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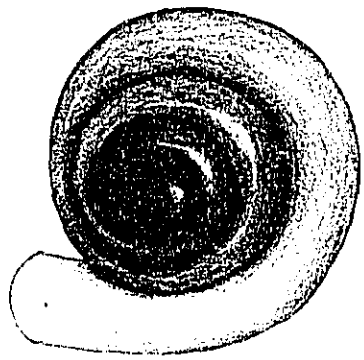
In defence of hearing



The indispensable sense

Hearing, sight, taste, smell and touch — of our five sense organs we are most dependent on the ears and the eyes. Sight is of paramount importance in our work and leisure activities, while hearing appears to be the most influential in shaping our personalities. Hearing in combination with speech allows us to communicate with each other, exchange ideas, opinions, learning and experience. It is also our most sensitive and fundamental warning mechanism. It is receptive to impressions from all possible sources and open to impulses whether we are awake or asleep. Modern technology with radio, TV and telecommunications has given hearing even greater importance in our daily life.

Unfortunately, modern living conditions have also made hearing the sense most often and easily damaged. Today our environment contains many different noises that the ears are neither designed to withstand nor shut out. Consequently, loud and incessant noise can damage the hearing apparatus to such an extent that the individual becomes completely or partially isolated from his surroundings. And deafness is a tragedy. Whereas blindness evokes our instant sympathy, deafness often goes unrecognised.

In our grandfather's day a loud, clanking machine was looked upon as a symbol of strength, power and affluence. Noise was something you got used to, or rather one of the many discomforts to be accepted in the course of making a living. That people working in noisy places eventually became deaf or hard-of-hearing was put down to age or considered just part of the job. Nowadays we no longer need to adopt this attitude. There are many ways of reducing noise, both at our place of work and outside in our everyday lives. What is needed is to make everyone aware of the hazards and the remedies and so generate a general movement to combat noise. According to many experts noise is likely to become one of our most serious environmental problems.

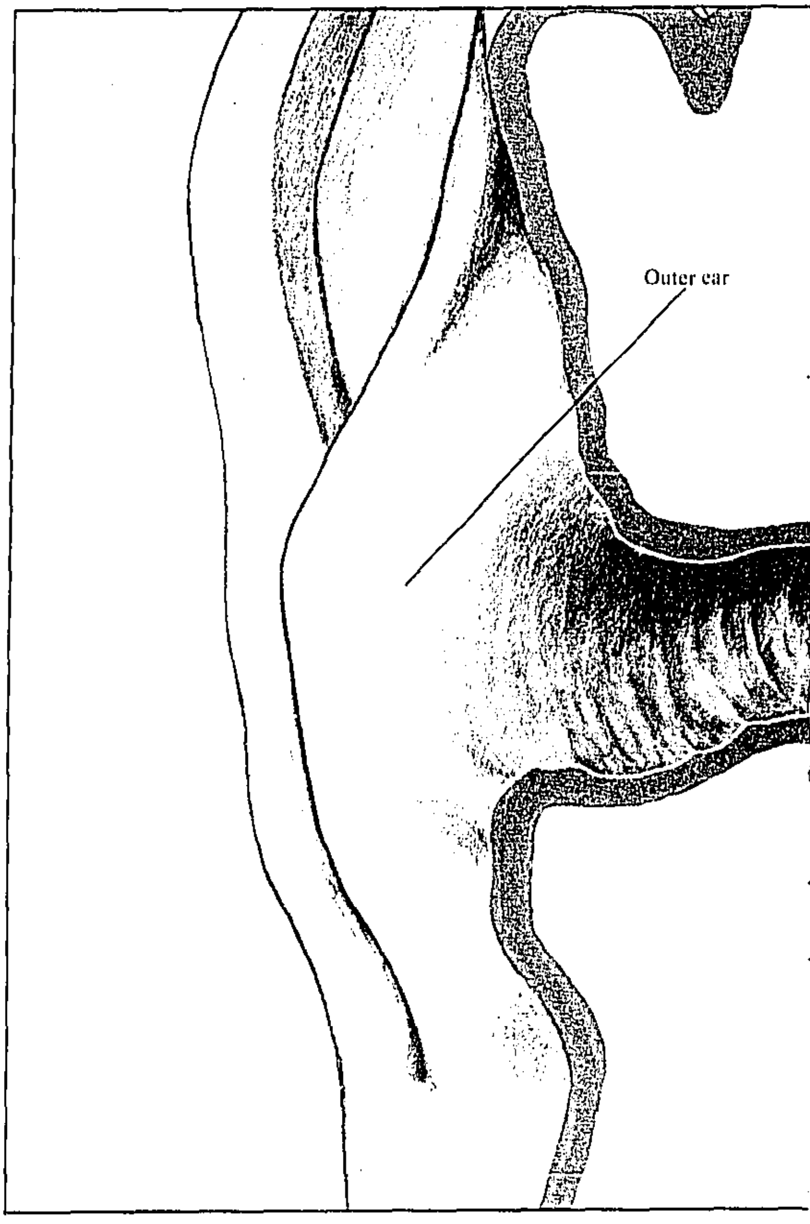
The intention of this publication is to relate in simple terms how our hearing functions, how it is affected by noise and how impairment can be prevented.

Physiology of hearing

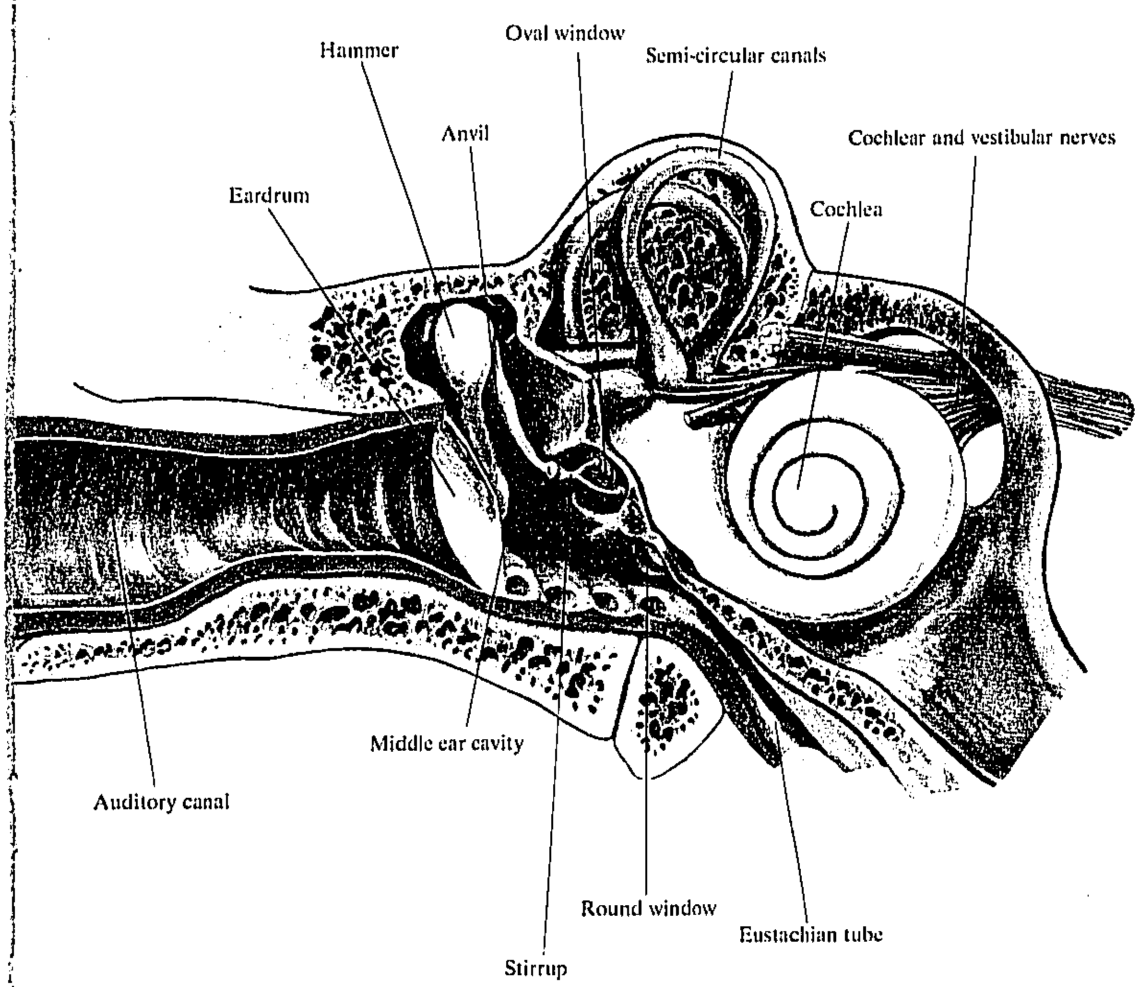
Sound or acoustic energy is created when the balance of the air is mechanically disturbed. The air pressure variations arising radiate in all directions from the source of the disturbance in the form of waves. When the vibratory energy impinges upon the ear it is registered by the brain via the three main parts of the hearing apparatures:
1) Outer ear with auditory canal,
2) Middle ear and 3) Inner ear.

The outer ear is so formed that the incident sound waves are collected and propagated through the air in the auditory canal (meatus) to set the eardrum (tympanic membrane) into vibration. Between the eardrum and the fluid-filled inner ear are the three small bones (ossicles) of the middle ear, known respectively as the hammer (malleus), the anvil (incus) and the stirrup (stapes). The hammer is attached to the ear drum and together with the anvil forms a lever that acts on the stirrup. The stirrup is attached to the oval window in the wall separating the middle and inner ears.

Since the area of the oval window is much smaller than that of the eardrum, the pressure exerted on the inner ear is considerably greater than that on the drum. In fact the middle ear acts as a sort of step-up mechanical transformer with a ratio of about 20:1. The middle ear also has two muscles, one acting on the eardrum and the other on the stirrup. These form a protective device and reduce the sensitivity of the ear when stimulated to reflex action by intense sounds.



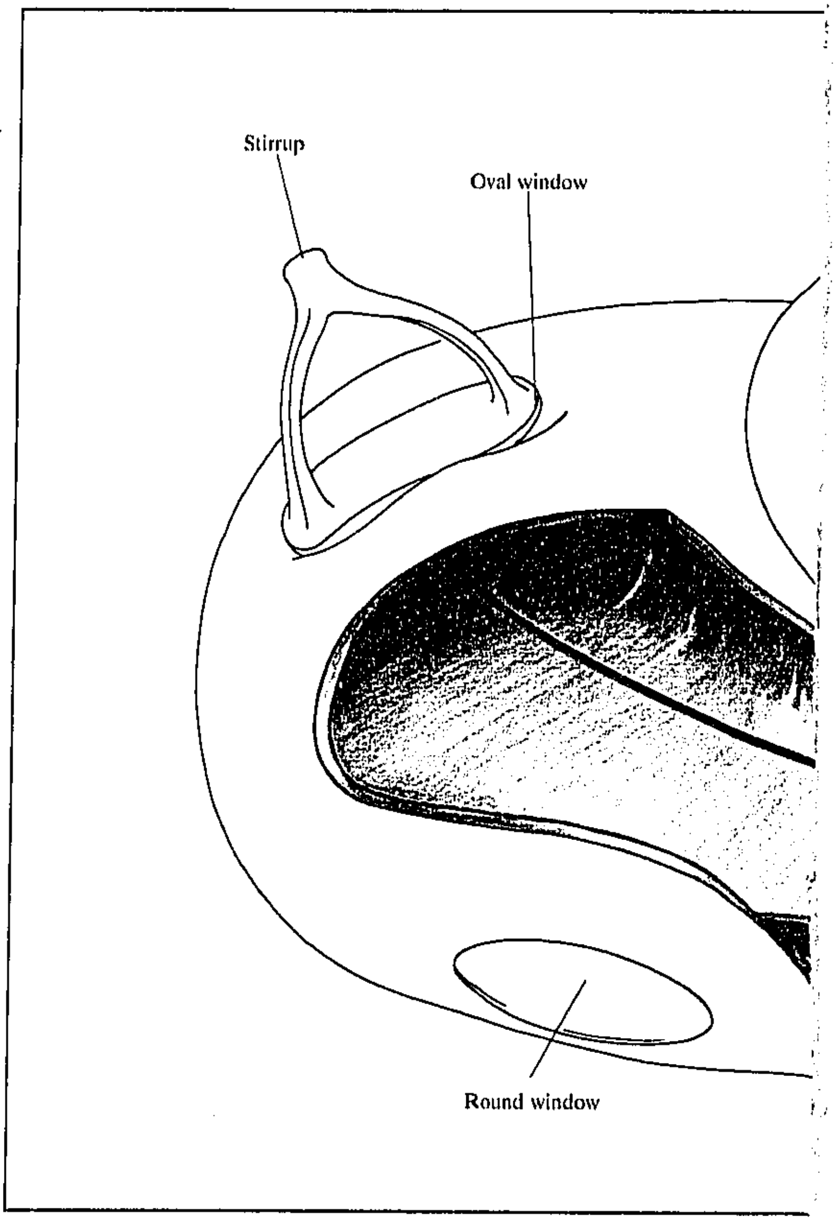
Anatomy of the ear


Hammer
Oval window
Semi-circular canals
Anvil
Cochlear and vestibular nerves
Eardrum
Cochlea
Middle ear cavity
Auditory canal
Round window
Eustachian tube
Stirrup

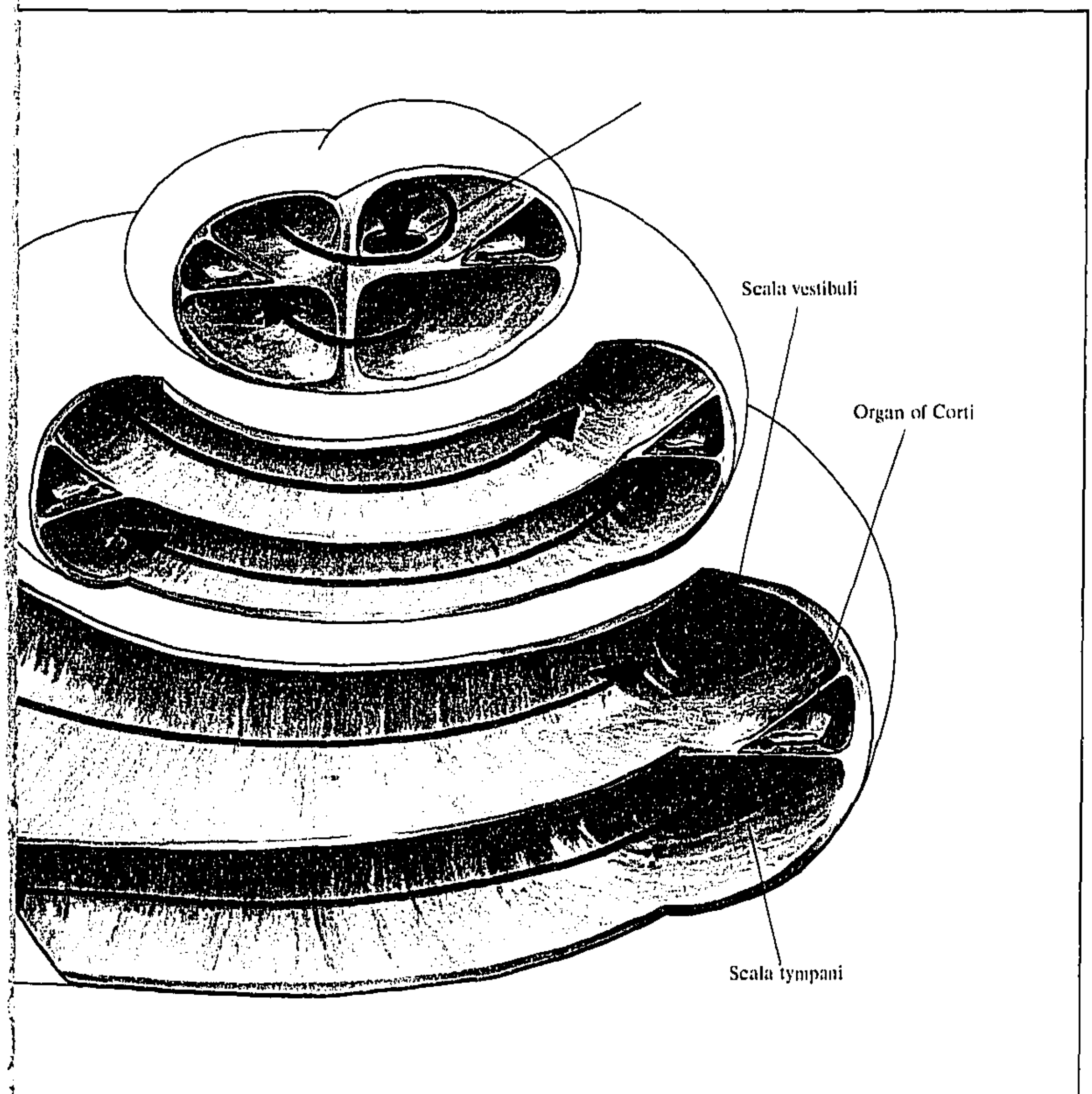
The middle ear, then, transmits sound energy in air to the fluid of the inner ear via the oval window membrane.

A complex set of small tubes and chambers embedded in solid bone constitutes the inner ear, or labyrinth as it is called. The part primarily concerned with hearing is the cochlea, a spiral cavity that resembles a snail shell. Uncoiled, the cochlea is about 35 mm long and is 3 mm in diameter at its first turn.

Dividing the spiral cavity into two passages is the cochlear duct with basilar membrane which runs almost to the apex of the spiral but leaves a small gap at the end known as the helicotrema. The upper passage (scala vestibuli) starts at the oval window. When a slowly applied pressure pulse is exerted by the stirrup on the oval window, fluid is displaced through the helicotrema into the lower passage (scala tympani). The lower passage terminates in another membrane, the round window, which then deflects to relieve the pressure.

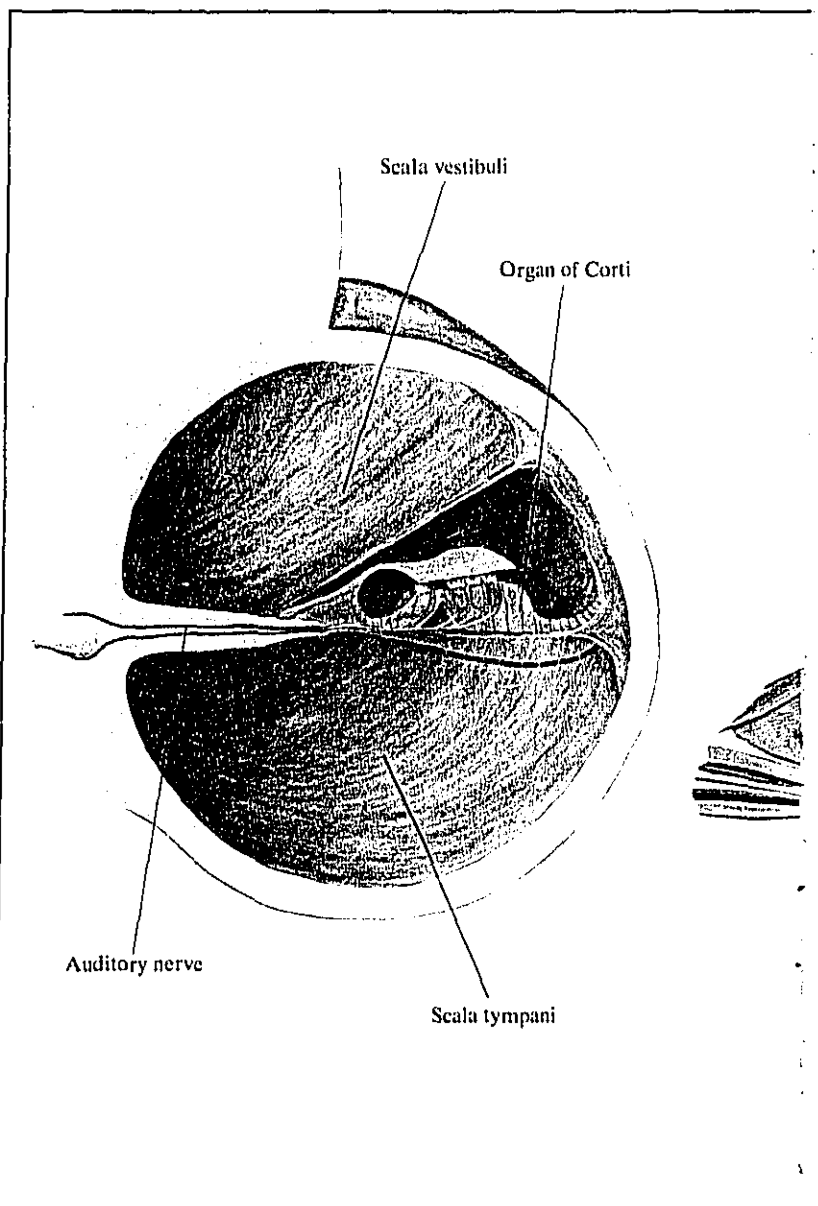


Bony cochlea section


Scala vestibuli
Organ of Corti
Scala tympani

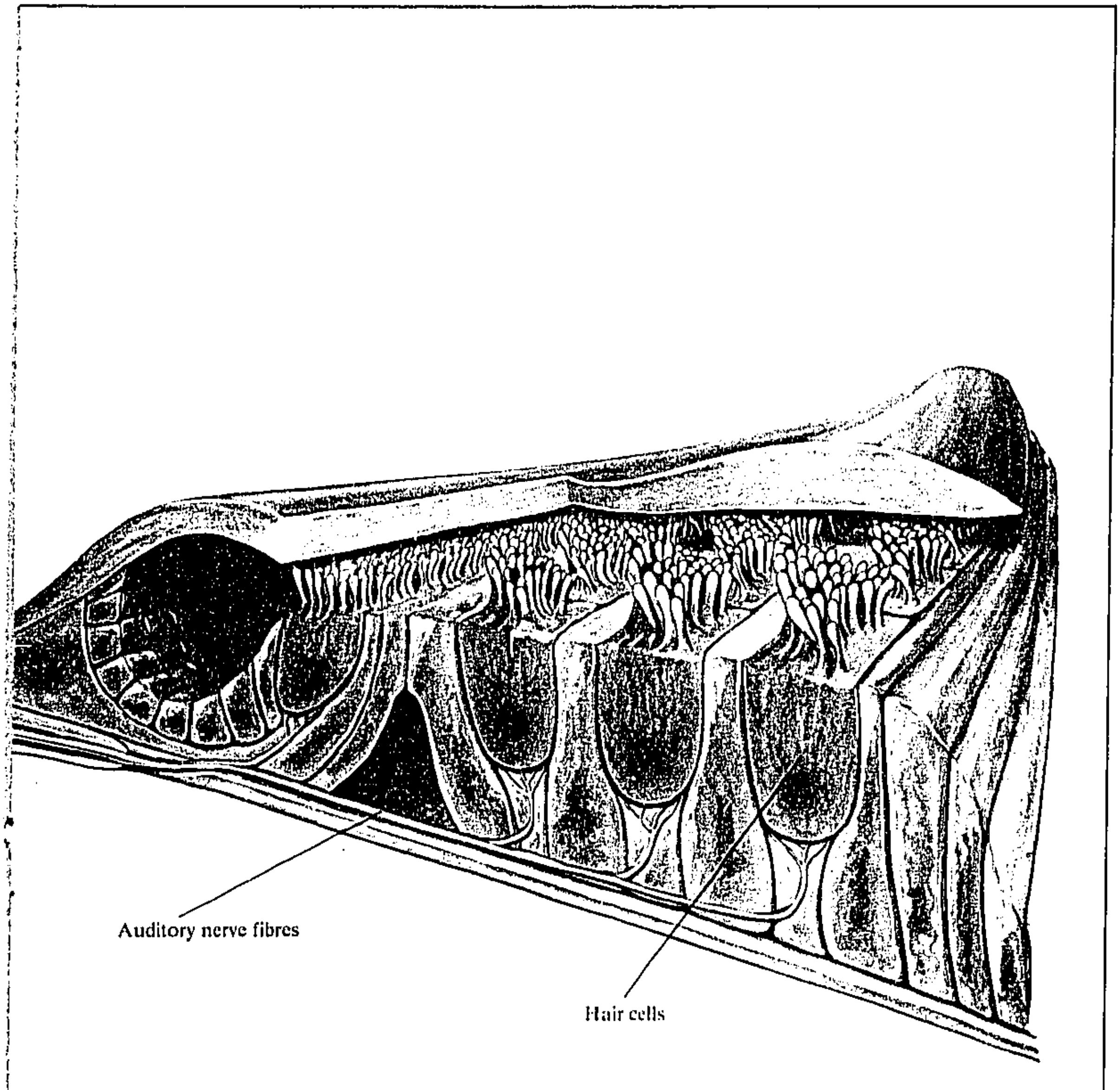
However, when the stirrup is oscillated at audio-frequencies a pressure differential is set up across the basilar membrane which is consequently distorted. On top of the basilar membrane is the organ of Corti, the sense organ of hearing. This is comprised of about 30 000 highly sensitive hair cells. Distortion of the basilar membrane bends the "tufts" on top of the hair cells, stimulating the nerve endings at their base. Thus the sound energy pattern is converted at the organ of Corti into action potentials in the auditory nerve. This then transmits the stimulation to the auditory centers of the brain.

The response of the basilar membrane varies with the frequency of the incident sound energy, each tone producing a maximum vibration in a different part of the membrane. High pitched sounds cause a short response that does not extend far from the oval window, but as the frequency is lowered the area of maximum displacement moves progressively away from the window end of the membrane.



Left: Section of cochlea
(The broken lines show deformation of the membranes resulting from vibration)

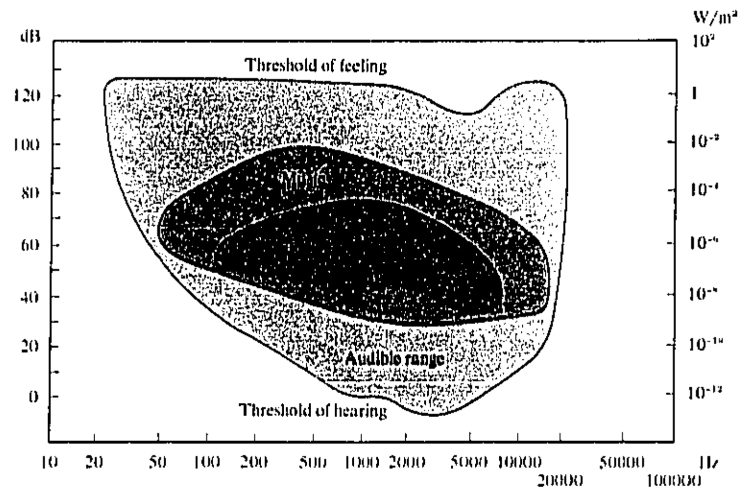
Right: Section of basilar membrane with organ of Corti.


Auditory nerve fibres
Hair cells

The sensitivity of the ear

Strictly speaking, of course, sound is something that exists only in the auditory apparatus of the hearer, but for practical purposes the term "sound" is taken to mean vibratory motion perceptible through the organ of hearing. Vibratory energy — or sound — travels in waves. And it is the frequency of the waves that determines the speed at which the eardrum and the other parts of the hearing organ vibrate, while the pressure level of the sound affects the magnitude of the oscillation. The brain then registers these movements as what we commonly call pitch and loudness.

In point of fact, we only hear a small portion of all the sounds we are subjected to every day. We cannot hear very weak sounds, nor sound waves with frequencies above or below certain limits. These limits or thresholds vary from person to person, but generally speaking the range of audible frequencies is from 20 to 20000 Hz. Loudness also has a lower limit (threshold of hearing), but its upper limit is more difficult to define. What is certain is that we can perceive very powerful levels of sound — but it causes discomfort or pain. The sound pressure level where the sensation of hearing converts to discomfort is termed the threshold of feeling. In order to compare differences in sound intensities, a logarithmic scale based on the threshold of hearing at 1000 Hz has been constructed, the practical unit being the decibel (dB).



A logarithmic scale is used because the sounds we are interested in range over such a vast span. For example the sound intensity represented by 120 dB (threshold of feeling) is in absolute terms 10^{12} times greater than at the lower threshold of audibility for a 1000 Hz note.

The ear is most sensitive in the frequency range 1000—4000 Hz. Outside this frequency band, the threshold of hearing is progressively higher, both up and down the frequency scale. On the other hand the threshold of feeling is roughly the same over the whole range of audible frequencies. The two threshold curves and the frequency range 20—20000 Hz enclose that area audible to humans.

But what lies outside these boundaries? No "unemployed" frequencies, to be sure. Dogs, bats and dolphins for instance have hearing organs that can detect ultrasonic frequencies. The audible limit for bats is 80000 Hz while for dolphins it is as high as 100000 Hz, a frequency that is easily propagated through water. It is maintained that dolphins can communicate with each other over distances of hundreds of miles. Infrasonic frequencies, below 20 Hz, can occur in machinery and can give rise to vibrations whose harmonics may produce audible sound waves.

	Sound intensity ratio	Sound level in dB(A)	Sound source
	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	100 000 000	80	Very busy traffic
	10 000 000	70	Private car
	1 000 000	60	Ordinary conversation
Safe range	100 000	50	
	10 000	40	Soft music from radio
	1 000	30	Quiet whisper
	100	20	Quiet urban dwelling
	10	10	Rustle of a leaf
	1	0	THRESHOLD OF HEARING

The sound intensity at the threshold of hearing for a 1000 Hz note is taken as 10^{-12} watts/m^2. The sound intensity ratio expresses how many times greater the intensity of a given sound is compared with the lower threshold value.

How we are affected by noise

The difference between sound and noise is usually defined by saying that noise is unwanted sound. Whether a sound is considered a noise or not is thus a purely subjective assessment, which often depends on our attitude to the source of the sound. When dealing with the damaging effects of noise there are three factors to be considered: its quality, the sensitivity of the individual, and the duration of exposure to the noise. The quality of noise can be defined as its strength, component frequencies and vibratory pattern. Individual sensitivity to noise can depend on inherited characteristics, health, age, sex, influence of drugs, etc.

In connection with noise, three types of effect are usually referred to: 1) Psychological 2) Masking 3) Physiological. The phychological or emotional effect is manifested in annoyance which can be caused by continuous or incessantly repeated noise. When it is a question of disturbed sleep or relaxation, the noise need not be of any great intensity — a dripping tap or traffic rumble can suffice. Irritating noise in cities or at places of work reduces a person's working capacity and efficiency. Generally it can be said that annoyance grows with the loudness of the noise and that noise patterns containing distinct tones are particularly disturbing.

A masking noise prevents the ear from registering other sounds, such as conversation and warning signals. Consequently this masking effect increases the risk of accident.

The chief physiological effect of noise is that the inner ear becomes damaged, either acutely due to sounds of very high intensity such as explosions or gradually as a result of long exposure to high industrial noise levels. Other physiological effects are increased blood pressure, metabolic function, and breathing rate. The blood circulation and digestive function slow down. All these responses can lead to headaches, nausea, muscle tension, general physical tiredness and nervousness, which in turn can impair alertness.

As previously mentioned, the ear is most sensitive to frequencies between 1000 and 4000 Hz. It can better withstand frequencies both higher and lower. This fact makes it difficult to prescribe a general sound pressure level above which noise becomes injurious after a certain time of exposure. Acceptable levels must therefore be determined for each frequency band.

The ISO (International Organization for Standardization) has formulated ratings for noises with respect to the risk of permanent hearing damage. The noise ratings are presented as curves which relate frequency with sound pressure level, having regard to the varying sensitivity of the ear with frequency. Each noise rating curve is given a number, eg. N-85.

N-85 curve has been recommended as the acceptable limit for steady, broad-band noise where the daily dose is five or more hours over a period of about 10 years.

The rating of a given noise is assessed by making an octave band analysis at the normal location of the person subjected to noise. This is to say that the sound pressure level at different frequency bands is measured. Certain octave band center frequencies are standard: 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. The sound pressure values in dB are then plotted on the N curve diagram. If the plotted spectrum does not penetrate the N-85 curve, the noise is acceptable. If the daily exposure is less than five hours, a higher noise rating No. than N-85 can be used.

If it is suspected that the noise level at a work location is excessive, it is not necessary to carry out an octave band analysis right away. Adequate evaluation of most noisy environments can be made by using a simple sound level meter with an A-weighted filter.

If the value thus obtained does not exceed the acceptable limit for the exposure duration, 90 dB(A) in the USA and the UK, no further measures are necessary. On the other hand, if the instrument reading exceeds the limit, an octave band analysis must be made to find out if the high noise level includes high frequencies that could be dangerous.

This risk evaluation assumes that the noise is steady and broad-band. However noise, and particularly industrial noise, fluctuates in strength and pitch with the number and types of machines in operation. To be able to utilise the noise rating curves, the readings should therefore be taken when the noise is at its maximum and preferably based on sample periods which are typical of the working day.

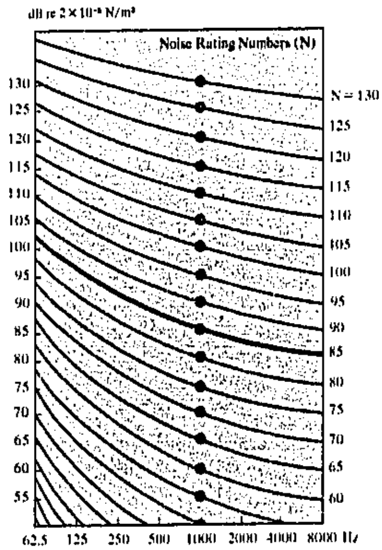
The problem is different when dealing with impulse noises, e.g. drop forge hammers, riveting, hammering of plate, etc. It is difficult to measure such sounds, and their cumulative effect on the hearing apparatus is still not known. What we do know is that a single rifle shot, thunder clap or sonic boom from an aircraft can cause irreparable damage to the hearing.

The use of ultrasound — frequencies higher than 20 000 Hz and consequently not registered by the ear — is increasing steadily both in industry and the field of medicine. The sound level here is normally below 90 dB.

Ultrasound above 90 dB can be identified by a mild feeling of nausea and a burning sensation in the auditory canals. At exceptionally high levels, above 120 dB, ultrasound can seriously damage the human organism, affecting the nerve cells in the brain and spinal chord. Long exposure to powerful ultrasonic fields can even prove fatal. In such conditions, hearing protection is not enough, because the vibrations are also conducted via the skin to the skeleton.

Even less is known about the effects of infrasound on the organs of the body. Weak infrasound affects the balance organ and causes fatigue, irritation and nausea. The brain is especially sensitive to a frequency of 7 Hz, which coincides with the alpha-waves in the brain. A person subjected to this frequency is not able to carry out any work requiring thought or concentration.

The infrasonic frequency range covers the natural frequencies for many parts of the body. Should these be vibrated at their resonance frequency the movement can be considerably amplified. Exposure to intense infrasound for any length of time can give rise to internal bleeding.
The somewhat modified saying, "What you don't hear won't hurt you", doesn't seem to apply here.



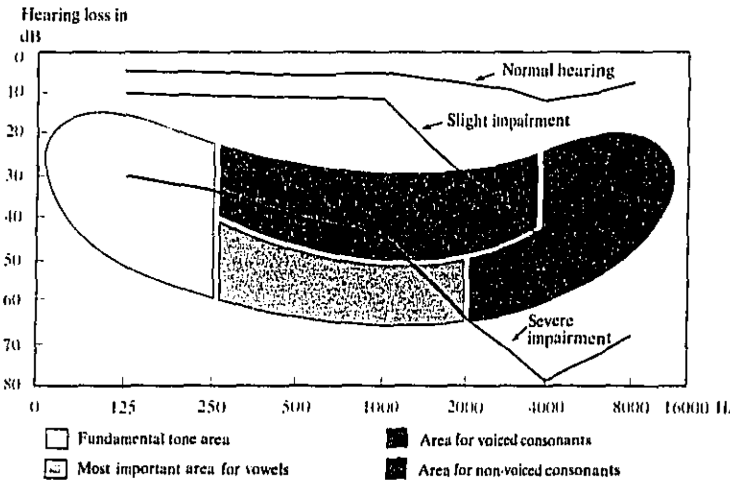
ISO Noise Rating Curves

How hearing injury is detected

Many delude themselves with the idea that noise is something one "gets used to". That a positive attitude to a noise can reduce a number of physiological responses is one thing. Quite another is the negative, often insiduous effects of noise on the inner ear: the overstimulation and eventual paralysis of hair cells in the organ of Corti. The reason why people after a time of exposure are no longer affected by a noise they have "gotten used to" is that they are suffering from hearing impairment over the range of frequencies corresponding to the loudest part of the noise. A person who is completely "used to" a noise can therefore have become insensitive to all the component frequencies of the noise.

As previously described, the sensation of sound arises when a pressure wave impinges on the ear and causes the basilar membrane in the cochlea to vibrate. The position of maximum vibration along the membrane is dependent on the frequency of the incident sound. At the point of maximum vibration the hair cells are bent by quite a considerable force. Thus if the same hair cells are powerfully and steadily excited for some considerable time they become tired and temporarily paralyzed. The subject then becomes hard of hearing. If the hair cells are allowed to rest after a not too intensive strain they recuperate and recover their normal function. But if the strain is repeated day after day, the hair cells eventually lose their ability to recover. The vascular supply and metabolism of the cells become so affected that they can no longer function.

The terrible thing about hearing loss is that its onset is not noticeable. The frequencies above the speech range are the first to go. It is not possible to hear the twittering of birds and the chirp of the cricket. In time, however, deafness spreads into the range of speech frequencies. First the consonants disappear, then the vowels. Progress can be surprisingly swift and devastating.



The colored sectors in this pure-tone audiogram give an approximation of the sound levels at different frequencies produced by normal speech at a distance of one meter.

Another reason why perceptive deafness is often discovered at so late a stage is that as hearing loss increases the sufferer without realising it starts to lip-read.

Hearing loss can be measured by the pure-tone audiometer or speech tests. In the first method, the patient sits in a sound-proofed room and listens to tones of different frequency and intensity through a pair of earphones. The sound pressure level of each tone is raised until the patient's hearing threshold for each frequency is found. The results are then plotted on an audiogram. By comparing the results with a normal speech curve, it is possible to ascertain those parts of the speech frequency range — and even the nature of the sounds — that no longer produce a reaction in the hearing organ. In speech tests the ability to distinguish recorded words at different levels of intensity is measured. Speech audiometry in a known level of noise can determine the patient's capacity to understand speech at his work location.

Noise-induced hearing injury often causes the generation of nerve impulses. This is experienced as a hissing, comprised of pure tones or a tone complex within a certain frequency band. The sensation of hearing is experienced without external stimulus. A symptom that can cause as much psychological distress as the damage to the hearing itself.

It is thus possible to "adjust oneself" to noise, but sooner or later the high price of this "adjustment" will have to be paid. **Noise-induced deafness cannot be cured.** That hearing loss as a result of external injury or inflamation of the middle ear can sometimes be cured by surgery is quite another matter.

Measurement of noise

As the sensitivity of the ear to different sounds is not linear, not much is gained from knowing the physical value of sound pressure as obtained with a sound pressure meter. For this reason weighting or attenuating filters are included in sound-level meter circuits to simulate the response of the ear to sounds of different levels and frequencies. Of these filters the 'A' weighting has now been generally adopted, as it approximates closest to the human response. Sound levels obtained with an A-weighted meter are expressed in dB(A).

Where more information is required about the composition of noise, the sound pressure level is measured over the entire audible frequency range. A convenient procedure is to record the noise on a tape recorder for later analysis in a laboratory. Frequency analysis is employed when the ISO noise rating curves are used.

Neither of the above methods of measurement takes account of the duration of exposure, which is one of the most important factors in determining the risk of noise-induced hearing loss. The time factor has to be "estimated". However noise is seldom constant and its composition also varies. For this reason, research workers are now working on an instrument that can accurately measure the amount of noise a person is subjected to over a longer period of time. A noise dose meter of this type should be able to be carried about everywhere. This means that the subject's exposure to noise can be integrated over a period of one, two or perhaps ten years.

How to combat noise

Noise control measures should be thought about at the planning stage of a factory building. In the choice of materials for the building, the disposition of the machine shops, the location of recreation space and canteen facilities. The design of machinery is also an important factor. Previously, in the detail design of a machine, little consideration was given to the noise produced, but nowadays the noise level has become an important selling feature.

In existing premises there are a number of measures that can be applied to effect noise reduction. The most effective and practical means for combating unwanted sound is to prevent it from spreading from its source.

Some machines and jobs involve impact against a backing of hard, massive metal. In such cases the loudness can often be reduced by replacing the metal with a more pliable material such as hard rubber or felt.

The bearings of all machinery should be regularly inspected. Old and worn bearings are a source of unnecessary noise. Further, transmission belting of reinforced rubber is to be preferred to belts of leather or canvas. And, on the whole, belt transmission is less noisy than gearing.

Noise radiation from rotating discs may be reduced by stiffening the discs, giving them a domed form or treating them with a sound damping composition.

Noise from engines and machines not only spreads through the air. The vibrations from these noise sources can be transmitted to the structure of the building. Propagation then takes place in the walls and floor, and can give rise to secondary sound development that can cause considerable annoyance in the whole building. Very heavy machinery should therefore be mounted on stable floats of metal or concrete. Where necessary these floats can be placed in a special hole in the concrete foundations on a layer of sound-absorbing material. Where the weight of the machine allows, it can be placed on special anti-vibration mountings. Lighter machines can also be mounted on layers of rubber, felt or cork.

Another way of reducing the noise from a machine is to provide it with a sound-insulating enclosure. Reductions between 20 and 30 dB can be attained in this way. The enclosure must be lined with a sound-absorbing material (e.g. mineral wool) and it should be made as airtight and heavy as is practicable. Any direct conduction of vibrations to the foundation should be prevented.

When all possible measures for noise control at source have been taken, further reduction of noise in a room can be achieved in certain circumstances by introducing sound-absorbing material in the form of cladding or portable baffles. Sound-absorbing materials absorb part of the sound energy, thus reducing the sound reflection in the room considerably.

Self-protection

The simplest way to protect people against noise-induced hearing loss is to provide them with individual hearing protection. This is often the only measure that can be taken at many work places such as mines, plate workshops, shipyards and airfields, for very practical reasons.

Individual hearing protectors prevent noise from entering the auditory canal. They are available in the form of ear plugs — of fine mineral fibre down, wax, rubber or solid plastic — which block off the external auditory canal, or ear muffs which completely enclose the ears and fit closely to the side of the head. Ear plugs can provide sound attenuation up to 30 dB, while with ear muffs attenuation can be as high as 40 dB. If both ear plugs and muffs are worn still better results are obtained.

The efficiency of individual protectors depends on whether or not they are correctly used. When first worn they may feel a bit uncomfortable and this can easily lead to their not being used when needed. Consequently it is essential to choose a hearing protector which provides a comfortable fit, and further to instruct the wearer in the importance of using the protection when entering noisy areas. In this, the individual's audiogram can be prove very instructional.

As noise-induced hearing loss cannot be cured, and the effects of noise are cumulative, early detection of any damage to the hearing is essential. The best way of doing this by means of regular audiometric tests on personnel. Periodic review will give early warning of incipient loss of hearing, and measures must be implemented to improve the protection of the persons concerned. If it proves impractical to reduce the noise at the work place in question, a system of job rotation between noisy and non-noisy work should be employed.

At the present time we have come a long way in our knowledge of how noise generation in various machines and processes can be reduced. Practical solutions exist for manufacture of quiet machines, modifying older machines, insulating them, and providing acoustic insulation in places of work. The decisive and most important aspect of the problem is, of course, the economic one. How much are we willing to pay to achieve a given standard of noise reduction?

Dr. Robert Koch, the discover of the tuberculocis bacillus and one of the most important scientists of all time, is reputed to have said a few months before his death in 1910: *"The day will dawn, when people have to fight noise as relentlessly as cholera and the plague"*.

The point is: can we afford to wait until this prediction comes true?

Notes

If you would like to know more, consult:

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