells.

Sensorineural hearing loss may be attributed to various causes, including presbycusis, viruses (e.g., mumps), some congenital defects, and drug toxicity (e.g., streptomycin).

Mixed Hearing Loss

Mixed hearing loss occurs when there are components and characteristics of both conductive and sensorineural hearing loss in the same ear.

Central Hearing Loss

A central hearing loss implies difficulty in a person's ability to interpret what he hears. The abnormality is localized in the brain between the auditory nuclei and the cortex.

Psychogenic Hearing Loss

A psychogenic hearing loss indicates a "nonorganic" basis for an individual's threshold elevation. Two conditions in which such a loss may occur are malingering and hysteria.

AUDIOMETRY

The pure tone audiometer is the fundamental tool used in industry to evaluate a person's hearing sensitivity. It produces tones which vary in frequency usually from 250 Hz to 8,000 Hz at octave or half-octave intervals. The intensity output from the audiometer can vary from zero dB to 110 dB, and is often marked "hearing loss" or "hearing level" on the audiometer.

Zero dB or zero reference level on the audiometer is the average normal hearing for different pure tones and varies according to the "standard" to which the audiometer is calibrated. Zero reference levels have been obtained by testing the hearing sensitivity of young healthy adults and averaging that sound intensity at specific frequencies at which they were just perceptible. It is to be differentiated from the 0.0002 microbar references for the sound pressure level measurements. If a person has a 40 dB hearing loss at 4,000 Hz, it means that for the individual to perceive a tone the intensity of that tone must be raised to 40 dB above the "standard."

The audiogram serves to record the results of the hearing tests. A graphic description of the faintest sound audible is obtained by plotting the intensity against the frequency. Examples of audiograms which indicate conductive and sensorineural losses are shown in Fig. 24-8. In conductive hearing losses, the low frequencies show most of the threshold elevation, whereas the high frequencies are most often involved with the sensorineural losses.

The recording of an audiogram is deceptively simple, yet for valid test results, one must have a properly calibrated audiometer, an acceptable test environment to eliminate interfering sounds, and a qualified audiometrician. When a marked hearing loss is encountered, bone conduction audiometry and more sophisticated hearing tests are often helpful in diagnosing the site and cause of the hearing loss.[5] For more details concerning appropriate American National Standard Institute (ANSI) standards and the objectives of a good audiometry program, refer to the preferred reading list.

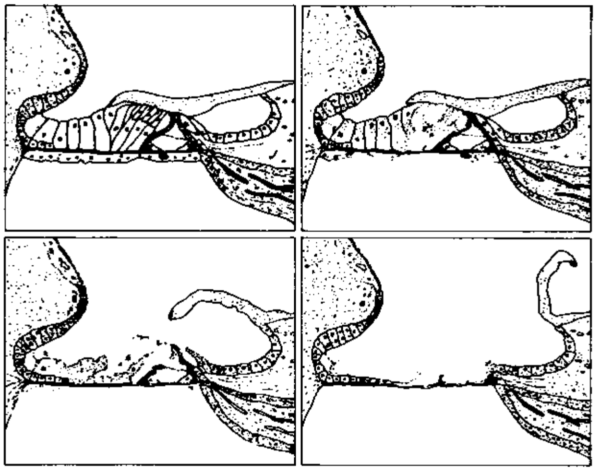
EFFECTS OF EXCESSIVE NOISE EXPOSURE

Since the ear does not have an overload switch or a circuit breaker, it has no option but to receive all the sound that strikes the eardrum. In industry, excessive noise constitutes a major health hazard. Such exposure can cause both auditory and extra-auditory effects.

Auditory Effects

Noise induced hearing loss (NIHL) can happen unnoticed over a period of years. At first, excessive exposure to harmful noise causes auditory fatigue or a temporary threshold shift (TTS). This shift refers to the difference in one's hearing sensitivity measured before and after exposure to sound. It is called "temporary" since there is a return of the individual's pre-exposure hearing level after a period of hours away from the intense sound.

However, repeated insults of excessive noise can transform this TTS into a permanent threshold shift (PTS). In fact, studies substantiate that the hearing sensitivity of factory workers in heavy industry is poorer than that of the general population. Fig. 24-9 depicts the stages of destruction



Lawrence M.: Auditory problems in occupational medicine. Arch. Environ. Health 3:2888, Copyright 1961, American Medical Association, Chicago, Ill.

Figure 24-9. Stages of Destruction of the Organ of Corti. (A) The normal organ of Corti. (B) A stage of hair cell degeneration following the first subtle changes within the cytoplasm of the cells. The internal hair cell remains intact. (C) Both inner and outer hair cells are gone, and the supporting structures are degenerating. (D) In the final stages, the entire organ of Corti is dislodged, leaving a denuded basilar membrane, which may become covered with a simple layer of eipthelial cells. (Arch. Environ. Health) of the organ of Corti in a laboratory test animal that was overstimulated by loud continuous noise.

Many factors influence the course of NIHL. The overall "decibel level" of the noise exposure is obviously important. If a noise exposure does not cause auditory fatigue, then such exposure is not considered harmful to one's hearing sensitivity.

Another consideration is the "frequency spectrum" of the noise. Noise exposure which has most of its sound energy in the high frequency bands is more harmful to a worker's hearing sensitivity than low-frequency noises.

Another factor is the daily "time distribution" of the noise exposure. In general, noise which is intermittent in character is less harmful to hearing than steady state noise exposure. As the "total work duration" (years of employment) of a worker to hazardous noise is increased, so too does the incidence and magnitude of his NIHL. However, no report of "total" hearing loss has been attributed to excessive noise exposure alone.[6]

Finally, the "susceptibility" of the worker to hazardous noise must be considered, since not every individual will suffer identical hearing impairment if exposed to the same noise intensity over the same time period. A small percentage of workers will be highly susceptible or, on the other hand, refractory to the degrading effects of noise.

The hearing loss from "acoustic trauma" should be differentiated from the insidious, irreversible sensorineural NIHL that results after months or years of exposure to excessive noise conditions. Acoustic trauma refers to the loss of hearing secondary to head or ear trauma, or after exposure to a sudden, intense noise such as that of firearms or explosions. A conductive type of hearing loss results when the trauma causes a perforated eardrum or disruption of the middle ear ossicles. The trauma can cause a sensorineural loss, but not infrequently, the hearing loss is temporary in nature. Besides causing hearing loss, hazardous noise levels can mask speech, be a source of annoyance, and occasionally degrade a worker's job performance.[7]

Extra-Auditory Effects

The extra-auditory effects of noise result in physiologic changes other than hearing. We are familiar with the reflex-like startle response of an individual to a loud, unexpected sound. Less commonly noted are the cardiovascular, neurologic, endocrine and biochemical changes secondary to intense noise exposure. Subjective complaints of nausea, malaise, and headache have been reported in workers exposed to ultrasonic noise levels. Vasoconstriction, hyperreflexia, fluctuations in hormonal secretions, disturbances in equilibrium and visual functions have been demonstrated in laboratory and field studies. These changes have been for the most part transient in character, and it remains to be clarified whether such noise exposure has long lasting ill effects on the organism.[8]

SUMMARY

The important function of the hearing mechanism is to convert the mechanical energy of sound pressure waves into an electrochemical response. Excessive noise exposure can tax the physiologic limits of the hearing mechanism and cause an irreversible, sensorineural hearing loss. Noise is just one of many causes of hearing loss, so that a relevant medical history and a detailed history of a worker's previous employment will eliminate many false conclusions concerning the cause of a worker's loss of hearing.

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Preferred Reading

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CHAPTER 25

NOISE MEASUREMENT AND ACCEPTABILITY CRITERIA

James H. Botsford

INSTRUMENTS FOR SOUND MEASUREMENT

There is probably a greater variety of instruments for measuring noise than for any other environmental factor of concern to industrial hygienists. Almost every measurement need can be satisfied with instrumentation available commercially today. Only those instruments more useful to the industrial hygienist will be discussed here.

Sound Level Meters

The standard sound level meter is the basic measuring instrument for the industrial hygienist. It consists of a microphone, an amplifier with calibrated volume control and an indicating meter. It measures the root-mean-square (rms) sound pressure level in decibels which is proportional to intensity or sound energy flow.

General Radio Co., Concord, Massachusetts.

Figure 25-1. A Standard Sound Level Meter.

Sound level meters of the same type differ mainly in external shape, arrangement of controls, and other convenience features that frequently influence the selection made by a prospective user. A typical sound level meter is pictured in Figure 25-1.

Standards for sound level meters[1, 2, 3] specify performance characteristics in order that all conforming instruments will yield consistent readings under identical circumstances. The more important characteristics specified are frequency response, signal averaging and tolerances.

TABLE 25-1

Relative Response of Sound Level Meter Weighting Networks

Frequency Hertz	Weighted Response, dB		
	A	B	C
31.5	−39	−17	−3
63	−26	−9	−1
125	−16	−4	0
250	−9	−1	0
500	−3	0	0
1000	0	0	0
2000	1	0	0
4000	1	−1	−1
8000	−1	−3	−3

Reproduced with permission of General Radio Company, West Concord, Mass., from "Handbook of Noise Measurement," 1967.

Three weighting networks are provided on standard sound level meters in an attempt to duplicate the response of the human ear to various sounds. These weighting networks cause the sensitivity of the meter to vary with frequency and intensity of sound like the sensitivity of the human ear.

The relative responses of the three networks are shown in Table 25-1 where the A, B and C weightings mimic ear response to low, medium and high intensity sounds respectively. Entries in the table show relative readings of the meter for constant sound pressure level of variable frequency. These A, B and C meter response curves correspond to the 40, 70 and 100 phon equal loudness contours. The D-weighting network is provided on some sound level meters for approximating the "perceived noise level" used in appraising the offensiveness of aircraft noises.

The A-weighting network is the most useful one on the sound level meter. It indicates the A-weighted sound level, often abbreviated dBA, from which most human responses can be predicted quite adequately.[4]

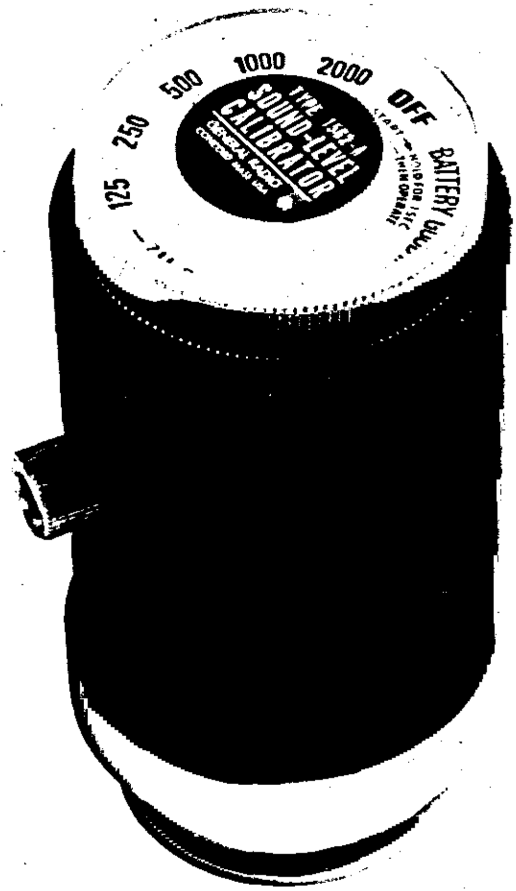
Action of the indicating meter may be selected as "fast" or "slow." Relatively steady sounds are easily measured using the "fast" response. Unsteady sounds can be averaged with the more sluggish "slow" response to reduce meter needle swings.

The speed of meter response affects the readings obtained for transient sounds. For example, the level of a whistle toot lasting 1/5 second would be indicated no more than 2dB low on the "fast" scale. On the "slow" scale, the level of a toot lasting 1/2 second would read 3 to 5 dB low.

American standard sound level meters are furnished in three types offering varying degrees of precision.[1] Designated Types 1, 2 and 3 in order of increasing tolerances, the Type 2 generally measures within 2 or 3 dB of true levels which is satisfactory for most purposes. Errors are about half as large with the Type 1 or "precision" sound level meter and about twice as large with the Type 3 "survey" instrument. These errors can be reduced somewhat by careful calibration.

Calibrators

The overall accuracy of sound measuring equipment may be checked by using an acoustical calibrator such as is shown in Figure 25-2. It consists of a small, stable sound source that fits over the microphone and generates a predetermined sound level within a fraction of a decibel. If the meter reading is found to vary from the known calibration level, the meter may be adjusted to eliminate this error. The acoustical calibration procedure supplements the electrical calibration incorporated in some meters to check the gain of all electronic components following the microphone. Sound level calibrators should be used only with the microphones for which they are intended in order to avoid errors and microphone damage.



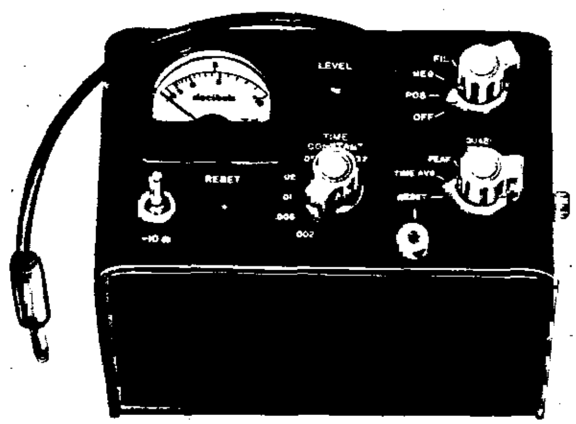
General Radio Co., Concord, Massachusetts.

Figure 25-2. A Sound Level Calibrator.

Impulse Meters

The sound level meter is too sluggish to indicate peak levels of transient noises lasting a fraction of a second such as those produced by hammer blows or punch press strokes. Such noises must be measured with a special meter that indicates the peak level.

Accessory impulse meters are available for connection to sound level meters and can be calibrated to indicate the peak level of the sound at the microphone. One of these is shown in Figure 25-3. In taking such readings, it is necessary to



General Radio Co., Concord, Massachusetts.

Figure 25-3. A Noise Peak Meter for Connection to a Sound Level Meter.

B&K Instruments, Inc., Cleveland, Ohio.

Figure 25-4. A Precision Sound Level Meter with an Octave Band Filter Attached to the Base.

be sure that the upper sound pressure limit of the microphone is not exceeded as the indicated level will then be too low. The upper limit of the sound level meter can be extended by replacing the standard microphone with a less sensitive one that is linear to higher levels. Such microphone substitutions affect the calibration of the sound level meter and must be taken into account when interpreting readings.

The sound level meter in Figure 25-4 is equipped with a circuit for measuring impulse noise according to a German standard. It has a rather slow rise time in order that the indication of impulsive sound will correlate with the loudness perceived by the ear. For impulses that rise abruptly, the reading with this circuit is lower than would be found with a true peak meter. However, the instrument shown has been provided also with an instantaneous peak reading circuit that will indicate the true peak.

Frequency Analyzers

It is often necessary to know the frequency distribution of the sound energy. It is important in noise abatement, for example, since the reduction afforded by control devices varies with frequency. Such information is provided by one of the several types of sound spectrum analyzers available. They may be connected to the sound level meter or other sound sensing system. The electrical signal from the microphone is filtered by the analyzer circuitry so that only signals within a limited frequency range are transmitted to the indicating meter. Measurement of sound pressure level in contiguous frequency ranges provides data for a plot of sound pressure level versus frequency.

Octave band analyzers are the types most commonly encountered. An octave band filter set is shown attached to the lower end of a sound level meter in Figure 25-4. The frequency range of each band is such that the upper band limit is twice the lower band limit. Formerly, octave bands were described by these cut-off frequency limits such as 300 to 600, 600 to 1200, etc. Currently they are designated by the geometric mean of the cut-off frequencies which are called center frequencies. Thus, when the 1000 Hz band is mentioned, it is understood that it extends from 710 to 1420 Hz. The center and cut-off frequencies of octave band filters in common use are shown in Table 25-2.

Often bands narrower than octaves are required for pinpointing the frequency of a tone. In such applications, the one-third and one-tenth octave analyzers are quite valuable. Some of these can be coupled to a graphic level recorder which tunes the analyzer through the frequency range and simultaneously plots its output on a moving paper chart. This equipment is very useful in determining sources of noise in machinery since sound of a particular frequency must be generated by mechanical events such as the meshing of gear teeth, passing of fan blades, etc. which are repeated at the same rate.

Accessory Equipment

As most sound is generated by vibration of some body, it is sometimes desirable to study the

TABLE 25-2.
Center Frequencies and Limits of Octave Bands.

Traditional bands, Hz			Preferred bands, Hz		
Lower limit	Center freq.	Upper limit	Lower limit	Center freq.	Upper limit
19	27	38	22	31.5	44
38	53	75	44	63	88
75	106	150	88	125	177
150	212	300	177	250	355
300	425	600	355	500	710
600	850	1,200	710	1,000	1,420
1,200	1,700	2,400	1,420	2,000	2,840
2,400	3,400	4,800	2,840	4,000	5,680
4,800	6,800	9,600	5,680	8,000	11,360

Reproduced with permission of General Radio Company, West Concord, Mass., from "Handbook of Noise Measurement," 1967.

vibration as well as the sound. Accessory vibration pickups are available for most sound level meters to make such vibration analysis possible. They are generally accelerometers for which the electrical output is proportional to the acceleration of the surface to which they are attached. Types sensitive to the velocity or displacement of the surface are also available. Complete vibration meters are supplied too, for greater convenience.

The vibration signal may be examined for frequency content using any of the sound analyzers discussed earlier. In this way, vibration at a particular frequency may be correlated with the sound of the same frequency it produces. Calibrators are available for checking the sensitivity of the vibration pickup to reduce errors in measuring the acceleration of a surface.

The cathode ray oscilloscope is useful for observing the wave-form of a sound. It plots the sound pressure versus time on a television-type screen. From observation of the wave shape, it is sometimes possible to determine the mechanical process responsible for the noise. It is also possible to observe the peak pressures of impulsive sounds. Cameras are available for photographing the face of the cathode ray tube to obtain a permanent record of the wave form.

A graphic record of sound level may be obtained by connecting a sound level meter to a graphic level recorder which plots the sound level on a moving paper chart. The pen speed of the recorder must be capable of following the fluctuations in sound level if an accurate record is to be obtained.

The magnetic tape recorder can be used to store a sound for later analysis on replay. An instrument of broadcast quality must be used to obtain high fidelity reproduction of the sound on playback. For analysis on replay, the recorder output should be connected to the analyzer input by means of a patch cord. Too much distortion will occur if the recording is played back through a loud-speaker and picked up with a microphone. If only the frequency content is of interest, then no precautions need be taken to keep track of level during recording and playback. However, if it is necessary to determine the true levels of the original noise on playback, careful recording of calibration tones must be undertaken. Generally, it is better to measure sound directly in the field if possible.

Sound Monitors

When sound level varies erratically over a wide range, it is difficult to describe the noise by meter readings. Therefore, statistical analyzers have been developed to assist in this process. They indicate the percentage of time that the sound level lies in certain predetermined level ranges. From these data, the mean level, standard deviation as well as other statistical indices may be calculated.

Another type of monitor evaluates noise exposures according to the rules established by the American Conference of Governmental Industrial Hygienists (ACGIH),[5] which will be described in a section that follows. These instruments may be exposed to varying noise for a work day and will indicate whether this exposure limit has been exceeded. One of the battery-powered, wearable types is shown in Figure 25-5.

A different type of noise hazard meter recently developed integrates the effects of noise like the ear does.[6] When exposed to non-impulsive noise of any duration, it indicates the amount of temporary shift in hearing threshold that a group of normal ears would experience in the same expo-

duPont de Nemours & Co., Wilmington, Delaware.

Figure 25-5. A Battery-Powered Noise Monitor That Can Be Worn by a Workman.

sure. Its reading is interpreted according to the theory that noise exposures producing little temporary hearing loss are not likely to produce much permanent hearing loss even after many repetitions.

ACCEPTABILITY CRITERIA

Criteria for the acceptability of noise are dictated by the effects which are to be avoided. The most important of these is hearing damage resulting from prolonged exposure to excessive noise. Another undesirable effect is speech interference or interruption of communications by noise. Annoyance is a third undesirable effect of noise more difficult to assess. There are also certain non-auditory effects of noise we are just beginning to recognize, which are discussed later in this chapter.

Hearing Damage

The damaging effect of noise on hearing depends on (1) the level and spectrum of the noise, (2) duration of exposure, (3) how many times it occurs per day, (4) over how many years daily exposure is repeated, (5) the effects on hearing regarded as damage and (6) individual susceptibility to this type of injury. All of these factors must be considered in establishing limits of acceptable exposures to dangerous noise.

Noise Evaluation. Early in the study of the effects of noise on hearing, it was learned that noise frequency as well as intensity influenced the effect produced. High frequency noise was found to be more damaging than low frequency noise of the same sound pressure level. Therefore, noise spectra were evaluated with standard octave band analyzers which were the only portable spectrum analyzers then available.

As knowledge of noise effects grew, some investigators began to feel that octave band analysis was a needlessly complicated evaluation of noise which could be replaced with the A-weighted sound level measured using a standard sound level meter. It seemed that the A-weighting network made the meter less sensitive to low frequency sounds to about the same extent that the ear is less susceptible to injury by these low frequency sounds.

In these studies, the damage to be avoided was impairment of ability to understand "everyday speech" as defined by the medical profession.[7] This medico-legal definition allows some observable change in hearing thresholds not sufficient to affect ability to understand everyday speech significantly.

Steady Noise. All day exposure to steady noise has been investigated to determine the level at which hearing damage begins after many years of redundant exposure. Such studies are the basis for the curves in Figure 25-6 which indicate the risk of hearing impairment associated with exposure to a steady noise level at work.[8] Each curve indicates on the vertical scale the percentage of workers that showed impaired hearing as defined by the medical profession after working continuously in the noise levels shown on the horizontal scale.

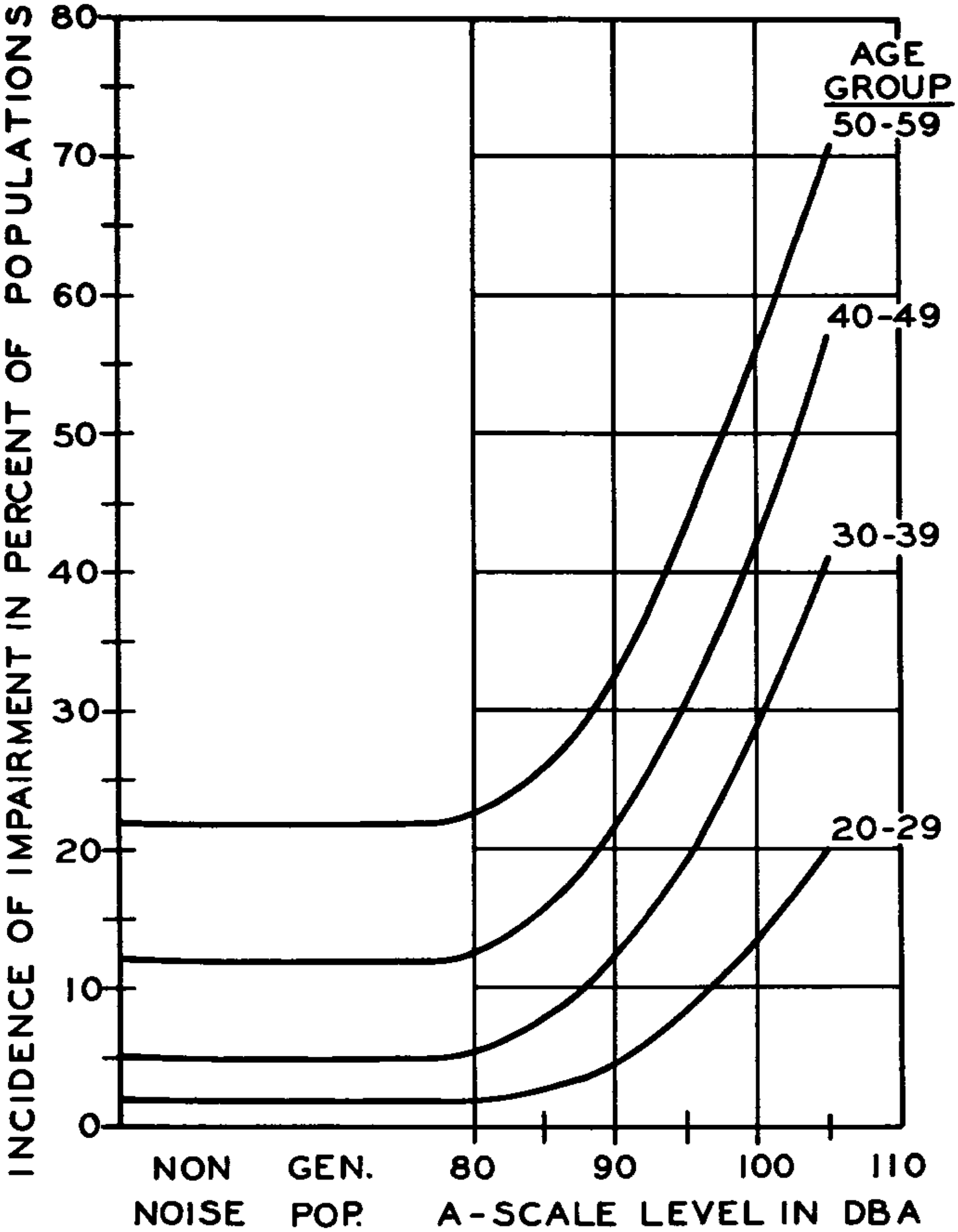
To interpret the Figure, note that the upper curve shows that in a group of 100 men aged 50 to 59 years, which has been exposed to 90 dBA at work for 33 years, 33 men should show evidence of impaired hearing. However, note that the lower flat portion of the same curve indicates that the general population and others not exposed to dangerous noise at work exhibit 22 cases of impaired hearing out of every hundred. Therefore, near-lifetime exposure to 90 dBA at work seems to produce about 11 more cases of impaired hearing per hundred surviving than would otherwise have occurred. As the data generating the curves of Figure 25-6 are not so consistent as the precise lines would indicate, this difference of 11 percentage points is about the smallest that can be considered significant. For lower age groups exposed for shorter periods, the increase in prevalence of impaired hearing is much less pronounced. The curves of Figure 25-6 suggest 90 dBA as one limit for steady exposure to continuous noise, a limit that has become rather widely accepted. Future standards may lower this limit.

Intermittent Noise. Most occupational noises are intermittent rather than continuous. Interrupting harmful noise allows the ear to rest and recover which reduces the likelihood of permanent damage.[9] Such intermittent exposures have not been studied much because of the great complexities of exposure description. As a result, theories are relied upon to set limits for intermittent noise.

The theory most generally accepted postulates that the hazard of noise exposure increases in proportion to the average temporary hearing loss which the exposure would produce in a group of normal ears. This theory arises out of the observation that those noise exposures that ultimately produce permanent hearing loss also produce temporary hearing loss in normal ears. Conversely, those noise exposures that do not produce permanent hearing loss do not produce temporary hearing loss in normal ears. While the true relation between temporary and permanent hearing loss has not been established, it is logical to assume that those noise exposures that do not cause much temporary loss will not cause much permanent loss either. Any temporary threshold shift (TTS) that disappears before the next exposure to noise commences is considered acceptable.

On the basis of this assumption, results of TTS studies have been used to define safe limits for all day exposures to steady noise. These limits agree with those established by permanent threshold shift studies.

TTS studies have also indicated that intermittent noise is much less harmful than steady noise. The laws describing growth of TTS during exposure and recovery afterwards have been used to calculate exposures producing acceptably small amounts of TTS.[10] Combinations of sound level, duration of exposure and degree of repetition that are considered acceptable for personnel exposures at work are shown in Table 25-3.[11] This method for appraising noise exposures was derived from the report describing hazardous exposure to intermittent and steady-state noise prepared by the National Academy of Science-National Research



Guidelines for noise exposure control. Sound and Vibration 4:21, 1970.

Figure 25-6. Prevalence of Impaired Hearing and Sound Levels at Work.

Council, Committee on Hearing, Bio-acoustics and Bio-mechanics, generally referred to as CHABA.[12] Maintaining exposures within the limits CHABA recommended will allow few additional cases of impaired hearing to occur.[13]

TABLE 25-3.

Maximum Permissible Sound Levels for Intermittent Noise When Occurrences Are Evenly Spaced Throughout the Day.

Total noise duration per day (8 hours)	Number of times noise occurs per day						
	1	3	7	15	35	75	160 up
8 h.	89	89	89	89	89	89	89
6	90	92	95	97	97	94	93
4	91	94	98	101	103	101	99
2	93	98	102	105	108	113	117
1	96	102	106	109	114	125	125 (1½ h)
30 m.	100	105	109	114	125		
15	104	109	115	124			
8	108	114	125			A-weighted	
4	113	125				sound levels,	
2	123					dBA	

Reproduced with permission from "Sound and Vibration" Bay Village, Ohio (4:16, 1970).

To use Table 25-3, select the column headed by the number of times the noise occurs per day, read down to the average sound level of the noise and locate directly to the left in the first column the total duration of the noise permitted for any 24 hour period. It is presumed that the noise bursts are evenly spaced throughout the work day so that an opportunity for rest and recovery between noise bursts exists. It is permissible to interpolate in the Table if necessary.

Table 25-3 shows that intermittency is as important as duration and level. For example, it shows that a continuous noise level of 91 dBA can be tolerated for 4 hours; 101 dBA can be tolerated also for 4 hours if it is presented in 15 evenly spaced bursts lasting 16 minutes each. Thus, the interruption of the higher noise reduces the effect on hearing to that which would be produced by a steady noise of equal duration 10 decibels lower. So you might say that the interruptions are equivalent to a 10 decibel noise reduction.

Impulsive Noise. Exposure limits for impulse noise are based on studies of the average TTS caused in normal ears by exposure to various impulses. Limits that will cause little TTS and, therefore, little expected permanent damage have been set.[14] These limits are complicated to apply and, as a result, have not been widely used.

However, an approximate method of determining whether these limits are likely to be exceeded can be carried out with the sound level meter using the C-weighting and "fast" meter response. To do so, set controls so that zero on the meter scale corresponds to a level of 130 dB. If the impulse does not cause the meter needle to jump above 125 dB (minus 5 on the meter scale), then it probably is not excessive.[15]

ACGIH TLV for Noise. The noise exposure limits expressed in Table 25-3 are inconvenient to use in practice. So, a simplification of the table was adopted in 1970 by the ACGIH as a threshold limit value (TLV) for noise.[5] It is shown in Table 25-4. The simplification embodies the presumption that practically all noise exposures are interrupted at least a few times a day by meals or rest periods, machinery stoppages, etc. The limits of Table 25-4 correspond very closely to those of Table 25-3 for noises that occur three to seven times per day. Since these exposure limits do not take proper account of intermittency, they do not provide a true evaluation of hearing damage potential of the noise exposure. They are too liberal for absolutely continuous noise and too conservative for noise that is interrupted very frequently.

If an exposure consists of two or more noise levels, the combined effect must be considered. To do so, it is necessary to compute the ratio of the duration of each level to the duration allowed by Table 25-4. The sum of these ratios for all noise levels involved in the exposure must not exceed unity if the exposure is to be acceptable. Noise levels below 90 dBA are not considered in these calculations. The graph in Figure 25-7 is convenient for calculation of exposures involving several levels.

For impulsive sounds, ACGIH proposed a limit of 140 dB peak which is quite conservative compared to the recommendations of Coles et al.[14]

TABLE 25-4

Threshold Limit Values for Non-impulsive Noise Adopted by the American Conference of Governmental Industrial Hygienists

Duration per day, hours	Permissible sound level, dBA
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
¾	107
½	110
¼	115 max.

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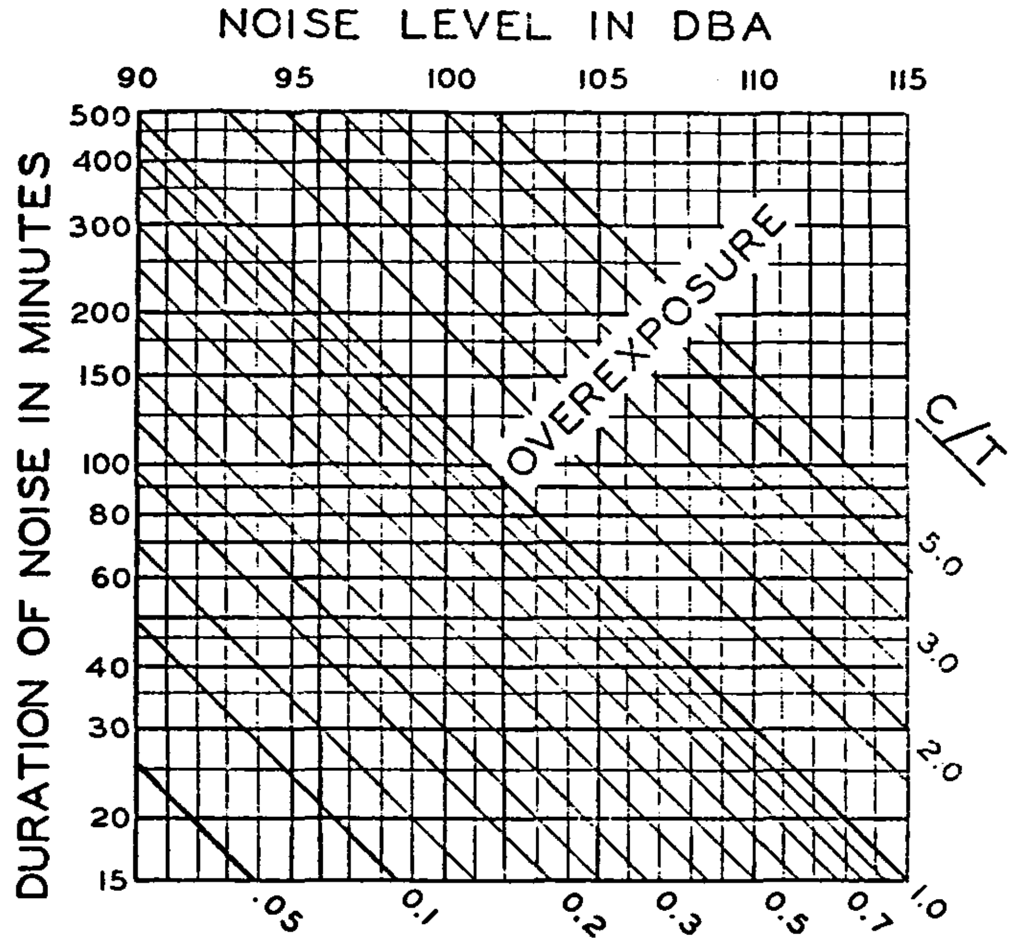


Figure 25-7. Graphical Presentation of ACGIH TLV for Noise. To use the graph, locate the point corresponding to the noise level and duration; then read off the exposure ratio C/T from the diagonal lines interpolating if necessary.

The ACGIH TLV for noise was accepted by the U.S. Department of Labor for promulgation under the provisions of the Occupational Safety and Health Act of 1970. It is being adopted also by many states for enforcement as part of their occupational health regulations.

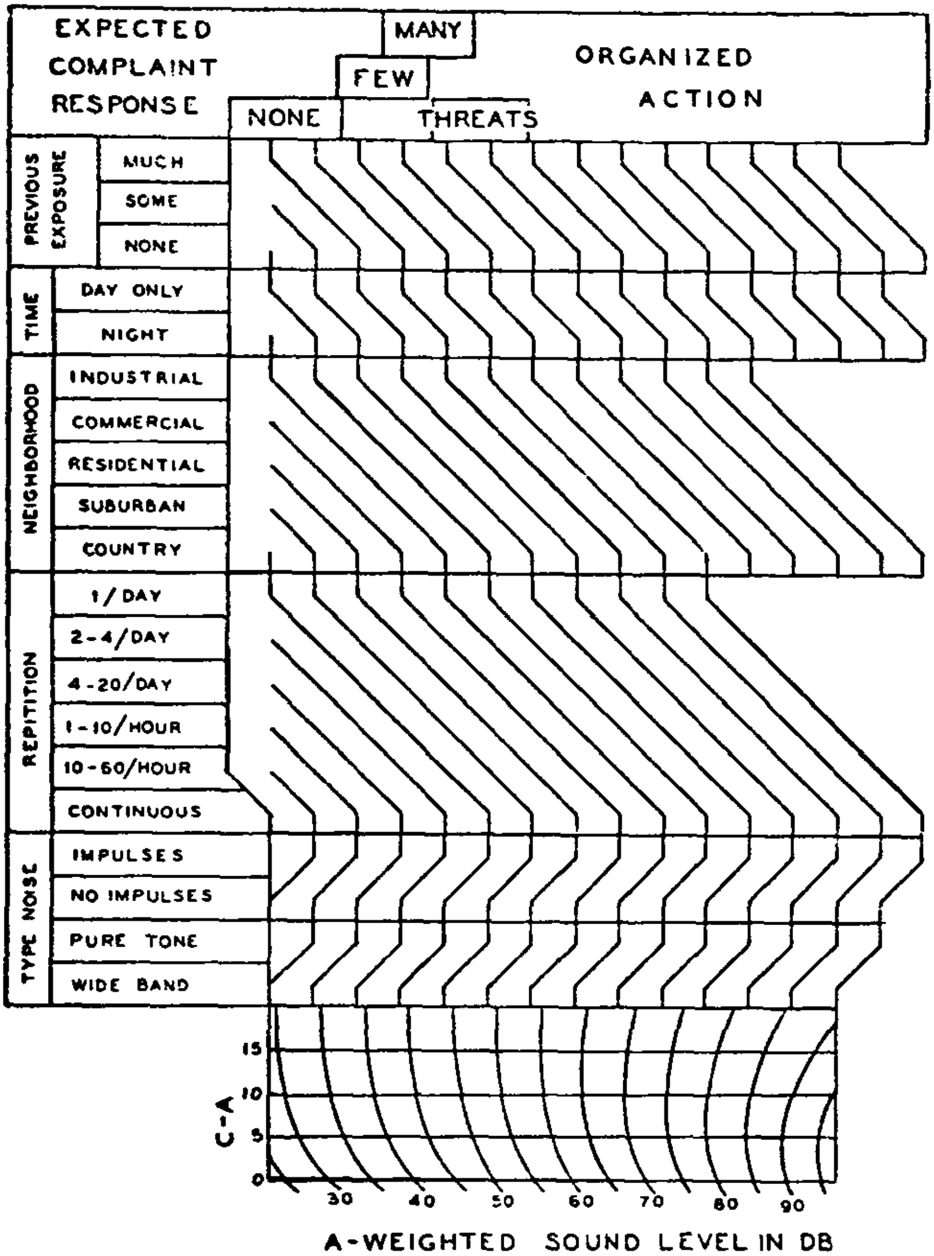
Non-occupational Exposures. All that has been said up to now about hearing damage applies to the noise exposures at work. Medical evaluation of hearing handicap from occupational noise exposure disregards changes in hearing that do not affect ability to understand everyday speech significantly.

When it comes to the non-occupational exposures in transportation vehicles, public places, etc., none of these mitigating influences exist. Yet levels equalling those in industry are often encountered and there is a tendency to apply industrial standards when appraising the hazard. Stricter standards of safety should be imposed for non-occupational exposures so that no change in hearing whatsoever can occur. Dr. Cohen has recommended limits 15 dB below the limits shown in Table 25-4.[16]

Speech Interference

Noise can mask or "blot out" speech sounds reducing the intelligibility of messages. Laboratory studies of these effects have appraised the disruptive potential of the noise by its "speech interference level" which is the average sound pressure level of 500, 1000, and 2000 Hz octave bands.[17] The distances at which difficult messages can be conveyed reliably are shown in Table 25-5 as a function of speech interference level. Simple, redundant messages normally used at work can be understood at greater distances.

The speech interference level is closely related to the A-weighted sound level. It is lower by 7 decibels for most common noises. Using this conversion, the speech interference effects of various noises may be estimated from A-weighted sound levels using Table 25-5.



Botsford J. H.: Using sound levels to gauge human response to noise. Sound and Vibration 3:16, 1969.

Figure 25-8. Chart for Estimating Community Complaint Reaction to Noise.
To use the chart, locate in the curved grid at the bottom the point corresponding to the sound levels of the noise under consideration (C-A is the difference between the C- and A- weighted sound levels). From this point, project directly upward into the first of the six correction sections bounded by the horizontal lines. When entering a correction section, follow the lane entered until reaching a position opposite the condition listed at the left which applies to the neighborhood noise under consideration, and then proceed vertically, disregarding lanes, until the next section is reached. In this way, work up through the lanes of the correction sections until reaching the top where the community reaction to be expected is shown.

Annoyance

Annoyance by noise is a highly subjective phenomenon which is very difficult to relate to the sound that causes it. Noises become more annoying as they get louder than the background noise on which they are superimposed. Noises that are unsteady or contain tones are most annoying as are those that convey unpleasant meaning.

Indoors, noise is likely to become annoying when the A-weighted sound level exceeds 30 dBA in auditoria or conference rooms, 40 dBA in private offices and homes, or 50 dBA in large offices or drafting rooms. Outdoors, a noise can be expected to prove annoying if it exceeds the background level by 10 dBA or more.

A procedure for rating the annoyance potential of a noise in the community is given in Figure 25-8.[4] It provides a method for estimating community complaint reaction to a given noise condition.

TABLE 25-5

Maximum Speech Interference Levels for Reliable Communication at Various Distances and Vocal Efforts.

Distance,	Vocal Effort			
feet	Normal	Raised	Loud	Shout
0.5	76	82	88	94
1	70	76	82	88
2	64	70	76	82
4	58	64	70	76
8	52	58	64	70
16	46	52	58	64
32	40	46	52	68

Reproduced with permission of General Radio Company, West Concord, Mass., from "Handbook of Noise Measurement," 1967.

Non-Auditory Effects

Audible noise produces other effects which are just beginning to be examined.[18] Laboratory studies have shown that noise reduces efficiency on some tasks, can upset the sense of balance, and can cause blood vessels to constrict, raising blood pressure and reducing the volume of blood flow. It causes the pupils of the eyes to dilate. Even when we are sleeping, noise can cause changes in electro-encephalograms and blood circulation without waking us. Noise can also cause fatigue, nervousness, irritability, hypertension and add to the overall stress of living. There is no convincing evidence so far that any of these effects become permanent and thus are deleterious to health.

Very intense noise below 1000 Hz can be felt as well as heard. Airborne vibrations can stimulate mechano-receptors throughout the body, including touch and pressure receptors and the vestibular organs. The respiratory system is affected by sounds in the 40 to 60 Hz range because of the resonance characteristics of the chest.

Sounds too high in frequency to be heard by the normal ear produce no significant effect when they reach the body by air pathways. However, transmission of ultrasound into the body through fluid or solid media is more efficient and can produce cavitation of the tissue as well as deep burns.

Intense sound below the audible frequency range can cause resonant vibration of the eye balls and other organs of the body. Dizziness and nausea can result. Levels of 130 dB or more are required to cause there effects, and are not often encountered in industry.

SURVEY TECHNIQUES

One should become thoroughly familiar with operation of noise measuring instruments through study of operating instructions before attempting to make noise surveys. Set up the equipment and check its operation before embarking. At intervals during the survey, batteries should be checked as well as overall instrument calibration.

When transporting instruments, they should be protected from vibration and shock as much as practical. Instruments should also be protected from extremes of temperature. Overheating, such as might occur in the trunk of a car parked in the sunshine, can damage circuit components. Allowing the instrument to become very cold in a car parked overnight in the winter will result in condensation of water vapor in the instrument when it is used in a heated space the next morning. Water condensed from the air can cause electrical leakage resulting in low readings.

When conducting surveys, it is important to be assured that the meter indication is due to noise and not to other influences. One way of doing so is to listen to the meter output with a pair of headphones to learn whether the sound heard is the noise being measured.

Wind blowing across the microphone causes a rushing sound that is registered on the meter. Use of a wind screen can minimize this effect. Electric and magnetic fields can also cause needle deflections. This interference may occur around welding on large assemblies and becomes apparent when the meter needle does not move in step with the loudness of the noise heard. These electromagnetic effects can be reduced by reorienting the meter until minimum coupling with the electrical fields is obtained as indicated by minimum meter reading. One particularly troublesome location where electrical interference is observed is around electric furnaces. Here, the electrical interference and the noise are coincident so that it is easy to confuse these spurious signals with noise.

When taking readings, one should obtain representative data. The microphone should be moved about to determine that standing waves are not present. If they are, a spatial average should be obtained.

Exposure Surveys

When conducting exposure surveys of various kinds, the most important consideration is to measure levels that are typical of those at the auditor's location. It is not necessary, in fact it is undesirable, to measure sound right at the ear since diffraction around the head can alter the sound field. It is better to measure at some location a few feet away where exploration with the sound level meter indicates levels are the same as at the auditor's location. When attempting to evaluate the potential for hearing damage, all factors of significance must be recorded such as sound level, duration, intermittency, etc., necessary to make proper evaluation of an exposure, using Table 25-3.

If one is merely attempting to determine compliance with the regulatory limits shown in Table 25-4, then the ACGIH exposure evaluation procedure must be followed. When noise levels are too variable to allow this procedure to be carried out with a sound level meter and stop watch, a noise monitor may be used. Several of these are commercially available to compute automatically the fractional exposure according to the prescribed methods. One of these monitors is shown in Figure 25-5.

Source Determination

When attempting to locate sources of noise in a room or in a machine, the simplest approach is to probe the sound field with the sound level meter. The noise will increase as the source is approached and disclose its location. Extension cables can be used to remove the microphone from the meter for greater convenience in these explorations.

Another aid to locating the original sources of noise is spectral analysis of vibrating parts, the frequency of the sound will be the same as the frequency of the part vibration. Thus, narrow band analysis will often reveal frequencies that can be correlated with repetitive mechanical events or multiples thereof. These clues point to the mechanical disturbances responsible for the noise.

SUMMARY

A complete array of instruments is available for measuring steady, intermittent and impulsive noises. Sound level meters, calibrators, frequency analyzers, and accessory equipment are provided by several suppliers. Sound exposure monitors which can be worn by roving workmen record individual patterns of exposure that could be assessed in no other way.

Criteria have been established for avoiding permanent hearing loss resulting from steady, intermittent and impulsive sounds. The Threshold Limit Value for noise, adopted by the American Conference of Governmental Industrial Hygienists, has been accepted widely. Non-occupational exposures require stricter limits to provide complete protection.

Criteria for avoiding speech interference and complaints of annoyance are also available. Several non-auditory effects of noise are being studied, but no harmful effects that require safety criteria have been discovered yet. Techniques for surveying noise conditions are well developed so that any noise problem can be readily evaluated.

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