AUDITORY FATIGUE FOLLOWING NON-STEADY SOUNDS - C. ROL

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PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN
DOCTOR IN DE GENEESKUNDE
AAN DE RIJKSUNIVERSITEIT TE LEIDEN
OP GEZAG VAN DE RECTOR MAGNIFICUS
DR A. E. VAN ARKEL, HOOGLERAAR IN DE
FACULTEIT DER WIS- EN NATUURKUNDE,
TEGEN DE BEDENKINGEN VAN DE
FACULTEIT DER GENEESKUNDE
TE VERDEDIGEN OP
WOENSDAG 23 MEI 1956
TE 16 UUR

DOOR

CORNELIS ROL
GEBOREN TE SCHOTEN
(THANS HAARLEM)
IN 1924

UITGEVERIJ EXCELSIOR - ORANJEPLEIN 96 - 'S-GRAVENHAGE

Promotor: Prof. Dr H. A. E. van Dishoeck

Aan mijn Ouders
Aan mijn Vrouw

Een deel van de apparatuur, waarvan in deze studie gebruik werd gemaakt, werd aan de Leidse Keel-Neus-Oor kliniek geschonken door de Stichting „Heinsius-Houbolt Fonds", een ander deel was welwillend in bruikleen afgestaan door het Nederlands Instituut voor Praeventieve Geneeskunde te Leiden.

Het technische gedeelte van het onderzoek werd verricht in samenwerking met de Heer A. Spoor, physicus van de Audiologische Afdeling; aan een groot deel der experimenten werd medewerking verleend door de Heer G. W. Meeuwisse, indertijd student-assistent van de Leidse Oorheelkundige Kliniek.

SAMENVATTING

De schadelijkheid voor het gehoor van geluid met wisselende intensiteit is, in tegenstelling tot de gevolgen van inwerking van continue geluid, nimmer onderzocht. Ten einde over dit onderwerp experimentele kennis te verkrijgen werd het traumatiserend vermogen van intermitterende zuivere tonen, van een intermitterende witte ruis en van meer samengestelde geluiden, o.a. het lawaai van een pneumatische boor, onderzocht.

Bij vergelijking van de gemeten met de berekende overall-intensiteit van deze geluiden, bleek dat de gebruikelijke methode van intensiteitsmeting bij intermitterende geluiden niet toegepast mag worden. Hieruit volgt dat ook het traumatiserend vermogen van een dergelijk lawaai niet bepaald kan worden door meting van de intensiteit per frequentie-band en vergelijking van deze meetwaarde met één der „Deafness Risk Criteria".

Om deze reden werd het traumatiserend vermogen van intermitterende geluiden langs experimentele weg bepaald, n.l. door opwekking van de gehoorvermoeidheid. Deze methode eist een vlugge en nauwkeurige bepaling van plaats en diepte van de vermoeidheids-dip. De continue audiometrie waarmee op verschillende intensiteitsniveaux de hoorspan bepaald wordt, maakt deze meting in $\frac{1}{4}$ minuut mogelijk. Vastgesteld werd dat het maximale gehoorverlies een juiste en goed reproduceerbare maat is voor de graad van gehoorvermoeidheid. Tevens werd aangetoond dat men gerechtigd is uit kortdurende experimenten conclusies te trekken met betrekking tot de genese van de lawaaidoofheid.

Met behulp van deze methode werd aangetoond dat voor continue zuivere tonen en 1/3 octaaf banden de empirische traumatiseringsdrempel afwijkt van genoemde „Deafness Risk Criteria" en dat er bovendien belangrijke individuele verschillen bestaan in gevoeligheid voor de verschillende frequenties. Bewezen werd dat deze verschillen o.a. afhankelijk zijn van de resonantie-karakteristiek van de uitwendige gehoorgang.

De gevonden traumatiseringsdrempels lopen niet parallel met de lijnen voor gelijke luidheid, echter wel met de lijn, die die intensiteiten verbindt, waarbij een zuivere toon een onzuiver en scherp karakter krijgt. Deze laatste lijn, die vlug en gemakkelijk te bepalen is, werd tolerantie-curve genoemd. Het maximum van deze curve geeft aan welk frequentie-gebied door een fabriekslawaai speciaal getroffen zal worden.

Het traumatiserend vermogen van een pulserend lawaai wordt bepaald door de intensiteit van het continue basislawaai en de hierop gesuperponeerde pieken. Daar de invloed van deze pieken het eigenlijke probleem vormt, werd het effect onderzocht van verschillende 2000 Hz-stimuli met een systematisch-gevarieerd, intermitterend karakter, en de hiermee verkregen uitkomsten getoetst aan een serie proeven met een intermitterende witte ruis als prikkel. Het bleek dat intermitterende stimuli minder schadelijk zijn dan continue stimuli van dezelfde berekende overall-intensiteit. Een snel puls-rhythme van bijv. 8 x per sec. is schadelijker dan een rhythme van 2 x per sec., mits de overall-intensiteit gelijk is. Wanneer de duur van de puls en van de pauze tussen de pulsen ongeveer gelijk zijn, is de schadelijkheid het kleinst.

Wanneer zowel het basis-geluid als de pieken een traumatiserende intensiteit hebben, bleek het traumatiserend vermogen van het totale lawaai gelijk aan de som van de traumatiserende vermogens der componenten. Als b.v. twee componenten van een lawaai in een bepaald frequentie-gebied een zelfde gehoorverlies veroorzaken, dan zal het gehoorverlies veroorzaakt door de gelijktijdige inwerking van de geluiden gelijk zijn aan dat van één der componenten met een 3 dB grotere intensiteit.

Uit de bovenstaande resultaten kan men concluderen:

1e. dat de geluidsdrukmeter, al of niet gecombineerd met bandfilters, geen exacte waarde geeft voor de schadelijkheid van pulserende geluiden;
2e. dat de „Deafness Risk Criteria" herziening behoeven;
3e. dat verzwakking van het basislawaai, b.v. door vermindering van reflectie, vaak slechts een beperkt effect zal hebben, omdat het traumatiserend vermogen der pieken grotendeels blijft bestaan;
4e. dat de schadelijkheid van lawaai te verminderen is door synchronisatie. Hierdoor zal enerzijds een nagenoeg continue lawaai een pulserend karakter kunnen krijgen en anderzijds een pulserend lawaai een langzamer rhythme gaan vertonen. Het beste resultaat mag verwacht worden als, bij een langzaam rhythme, de duur van de piek en van de pauze tussen de pieken ongeveer gelijk gemaakt zijn.

CONTENTS

Chapter I

INTRODUCTION

§ 1. Occupational deafness

In the last century and a half, the number of people suffering from occupational deafness has increased in proportion to the increase in horse power used in industry. At first only noise-deafness occurring in boilermakers was recognized (Fosbroke, 1831). After the appearance of the steam engine attention was drawn to similar cases appearing in railway personnel. At present, in addition to the above two occupations, noise-deafness may occur in all kinds of occupations ranging from telephonists to workers in the heavy industry.

The increase in the number of patients called more and more attention to the etiology, the symptomatology and the prevention of noise-deafness. In human and animal experiments, researchers endeavoured to determine the pathologic-anatomic damage caused by noise-exposure. Habermann (1890) was the first to examine, post mortem, the cochleae of boilermakers. He found disappearance of the hair cells of the basal winding, and in some cases, locally, the whole Organ of Corti proved to be destroyed, while the accompanying nerve fibers were atrophic. Crowe, Guild and Polvogt (1934) examined post mortem the cochleas of people of whom audiograms had previously been made. When there was an abrupt high tone-loss above 1000-2000 cps (not only in noise-deafness) they found, in the basal winding, atrophy of the Organ of Corti and of the nerve fibers.

The meager pathologic-anatomic information obtained from human study was supplemented by very numerous animal experiments. Here beyond all doubt, it was confirmed that noise-deafness is a perception deafness, caused by damage to the basilar membrane. All different kinds of noise and also explosions, and even skull traumas can cause damage similar to that produced in man by noise.

In pure tones the location of the trauma depends on the frequency of the tone, the high-tone trauma being located nearer the windows. The lesion of the lower tones extends over a larger area of the basilar membrane, and is sometimes located not only in the apical coil, but also in the basal or middle portion (Alexander & Githler, Smith etc.). This is in contradiction to the expectation based on the place theory.

The pathologic-anatomic localization of the damage by noise was related to the clinical symptoms. Uffenorde (1922) had already noticed that hearing acuity for the tuning forks c^{IV} and c^{V} (2048 and 4096 cps) was diminished, lower frequencies being normal. Later, in audiometric investigation, imitating the tuning fork method and measuring on the octaves of C but also on higher frequencies than 4096 cps, a hearing loss was found for the same frequencies, the highest frequency being normal (Shambaugh 1935, Bunch 1937, Larsen 1949). Thus the notion of the c^{V} dip, as a symptom of noise-deafness, was introduced. However, on measuring the threshold of the intermediate frequencies van Dishoeck & van Gool (1948) proved that this conception of the c^{V} dip could not be maintained; the localization of the maximum hearing loss varied per individual between 3000 and 7000 cps, with a statistic top at about 6000 cps (van Gool, 1952).

As already stated this dip is the result of an inner ear lesion. Consequently the air conduction and the bone conduction audiograms are identical and the phenomenon of recruitment is positive (de Bruïne-Altes, 1946).

Apart from this high-tone deafness, which at first is not noticed by the patient, his chief complaint is tinnitus. Later on this complaint disappears; either because the patient becomes accustomed to the tinnitus or because of the steadily progressing damage. Pathognomonic of noise-deafness, however, is not only the dip between 3000 and 7000 cps and the tinnitus, but rather a certain degree of recovery after a period of rest, for an acoustic trauma which has not existed for too long a time may disappear completely. If the lesion is often repeated, as in factory workers, recovery becomes gradually incomplete, until finally part of the loss, becomes permanent. A recent opinion is that the greatest permanent loss takes place in the first weeks or months of the exposure to noise (Mc Coy, Larsen, van Leeuwen).

Goldner (1953) found no relation between exposure-time and amount of hearing loss, but rather a relation between hearing loss and age. However, Rosenblith (1954) found that after tens of years of exposure, a greater increase in hearing loss occurs than could adequately be explained on the basis of presbyacusia. The supposition that older people are more sensitive to acoustic trauma might reconcile these results, as in that case the trauma acquired in old age would be greater than that acquired at an early age.

We already mentioned the recovery as an important phenomenon of the acoustic trauma. Campbell & Hargreaves, Dickson & Ewing, Davis and others believe that no permanent trauma need be feared, as long as hearing is completely restored before a new exposure to noise. Mc Coy, Eldredge and Davis point out that years of exposure can go by before a permanent hearing loss is demonstrable. It is as yet unknown whether the recovery is completely independent of the repetition of exposures. If this were the case, a maximum admissible temporary hearing loss per working day, would be an important factor in the prevention of noise-deafness. We shall return to this point later.

An effective therapy for a permanent noise trauma is not known. This should not surprise us, considering the irreparable destruction of the organ of Corti which is found by pathologic-anatomic examination. Only reversible damage can be influenced therapeutically. Such a therapy aims at a more rapid and more complete recovery than is obtained by rest only. In experimental trauma, Willemse (1952) and Ruëdi (1954) saw a more rapid recovery as a result of previous administration of vitamin A. Ruëdi moreover found that vitamin A improved the tolerance for noise. As vitamin A is still a rather expensive medicament one will have to depend in practice on other preventive measures.

§ 2. Prevention of occupational deafness

Measures to prevent noise-deafness can be divided into three groups, viz. those which concern the factory worker, those which improve the machine and those which deal with the environment.

The sensitivity of the factory worker can be decreased by obstruction of the external auditory canal by some kind of ear defender. Unfortunately the common ear defenders are not popular among factory workers. The young workers are not sufficiently conscious of the danger of becoming gradually deaf and not aware that they will run into hearing difficulties, when they get older. They are also too used to easy conversation. The older workers are already deaf, and for this reason they can expect very little return in exchange for using ear defenders. A certain degree of recovery, however, can be expected from this measure.

Another attempt is to exclude those workers who are abnormally sensitive to noise. To this purpose some sensitivity experiments are recommended, all of which are based on the measurement of the threshold shift caused by exposure to a sound of a certain intensity for a certain time. For this purpose tone stimuli are recommended of 1000 cps (Peyser, 1940), 2000 cps (Wilson, 1944) and 2500 cps (at the Leyden clinic). While Peyser measured the threshold shift at the stimulus frequency and Wilson at one octave above the stimulus frequency, Theilgaard (1949) pointed to the fact that the maximum of the tone-dip is located at about one-half of an octave above the stimulus frequency and consequently should be looked for at this point. Moreover Theilgaard found that the most damaging frequency is a matter of great individual variation, and for this reason he and Wheeler advised the use of a white noise. Their advice, however, to measure the effect of this white noise at 4000 cps has the same shortcomings as the previously discussed methods. Van Dishoeck & van Gool solved this problem by means of the continuous audiometry technique which will be discussed later on. They established the exact pattern of the hearing loss and thus the maximum was always found. As a sound stimulus they used a magnetophone recording of the factory noise to which the worker is exposed. This procedure is supported by van Leeuwen (1955), who found that the temporary hearing loss of a factory worker at the end of a day shows a definite relationship with the permanent deafness which the older workers show under the same noise conditions.

A third possibility of preventing acoustic trauma consists in regulating the working time of the factory worker in such a way that the hearing loss which arises during his work can recover completely in a subsequent interval. A permanent survey of the employees is necessary. In our opinion such a repeated audiometric control is the only effective prevention.

Improvement and better maintenance of machines can in many cases cause a definite lowering of the intensity of noise. Changes in the rotation speed will have an effect on the distribution of the noise over the frequency spectrum, and change the pulsating character of the noise. Synchronisation or desynchronisation of movements will affect the number of sound impulses per unit of time. In chapter VIII we shall deal extensively with this problem.

The walls of the workshop are of great influence on the overall-intensity of noise. If the intensity peaks which arise from the machine are reflected almost completely, the measured intensity and the observed loudness of the noise will differ only little. The interval between the peaks will be filled with a strong basic noise whose intensity does not differ greatly from the peak intensity. The acoustic trauma caused by such a noise will probably be elicited in a considerable degree by this basic noise. If the walls are sound-treated, the basic noise may be diminished to an intensity below the traumatizing level. The sound impulses from the machine however will remain about the same, as they reach the factory worker directly. Thus in this case the trauma which may arise is determined by these intensity peaks. Sound-treating a factory is a very expensive matter; consequently the sound engineer should calculate the probable result and the remaining traumatizing power of the noise.

§ 3. Schedule of investigation

In order to compare the noxiousness of different kinds of noise, we must know what is meant by the concept of traumatizing power. By this term is understood the power of a noise to cause a certain degree of damage to the inner ear in a certain exposure time. The method to determine the traumatizing power of a sound consists in determining the degree of auditory fatigue produced by stimulation with the sound during a short time.

After the introductory chapter I giving general considerations about noise-deafness and its prevention, in chapter II the method of investigation and the technical equipment is discussed. In chapter III the exactness of this method will be demonstrated for both steady and non-steady sounds. In this study, by non-steady sounds are understood those sounds, which show one or more large fluctuations of the intensity per second. In chapter IV, the non-steady noise which we used in our experiments, viz. the magnetophone recording of a pneumatic drill in a hard-walled cellar, is analysed. In addition the sound levels of non-steady sounds were studied. In this way valuable information was obtained about the reliability of sound-measurement in factories. In chapter V, after the discussion of the deafness risk criteria, the traumatizing power is studied as a function of the frequency. In chapter VI the traumatizing power is studied as a function of intensity. In chapter VII the traumatizing power of interrupted sounds is studied. The influence of the duration and the rate of repetition of tone-pulses of 2000 cps is investigated and the results of this are compared with a series of experiments performed with pulses of a white noise.

Finally we tried to imitate a real non-steady noise by means of a white noise and tone pulses. In chapter VIII the traumatizing power of such synthetic noises is examined. The results are compared with those obtained by stimulation with the real noise to obtain an insight into the proportions and degree in which basic noise and intensity peaks contribute to this traumatizing power.

Chapter II

TECHNICAL EQUIPMENT AND METHOD OF INVESTIGATION

The traumatizing power of noise in man has been determined in two ways:

a. We can study groups of workers, who have been exposed to noises of known intensity and frequency characteristics (van Leeuwen, Rosenblith, Goldner and others).

b. We can produce auditory fatigue with sound stimuli of short duration. This auditory fatigue will be discussed later on. In chapter III will be explained, why it is correct to apply conclusions obtained from experiments of such short duration, to prolonged exposure to noise in industry.

§ 1. Apparatus

In our experiments the stimuli were supplied by the following devices:

A tone generator, mark Philips, type G.M. 2307;

A thermal noise generator, constructed in the electro-acoustical laboratory of the Ear, Nose and Throat Department of Leyden University;

A magnetophone tape of the noise caused by a pneumatic drill.

These sounds could be led through a 1/3 octave band filter, mark Brüel & Kjaer, type 2109, and through a pulse generator, which was constructed in the electro-acoustical laboratory of the Leyden Ear, Nose and Throat Clinic.

With the aid of the latter instrument of a continuous sound pulses of adjustable duration, viz. from 20 m.sec. until 3 sec., could be taken out. The possible number of sound pulses ranged between 1 in 6 sec. and 20 per sec. This pulse generator had 2 canals, so that it was possible to apply a continuous sound and a periodically intermittent one at the same time. With the aid of an artificial ear and a cathode ray oscilloscope, mark Nagard type 103, the pulse generator was so adjusted that the rise-time and decay-time of the pulse both amounted to ca. 6 m.sec. for each stimulus intensity and frequency used. There was no perceptible acoustic click.

The characteristic of this pulse is reproduced in fig. 1 as visualized on the oscilloscope. The time elapsing between the points in which the intensity increases and decreases to 5/6 of the pulse maximum, was per definition assumed as the pulse-duration. This value was chosen because of the in-

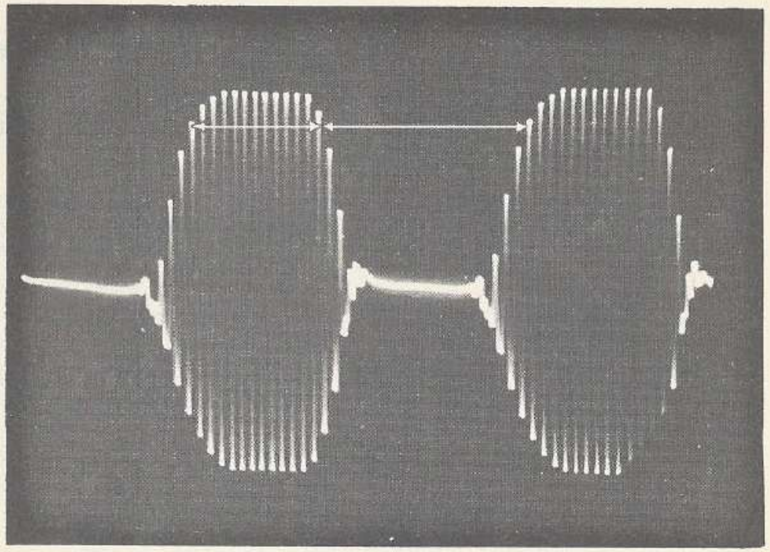

Figure 1

Oscilloscopic picture of an intermittent 500 cps tone. The rate of repetition of the pulses was 16 per second. The duration of the single pulse is measured at 5/6 of the maximal amplitude and amounts to 24 m.sec. = 1/42" (notation: 16 x 1/42"). The rise- and decay-time are approximately 6 m.sec.

accuracy in measuring the width of the pulse at the top. If this width is determined at 5/6 of the pulse maximum, it can be calculated that the error in the calculated overall-intensity will be at most 0.3 dB, provided the duration of the pulse is greater than 30 m.sec. The duration of the interval between 2 pulses was calculated from the pulse-duration and number of pulses per sec. The ratio between pulse-duration and interval-duration was called pulse-interval ratio. Intermittent stimuli consisting of, e.g., 8 pulses of 1/16 sec. duration per sec., and of a maximum pulse level of 100 dB, stimulating during 5 minutes, will be briefly indicated as 8 x 1/16" 100 dB, 5'.

In all experiments the sound was presented to the test person after being amplified by a power-amplifier, mark Peekel, type 20A, via a headphone, mark Standard Telephone & Cables, type 4026 A. The background-noise inherent in the amplifier had a maximum intensity of 60 dB re 0,0002 micro bar.

The intensity of the stimuli used was measured in dB with an artificial ear and level-meter, mark Brüel & Kjaer, type 4109, resp. type 2105, and will be marked in dB re 0,0002

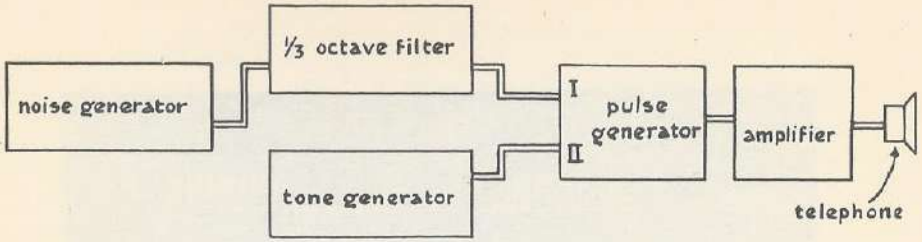

Figure 2
Scheme of arrangement to produce the sounds used in our experiments. These sounds were: continuous and intermittent stimuli of pure tones and of a white noise, combinations of two of these sounds, and 1/3 octave bands of the white noise.

micro bar. The artificial ear was calibrated in the P. T. T. Laboratory at Leidschendam, Netherlands.

The percentage of overtones in the continuous sound stimuli was determined with the abovementioned artificial ear, for the frequencies 500, 1000, 2000 and 3000 cps. On amplifying up to 125 dB the strongest overtone remained in any case 35 dB weaker than the fundamental tone. The 1/3 octave band analysis of the thermal noise was made in the same manner and is plotted in reference to the normal threshold for the geometric mean frequencies of the 1/3 octave bands in fig. 14.

The threshold of hearing before and after the exposure was determined with an audiometer, mark Peekel, type D4, and with a Western Electric 6 BP audiometer, adapted to continuous audiometry.

All experiments were carried out in the sound-treated room of the Leyden Ear, Nose and Throat Clinic.

§ 2. Measurement of auditory fatigue

Volunteer test persons, mostly medical students between 25 and 35 years, with a normal threshold audiogram, which means no more than 10 dB hearing loss on any frequency below 6000 cps, were exposed to a traumatizing sound stimulus during $2\frac{1}{2}$, 5, 15 and 45 minutes. The headphone was placed on the ear of the testee by the investigator so that the acoustic leak to the outside was reduced as much as possible. During the exposure the testee's head was in an upright position. Directly after the stimulation the telephone of the sound-source was replaced by the telephone of the audiometer. Half a minute after the end of the stimulus measuring of the fatigue was started.

Measuring the auditory fatigue carries problems and demands a special technique. If the hearing threshold should be measured in the usual manner on the octaves of C, the chances of measuring the maximum threshold shift are very small. If one tries to improve this procedure by measuring a certain number of intermediate frequencies, the time required for the determination increases considerably. As the pattern of a dip changes rapidly (van Gool), incorrect measurements will be obtained, and moreover the patient will get tired and accordingly will indicate inaccurately. The same objection holds true in an even higher degree for determinations with the von Békésy-audiometer. This quick threshold measuring on as many frequencies as possible is a primary necessity.

Van Dishoeck introduced continuous audiometry as the most suitable method for the determination of dips in the audiogram. In continuous, i.e. sweep-frequency, audiometry, a sweep-tone is presented to the test person on different intensity levels. The testee indicates when he begins to hear the sweep-tone and when the hearing ends. Thus the hearing-span is recorded for each intensity level. The successive ranges of hearing loss form the pattern of the dip. In the Peekel continuous audiometer the 0-level is adapted to the normal threshold. This method has the following advantages:

1. In a short time, viz. 2 minutes (by the trained investigator), the complete contour of the hearing loss can be measured with greater accuracy than is possible with octave audiometry (v. d. Waal).
2. In a still shorter time, viz. in $\frac{1}{4}$ minute, the maximum and place of a dip can be measured.
3. Test persons who complain of tinnitus after exposure to the traumatizing sound can correctly discriminate between their tinnitus and the sweep-tone.
4. A dip with an abnormal contour can be easily recognized. With this method the maximum hearing loss was first determined, and subsequently the complete contour of the treshold rise. Before a testee was subjected to the next experiment it was ascertained that the hearing threshold was back to normal.

§ 3. Evaluation of auditory fatigue

By this method the traumatizing power of a sound is determined by the degree of auditory fatigue, especially by the height and extent of the threshold shift. In experiments of this kind it is necessary to express the effect in a cipher, in order to create the possibility to compare the results of different experiments or different test persons.

Davis (1950) assumed as a measure the average of the numbers of dB hearing loss, that were found at a certain number of frequencies in the first two octaves above the stimulus frequency.

Harris (1953) measured the threshold shift caused by stimulation with the 750 cps tone, at 1000 cps.

Plomp (1955) determined the effect of pure tone stimuli for the $\frac{1}{2}$ octave higher frequency, and the effect of octave band stimuli for the frequency a $\frac{1}{2}$ octave above the geometric mean frequency of the octave.

Van Gool (1952) measured the threshold shift along the whole frequency axis starting a $\frac{1}{2}$ minute after the end of stimulation. The effect was indicated by the maximum hearing loss in dB in the first octave.

The same evaluation as that indicated by van Gool, was used in this study. Although the audiometers operated by intensity steps of 5 dB, it is possible to calculate the maximum hearing loss more accurately by taking into account the measured loss on the surrounding frequencies. In this way differences in hearing loss of $2\frac{1}{2}$ dB can be estimated.

Chapter III

AUDITORY FATIGUE AS A MEANS OF DETERMINING TRAUMATIZING POWER

Our research of hearing impairment caused by sounds is carried out by producing auditory fatigue with short-acting sound stimuli. However, before obtaining quantitative data about the traumatizing power of different sounds with this technique, one should be thoroughly familiar with the general properties of this phenomenon.

§ 1. General characteristics of auditory fatigue

The threshold shift has the form of a dip, by which is understood a hearing loss on a restricted frequency area with normal thresholds on both sides of this area. This loss is asymmetrical in relation to the stimulus frequency. Its maximum is situated at ca. $\frac{1}{2}$ octave above this frequency.

It is only produced by stimuli with intensities greater than 70 dB. Its size depends on both the intensity and the frequency of the stimulus. As a rule tones of 2000 cps and higher are traumatizing at a lower intensity above threshold than tones of a lower frequency.

As in the case of clinical noise-deafness, in the frequency area concerned the recruitment phenomenon is positive. As a rule it is accompanied by tinnitus and characterized by a phase of recovery varying from some seconds to several days.

By the above mentioned characteristics, it is easily distinguished from other effects of stimulation of the ear, especially the following:

a. The persistence of adaptation, which manifests itself after any sound stimulus of any duration and intensity. It is of a very short duration, i.e. some milliseconds, and consists of a threshold shift mainly on the stimulus frequency and in a lesser degree on the surrounding frequencies. It is a phenomenon inherent in every nerve stimulation.

b. The loudness adaptation by which is meant the decrease of loudness that accompanies stimulation with a continuous sound. It is a phenomenon known to everyone who enters a factory. At first the sound is deafening but after approximately 2 minutes one gets adapted to it.

c. The masking effect which occurs while a sound is acting upon the ear. It causes a threshold shift for other tones, asymmetrical with respect to the stimulating frequency, the higher frequencies being more masked than the lower ones. The pattern of masking partly resembles the acoustic trauma.

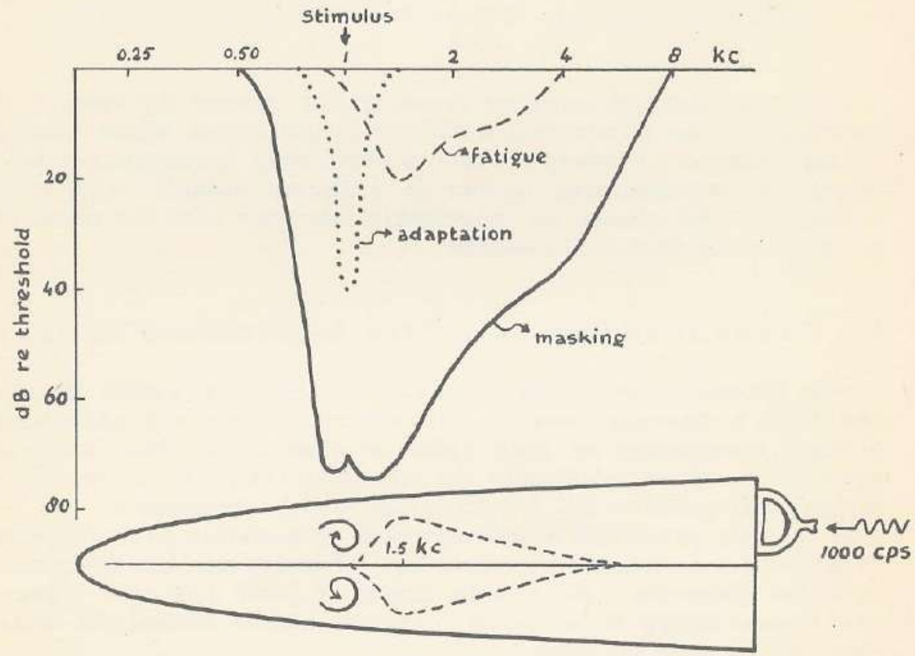

Figure 3
Schematic representation of the phenomena auditory fatigue, adaptation and masking, based on the distortion theory of van Dishoeck and van Gool. The adequate stimulus, viz. the eddy in the perilymph, is responsible for the hearing sensation and the adaption. The inadequate stimulus, viz. the travelling-wave motion of the basilar membrane, which is maximal between the eddy and the windows, is responsible for the phenomena auditory fatigue and masking.

In fig. 3 the phenomena auditory fatigue, adaptation and masking are shown and compared with a schematic representation of the stimulation effect in the cochlea, as suggested by van Dishoeck & van Gool. In § 8 of this chapter the relation between the two will be explained.

§ 2. Reproduceability of the experiment

The quantitative determination of the fatigue phenomenon by means of a certain technique and equipment must be preceded by a study of the reproduceability of the phenomenon.

A closefitting head telephone, provided with a foam-rubber rim was used in a first group of experiments. The results obtained in this way with a 2000 cps tone were disappointing

Table I
Reproduceability of experimental dips

A. in using a headphone with a foam-rubber rim

stimulus: 2000 cps tone
stimulation-time: 15 min.

sequence of experiments	2 x 1/8" 110 dB subj. Ga	8 x 1/16" 100 dB subj. Gr	2 x 1/16" 110 dB subj. Ti	8 x 1/32" 110 dB subj. Be
1st exper.	15	20	25	22½
2nd exper.	15	20	15	25
3rd exper.	10	17½		
4th exper.	10	7½		
5th exper.	10	30		

B. in using a headphone without soft rim

	stimulus: 2000 cps tone stimulation-time: 15 min.				stimulus: 3000 cps tone stimulation-time: 5 min.	
sequence of experiments	2 x 1/8" 100 dB subj. Me	2 x 1/8" 100 dB subj. Pl	8 x 1/16" 100 dB subj. Tr	8 x 1/16" 100 dB subj. Bo	cont. 95 dB subj. Gh	cont. 80 dB subj. EE
1st exper.	20	10	22½	30	22½	25
2nd exper.	15	5	20	32½	20	25
3rd exper.	15	5	17½	32½	22½	25
4th exper.	15	5	22½	35	25	25
mean value	16	6	21	32½	22½	25
standard deviation	σ = 2½	σ = 2½	σ = 2½	σ = 2	σ = 2	σ = 0

Tables representing the maximal hearing losses in dB caused by experiments with the same stimulus per test person.
Only by using a headphone without soft rim, which was placed in such a way that sound leakage was minimal, could satisfactory results be obtained.

because the telephone was placed on the ear in different ways (table I A). After removal of the foam-rubber rim a second group of experiments was performed. The telephone was now placed on the ear in such a way, that there was the least possible leaking of sound. In addition the test person was asked to keep the head still and in an upright position. The reason for this was that a prone or supine position proved to produce marked differences in loudness, presumably as a result of bending resp. stretching of the external meatus. The results were now much better (table I B). The dispersion in the size of the dip obtained with the same stimulus and in the same test person was 5 dB; the standard deviation being $2\frac{1}{2}$ dB or less in each test person.

In comparing the effect of two different stimuli in the same group of test persons we calculated the difference between the average values, and the standard error of this difference. In this way we found in most series of experiments a standard error of 2 dB or less. Consequently, according to Student's t-distribution, a difference of 6 dB will be significant ($p = 0.05$) and a difference of 4.5 dB will be due to chance in only ten out of a hundred cases ($p = 0.10$).

However, by making more than two experiments in each series and by making more than one series relating to the same question, smaller differences may be called significant, provided the results are in agreement with each other. As will be shown, this condition is fulfilled in our experiments with one exception, described in chapter VII § 3.

§ 3. Non-reproduceable dips

In sporadic cases there was either a threshold rise on a lower or higher frequency area besides the typical dip, or an entirely different localization of the dip's maximum that could not be reproduced. They occurred 6 times in a total of circa 800 experiments. Fortunately we never caused permanent hearing loss.

As reported by other investigators, exceptionally large dips occurred after moderate stimuli. Davis (1950) mentioned 3 patients in which moderate stimuli of 500, 2000 and 4000 cps produced hearing losses on resp. 3400, 8000 and 4000 cps, which failed to recover or recovered only after a very long time. Here too the extra loss occurred evidently in a frequency area which normally is either not traumatized by the above stimuli or in a lesser degree.

In every day life too we may encounter such unexpectedly great traumata. We saw a soldier after starting a jet engine, who acquired a unilateral hearing loss, though he had been

exposed to the same noise many times previously without important trouble.

A satisfactory explanation of such dips has not yet been put forward. Changes in the sensitivity of the middle ear are perhaps responsible.

In our study these non-reproduceable atypical dips were left out of consideration, because they do not give a correct idea of the traumatizing power of the stimuli used. This does not imply that they are of no consequence in originating noise deafness.

§ 4. Localization of the maximum of the dip

Usually after stimulation with frequencies above 1000 cps the maximum hearing loss is situated at $\frac{1}{2}$ octave above the stimulus frequency, but this localization is not exactly the same for all test persons. Moreover van Gool, working with 1000 cps stimuli found that the place of the maximum shifted towards the frequency of the stimulus if the exposure time was prolonged. This phenomenon, though in a lesser degree exists also in 2000 cps stimuli if duration and intensity are increased.

It appears from our experiments with interrupted tones that an increase in intensity only affects the place of the maximum if the depth of the dip is increased. Thus an amplification of the continuous tone with 10 dB causes the dip's maximum to shift to the left. If the tone is amplified with 10 dB, but its traumatizing power lessened at the same time by in-

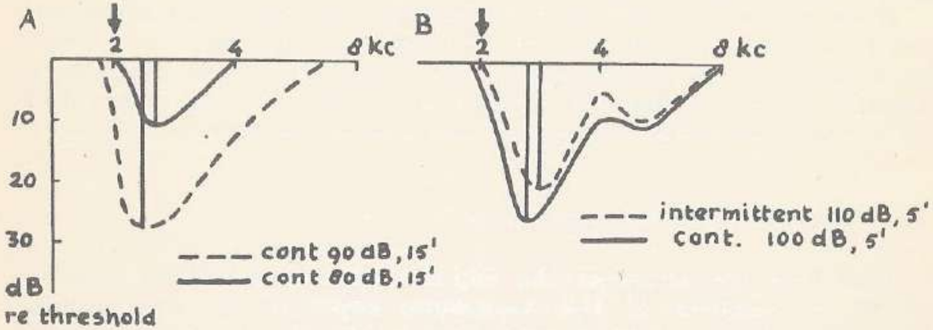

Figure 4
Examples of the localization of the maximal hearing loss after stimulation with a 2000 cps tone.
Increase of intensity causes a shift of the maximum to the left (A), but only if the traumatizing power is also increased. Increasing the intensity, but at the same time lessening of the traumatizing power, e.g. by periodical interruption of the stimulus (B), causes a shift of the maximum to the right. Consequently the place of the maximum is determined by the depth of the dip.

terrupting it periodically, the maximum shifts to the right (fig. 4).

Dips of an equal maximum hearing loss overlap entirely. It follows that the form of the dip is entirely determined by the size of the maximum hearing loss, provided that the same stimulus frequency is used in the same test person.

§ 5. Form of the dip

The dipform may differ from the typical one given in fig. 3, showing not only a maximum in the first octave above the stimulus frequency, but also in higher octaves. These accessory maxima too are reproduceable. They occur as a rule after stimulation with tones of 500 cps and lower, but also, though less frequently, after stimulation with 1000 and 2000 cps (vide fig. 5 A).

From the localization of these accessory dips the conclusion may be drawn that they are the effect of traumatizing overtones. Sometimes the effect of the 2nd harmonic surpasses that of the 1st; in other cases one of the harmonics appears to be more harmful than the fundamental tone.

As our measurement reported in chapter II showed, the overtones in the stimuli we used were at least 35 dB lower than the intensity of the fundamental. Barring one exception, in these experiments on overtones we never used intensities above 110 dB, so that the intensity of the overtones was never above 75 dB, and thus below the traumatizing threshold. The very interesting conclusion must be that these overtones originate in the ear itself.

It is evident from fig. 5 B that this phenomenon does not occur exclusively as a result of pure tone stimuli. A 1/3 octave band of a white noise with 1000 cps mean frequency equally produces dips which may be imagined to be generated as a result of bands situated 1 and 2 octaves higher.

§ 6. Recovery of the dip

Just like the form of the dip the time of recovery proves to be a function of the maximum depth of the dip. From Harris' (1953) experimental data about the recovery from fatigue caused by 750 cps stimuli, it appears that the time of recovery is also dependent on the size of the hearing loss, irrespective of the manner in which it was effected. Davis (1950) found that generally the diminution of hearing loss in dB was proportional to the logarithm of the time, and was not affected by the purity, the frequency or the time of exposure of the stimulus.

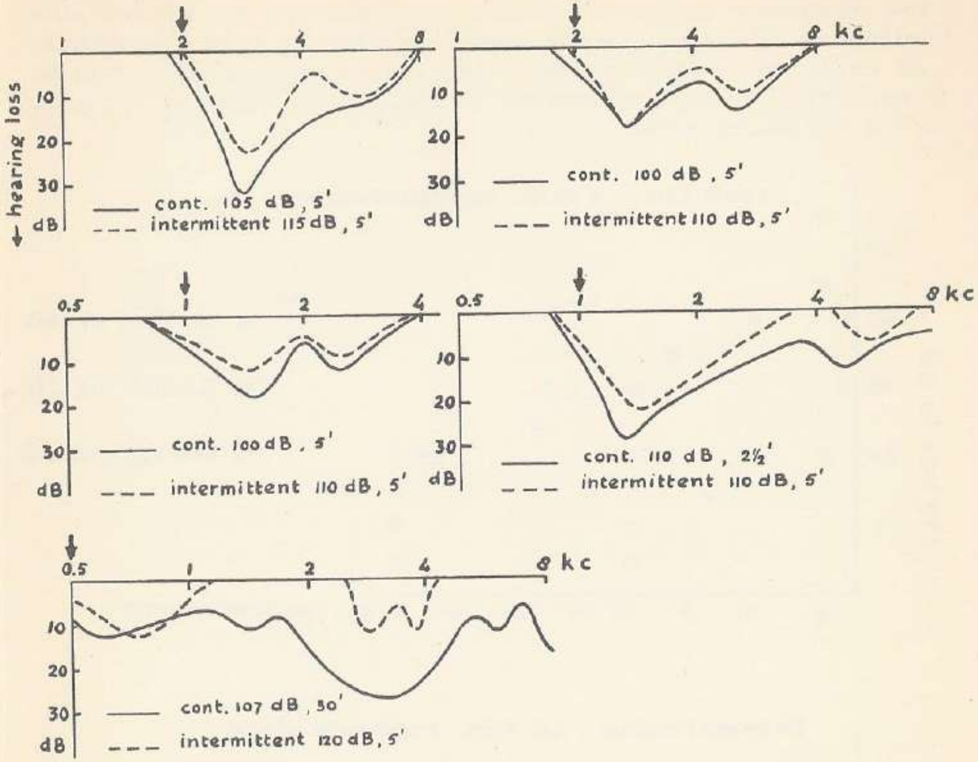

Figure 5A
Examples of accessory dips following exposure to pure-tone stimuli of 2000, 1000 and 500 cps, possibly caused by overtones. As the intensities of the overtones, present in the stimulus, never exceeded the traumatizing threshold but for one exception, namely 500 cps intermittent 120 dB, these overtones must originate in the ear.

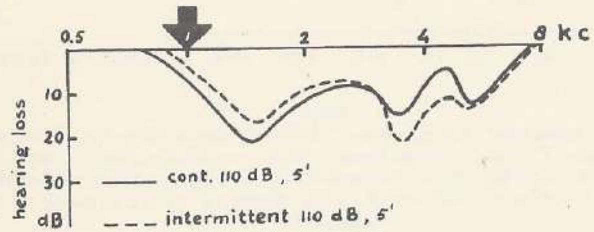

Figure 5B
Stimulation with a 1/3 octave band may produce similar accessory dips.

In order to verify if these results are applicable also to non-steady noise, the rate of recovery of dips caused by such stimuli was determined in one test person. It appeared that the recovery happened rather irregularly. An appreciable influence of the manner in which the hearing loss was effected could not be determined. The recovery time proved to be dependent on the maximum hearing loss existing directly after the stimulation.

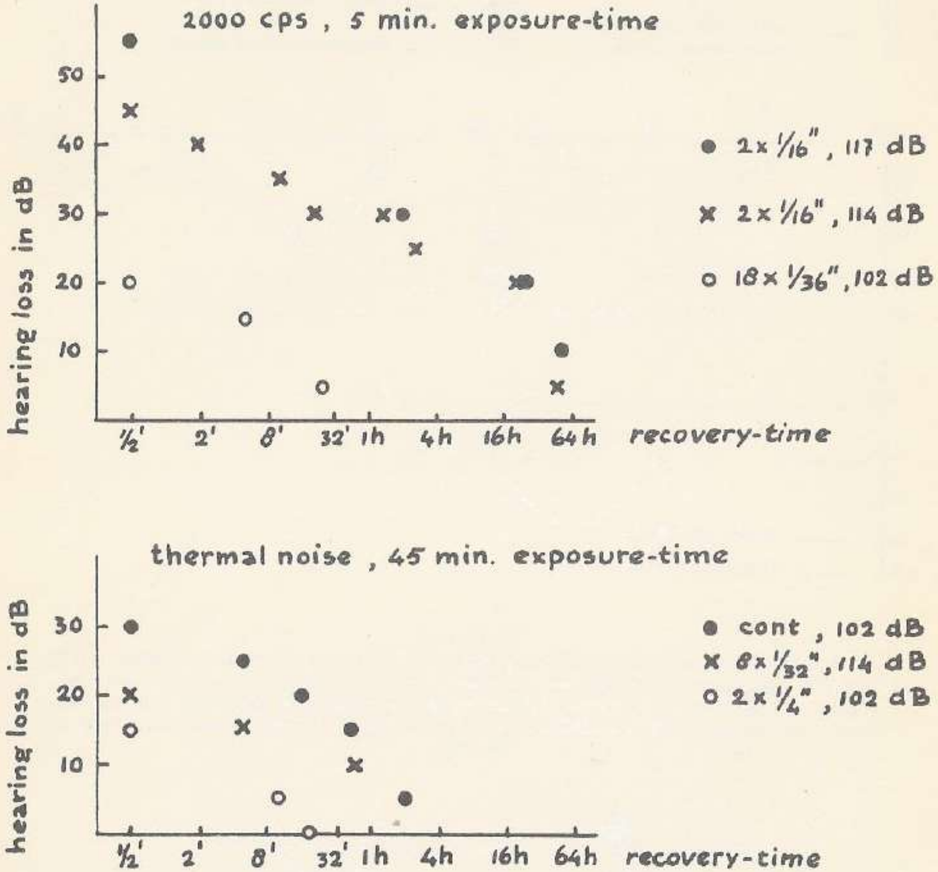

Figure 6
Values of the maximum hearing loss at different times after the cessation of very different stimuli. The recovery proceeds rather irregularly, but the total recovery-time apparently depends only on the maximal hearing loss shortly after the stimulation, and is not clearly influenced by the character of the stimulus or the exposure-time.

With our technique there was no evidence of a second threshold shift one minute after the end of stimulation, as reported by Hirsh and Ward (1952). So there was no reason to wait three minutes before determining the post-stimulatory threshold, as suggested by Plomp. On the other hand the recovery occurs with irregular speed, so it is advisable to measure the threshold shift shortly after the stimulation.

§ 7. Relation of auditory fatigue to permanent hearing loss

In using short-acting stimuli to study the relationship between occupational deafness and the noise, the assumption is implied that the ratio of the traumatizing powers of two sounds does not change on prolongation of the time of exposure. This assumption was proved for continuous pure tones. The hearing loss caused by different tone stimuli increases according to a similar pattern, viz. rapidly in the first few minutes, more slowly afterwards (Davis, van Gool, Plomp). Harris is the only investigator who does not agree with this opinion. Van Leeuwen found that recently engaged workers showed the same hearing loss after a day's work as older workers of the same department had acquired permanently. This also indicates that a prolongation of the same time of exposure ranging from one working day to many years has a similar effect on the size of the hearing loss for all kinds of noise.

All this applied to continuous sound stimuli. We shall have to investigate the validity of these rules for non-continuous sounds. To this end we exposed 2 test persons (3 ears) to stimuli during 5, 15 and 45 minutes:

a. pulses of a white noise of $\frac{1}{4}$ sec. duration and applied 2 times per sec. with an intensity of 97 dB (notation: white noise 2 x $\frac{1}{4}$ sec. 97 dB);

b. pulses of a thermal noise of 1/32 sec. duration and applied 8 times per sec. with an intensity of 109 dB (notation: thermal noise 8 x 1/32 sec. 109 dB);

c. pulses of a thermal noise also of 1/32 sec. duration and applied 2 times per sec. with an intensity of 105 dB (notation: thermal noise 2 x 1/32 sec. 105 dB);

d. thermal noise continuously applied with an intensity of 97 dB (notation: thermal noise continuous, 97 dB). The intensity of the stimuli was arbitrarily chosen so that a measurable hearing loss was obtained, not greater than 30 dB (table II).

From these experiments it is evident that, between the different stimuli, there are no appreciable differences as to the increase of the loss by prolongation of the time of exposure from 5 to 15 and 45 minutes. This result lends plausibility to the assumption that still a greater prolongation of the stimulation time does not affect the proportion of the traumatizing powers of different stimuli. Thus we are justified in making use of experiments of short duration to determine the traumatizing power of a sound.

Table II
Effect of prolongation of exposure-time to different stimuli
Stimulus: white noise

exposure-time	cont. 97 dB				$8 \times \frac{1}{32}$" 109 dB			
	CR l.	CR r.	00	mean	CR l.	CR r.	00	mean
5 min.	$12\frac{1}{2}$	$7\frac{1}{2}$	$7\frac{1}{2}$	9	10	10	5	8
15 min.	$17\frac{1}{2}$	$17\frac{1}{2}$	10	15	15	$12\frac{1}{2}$	$7\frac{1}{2}$	12
45 min.	$22\frac{1}{2}$	25	10	19	20	$17\frac{1}{2}$	$12\frac{1}{2}$	17

	$2 \times \frac{1}{32}$" 105 dB				$2 \times \frac{1}{4}$" 97 dB			
	CR l.	CR r.	00	mean	CR l.	CR r.	00	mean
5 min.	5	$7\frac{1}{2}$	10	$7\frac{1}{2}$	5	5	5	5
15 min.	$7\frac{1}{2}$	$7\frac{1}{2}$	10	8	$7\frac{1}{2}$	10	5	8
45 min.	10	$12\frac{1}{2}$	$12\frac{1}{2}$	12	10	10	$7\frac{1}{2}$	9

Table representing the maximal hearing losses in dB caused by exposure during 5, 15 and 45 minutes to different white noise stimuli. The same sequence of averaged dip - sizes exists for all exposure-times used.

§ 8. Theories on the origin of the auditory fatigue

Most of these theories are concerned with the explanation of the so-called c^V dip. They ascribe the special sensitivity of this region to the fact that the blood supply is less, because of the course of the arterial vessels.

Another explanation is given by Rüedi and Furrer (1946). They assume that in low-tone stimulation eddies arise in the cochlea that shift the basilar membrane towards the helicotrema, and in high-tone stimulation towards the windows. When stimulating with a mixture of tones or a noise, the critical area will be at 4000 cps and at this place the two eddies would act in opposite directions, causing a stretching of the membrane. The authors try to prove, by applying tone mixtures, that complex sounds, consisting of frequencies below and above 4000 cps, always cause a hearing loss at c^V.

The objection of van Dishoeck (1953) and van Gool (1952) against this theory is that the trauma of the 4000 cps tone also occurs on a higher frequency and not at 4000 cps. In addition van Leeuwen (1955) observed that high-pitched noise caused a trauma well above c^V.

They considered fatigue to be a result of inadequate stimulation of the basilar membrane, the adequate stimulation being the eddy in the perilymph. According to the experiments of von Békésy a travelling wave motion appears between this eddy and the window, which causes no sound perception. The place of the maximum of this motion depends on the frequency of the stimulating tone and is situated at a place as calculated by Reboul. This inadequate stimulus will cause a distortion of the haircells and consequently a hearing loss. The contour of this hearing loss resembles the pattern of the masking effect of the stimulating tone. This suggests that masking and fatigue are kindred phenomena (vide fig. 3).

Chapter IV

INTENSITY MEASUREMENT OF STEADY AND NON-STEADY SOUNDS

§ 1. Practice of sound measuring

In determining the quantitative relationship between sound stimulus and auditory fatigue it is necessary to measure the intensity of the sound. In practice one confined oneself at first to determining the overall sound pressure level in dB re 0,0002 dyne per cm^2 by means of a sound-level meter with a so-called flat curve. By this is meant a sound-level meter which is not adapted to the sensitivity curve of the ear. Later on the sound-level meters were provided with weighting networks to approximate the frequency characteristics of the human ear for pure tones. By means of the latter instruments the sound level can be determined in phons.

Since Kryter (1950) pointed out that the distribution of the sound energy over the different frequencies determines to a high degree the traumatizing power of the noise, one proceeded to measure the sound-pressure level per octave or even in a narrower frequency band. It should be realized that in this way exact values can only be obtained for a pure tone. Even in the case of a thermal noise the pointer of the meter is not at rest, so that one must be content with an approximate reading. This holds true in a much higher degree for the measurement of the very unsteady factory noises. In most kinds of factory noise such an average reading can be taken only by very rough approximation.

An attempt to minimize this difficulty is made by prolonging the indication time of the meter. The values obtained with such a meter, which indicates very slowly, do not satisfy any claims to exactness.

Already McGrath (1952) realized that the sound-level meter is not reliable as an indicator of the traumatizing power of factory noise. For this reason he gave a formula to calculate the damaging effect of intermittent noises. He distinguished an "average high intensity level" and an "average low intensity level". In the case of a difference of 6 dB between these measured values, the lowest value must be increased by 0.6 dB for every 10% of the total exposure time that the intensity of the noise is at the higher level. If the difference between both intensity levels is n x 6 dB and the exposure time per pulse is t, the total exposure time being T, the formula becomes $I = I_{low} + n\,(\Sigma t/T) \times 10 \times 0.6$ dB.

McGrath was not able to measure with his equipment the relation between Σ t and T. Recently Peterson (1956) described an impact noise analyzer. With this analyzer three characteristics can be measured: the "quasi peak", the "peak" and the "time average". The quasi peak is a continuously indicating measure of the higher sound-pressure levels and useful for repeated impacts. The peak is the maximum sound pressure reached by the noise; the time-average level is a measure of the level maintained over a period of time. The difference between the peak level and time average is a measure of the time of the sound wave. So the two characteristics of a single impact: peak level and duration time, are known.

Probably it is possible with this method to measure the duration and intensity of the peaks of other non-steady noises with more exactness than that by the usual measuring technique with a sound-level meter.

§ 2. Measurement of non-steady synthetic noise

In order to study the importance of the inexactness of the sound-level meter method, we performed experiments with synthetic noises of which the intensity of the component sounds could be measured accurately. For this purpose sounds were produced consisting of a thermal noise and pure tone pulses, both of known intensity (table III) so that the overall-intensity could be calculated. This can be done in the following manner: if the pulse-interval ratio is 1 : x the calculated overall-intensity of the pulses amounts the peak-intensity of the pulses diminished by 10 log. (1 + x) dB. The peak-intensity is known as the intensity of the continuous sound from which the pulses are produced. The calculated overall-intensity of the synthetic noise is given by adding together the overall-intensities of the components in the usual way.

From these experiments we may conclude that short intensity-peaks followed by long intervals affect the meter reading so little that the calculated overall-intensity is not expressed. If the pulse duration is greater than the interval between two pulses, the meter indicates a value which agrees well with the overall-intensity. In the same way the more the peak-intensity differs from the basic intensity, i.e. in the case of "high peaks", the greater the difference between calculated intensity and meter reading will be. If the difference between peak- and basic intensity is only 10 dB this discrepancy will be small.

Table III

Measurement of intensity of non-steady sounds

pulse notation	pulse-interval ratio	basic intensity 60 dB	70 dB	80 dB	90 dB
$8 \times \frac{1}{64}''$ 100 dB	1 : 7	85 (91)	$85\frac{1}{2}$(91)	88 (91.4)	$93\frac{1}{2}$(93.5)
$8 \times \frac{1}{32}''$	1 : 3	89 (94)	89 (94)	91 (94.2)	95 (95.5)
$8 \times \frac{1}{16}''$	1 : 1	95 (97)	95 (97)	$95\frac{1}{2}$(97.1)	$97\frac{1}{2}$(97.8)
$8 \times \frac{3}{32}''$	3 : 1	98 (98.8)	98 (98.8)	98 (98.9)	99 (99.3)
$16 \times \frac{1}{64}''$	1 : 3	$90\frac{1}{2}$(94)	91 (94)	92 (94.2)	95 (95.5)
$16 \times \frac{1}{32}''$	1 : 1	94 (97)	94 (97)	$94\frac{1}{2}$(97.1)	97 (97.8)
$16 \times \frac{3}{64}''$	3 : 1	97 (98.8)	97 (98.8)	97 (98.9)	$98\frac{1}{2}$(99.3)

Table representing the values indicated by a sound-level meter for synthetic sounds, constructed from a white noise and pulses of a pure tone. These values are always less than the calculated values ( ), the difference being maximal for the smallest pulse-interval ratio and the lowest basic intensity.

3. Analysis of the non-steady noise of a pneumatic drill

As an example of non-steady noise we studied the noise of a pneumatic drill in a hard-walled cellar, recorded with the magnetophone. A section of the magnetophone-tape of 6 sec. play-time in which the drill functioned regulary, was selected and mounted as an endless band so that the same noise might be produced for any length of time. In order to study the factors, which determine the traumatizing power of this noise, firstly a 1/3 octave band analysis was made with the aid of the 1/3 octave band analyzer and the levelmeter (fig. 7).

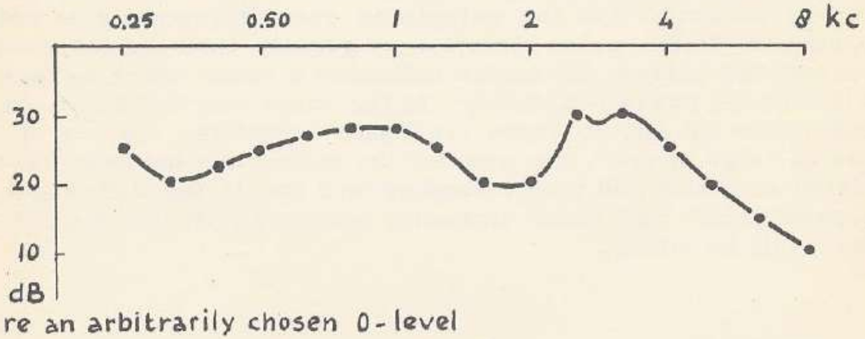

Figure 7
Diagram of the 1/3 octave band analysis of the noise caused by a pneumatic drill.

This curve shows that the greater part of the sound energy is concentrated in two frequency-ranges, viz. in the range 500-1250 cps and in the 1/3 octaves of 2500 and 3200 cps geometric mean frequency, the latter bands being the most traumatizing. However, these intensity values were determined by averaged meter readings. As proved in the preceding § these values are inexact in respect to the real overall intensity. In order to measure the changes of intensity as a function of time, an apparatus with a very small indication time must be used. The cathode ray oscilloscope meets this demand. The oscillogram of the unfiltered noise (fig.8) shows distinct pulses with a rate of ca. 27 per sec. If the noise is led through a 1/3 octave filter with a geometric mean-frequency of 3200 cps or 2500 cps these pulses are even higher relatively to the basic noise (fig. 9).

This means that the sound-pulses produced by the drill consist for the greater part of frequencies of these bands. As these bands are the most traumatizing it is important to know the intensity, duration-time and rate of repetition of the peaks in these bands. We tried to estimate these values for the 1/3 octave band of 3200 cps mean-frequency.

A simple approximation of these values may be obtained by an imitation of the oscilloscopic picture by using a thermal noise and intermittent tone pulses as used in the previous paragraph. In order to investigate this possibility we constructed, by combining a thermal noise and tone pulses of 3000 cps, a synthetic noise of the same oscilloscopic appearance as the pneumatic drill noise. Both the unfiltered and filtered synthetic noise (fig. 10 and 11) show a fair resemblance to the analogous oscillograms of the drill noise. Unfortunately our pulse generator did not permit a rate of 27 pulses per sec. For this reason a pulse-rate of 16 per sec. was chosen. The pulse-interval ratio of our synthetic noise, however, was the same as that of the pneumatic drill noise. The pulses produced lasted from 5 to 6 m.sec.; the pulse-interval ratio was 1 : 9 to 12.

Now the intensity level of our synthetic noise and the noise of the drill must be equalized. This is easily done by amplifying the synthetic noise to the same meter-reading as that of the actual noise. Though the difference between peak- and basic noise level was 20 dB, the meter reading in the synthetic noise exceeded the basic noise level only by 3 dB. The calculated difference was 10 dB. If the measured value on the level meter and also the images on the screen are the same, we are allowed to conclude that the two sounds must be similar in respect to the intensity level of peaks and basic noise and thus also in traumatizing power. Evidently sound measuring in this way is still relatively inexact.

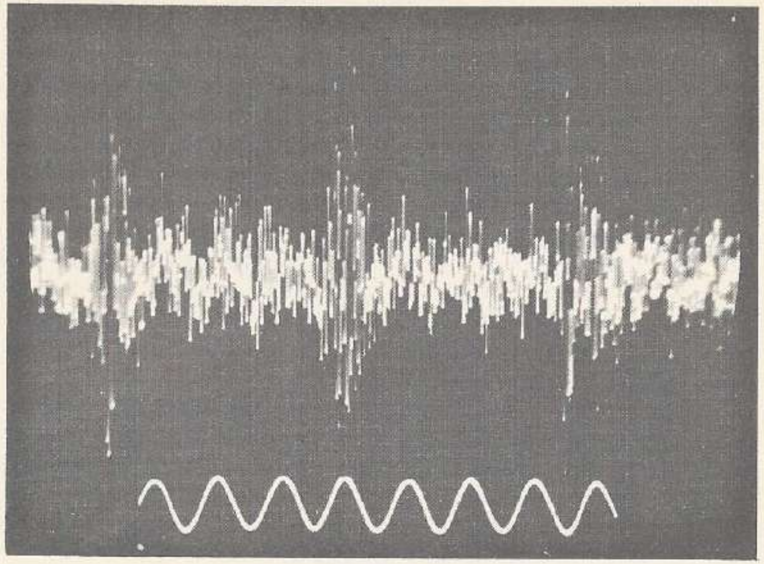

Figure 8
Oscilloscopic picture of the unfiltered noise of a pneumatic drill. There are distinct intensity-peaks with a rate of repetition of 27 per second.

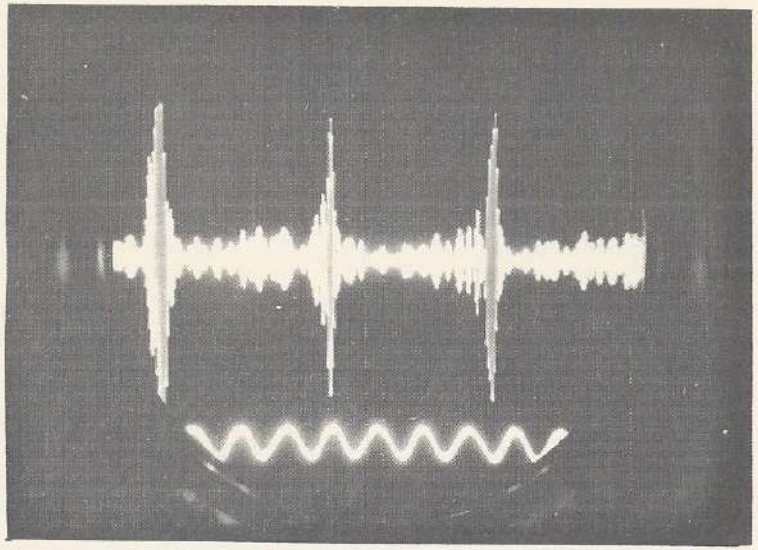

Figure 9
Oscilloscopic picture of the 1/3 octave band of 3200 cps geometric mean frequency of the same noise. In this frequency-range the peaks are much higher relatively to the basic intensity level.

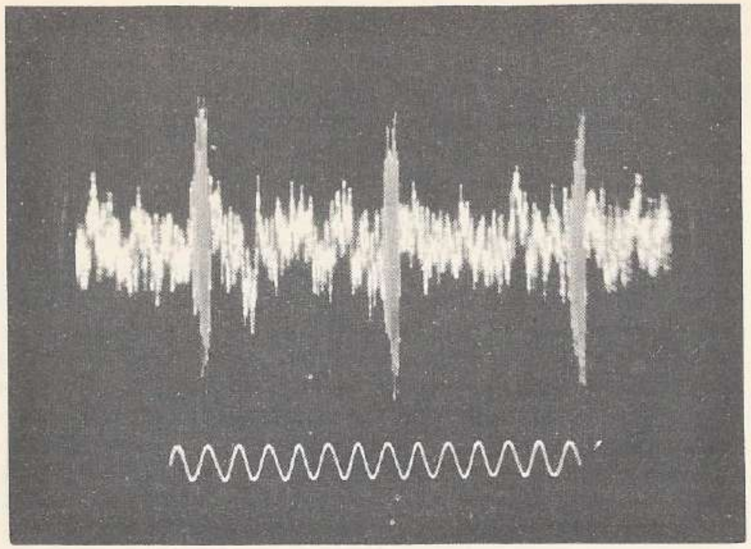

Figure 10
Oscilloscopic picture of the unfiltered noise by which the drill noise was imitated. This noise was constructed from a continuous white noise and tone pulses of 3000 cps. As the pulse generator could not produce a pulse rate of 27 per second, a pulse-rate of 16 per second was chosen.

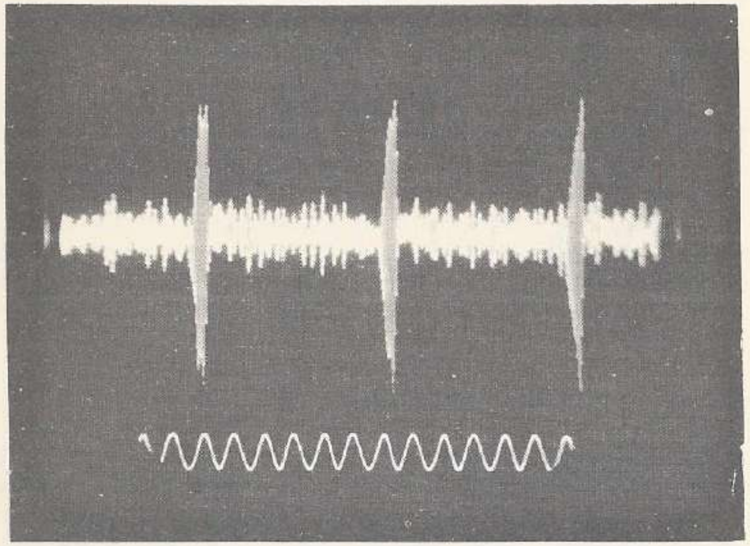

Figure 11
Oscilloscopic picture of the 1/3 octave band of 3200 cps geometric mean frequency of the same synthetic noise. To equalize this picture to that of the same band of the drill-noise (fig.9), the peak-intensity had to be made 20 dB greater than the intensity of the white noise, whereas the pulse-interval ratio had to be circa 1 : 10.

Chapter V

THE INFLUENCE OF FREQUENCY ON THE TRAUMATIZING POWER

§ 1. Previous experiments

Already Rawdon Smith in 1934 had found that the 1000 cps tone gives a hearing loss at a lower intensity than the 500 cps tone. Davis (1950) established as the order of harmfulness: 500 cps less than 1000 cps = 2000 cps less than 4000 cps. Van Gool (1952) established the fact that the sensitivity to 1000 cps is less than to 2000 cps, and that all frequencies above 2000 cps are equally harmful, provided the intensity is referred to the normal hearing threshold. Theilgaard (1949) demonstrated that the order of harmfulness of the different frequencies can differ remarkably as between the different test persons. In 1955 Plomp published a similar investigation in two testees.

In addition the same sequence holds good, if not the critical intensity is determined, but the intensity needed to obtain a hearing loss of a certain size.

Using octave bands of a noise instead of pure tones an order of harmfulness appeared that approximately corresponded to the order found for the mean frequencies (Davis, Plomp, van Leeuwen).

However, in our opinion such conclusions about the harmfulness of a stimulus measured at a single frequency are not conclusive. As fig. 5 shows there may be several dips, part of which is probably due to overtones. Moreover, if low frequencies are used the trauma may be situated in the speech area, and thus, though the depth of the dip may be the same as on higher frequencies, the result for the patient may be worse.

§ 2. Deafness Risk Criteria

At first the traumatizing threshold of all sounds was estimated at from 80 to 90 dB re 0.0002 micro bar. Since the experiments with pure tones had proved that high frequencies are more traumatizing than lower ones, and since experiments with bands filtered out of a noise (Davis, van Leeuwen and others) had proved the same, it became necessary to introduce a curve indicating the traumatizing threshold for

each frequency. Several of these curves, called Deafness Rick Criteria, were proposed.

Kryter (1950) was the first to divide a given noise into bands and to measure the intensity for each band separately. He estimated 85 dB per critical band, even in the case of long exposure, not to be damaging. A critical band means the narrowest band that can completely mask the tone of the mean frequency of equal intensity.

Beranek (1951) pointed out, that the slight harmfulness of the lower frequencies found relatively inadequate expression in Kryter's proposal, and he consequently raised the critical intensity of the low bands. Parrack (1952) calculated from Beranek's criterion his "Deafness Risk Criterion" for octave bands. McGrath's (1952) criterion differs from that of Beranek. His equivalent impairment level is 6 dB less for each higher octave. Hardy (1952) started from the calculation of Harvey Fletcher (1951) from which it was evident that the curve for equal amplitude of the basilar membrane corresponds well to the equal-loudness curve. Therefore he assumed that:

a. Loudness of a critical band is a function of the maximum stimulation energy on the nerve endings.

b. Fatigue is also a function of this maximum stimulation energy, independently of the frequency. From this it was concluded that:

c. Sounds which are perceived with equal loudness must possess an equal traumatizing power.

From Hardy's own experience, and the scarce data in the literature the limit between harmful and harmless noise would be between 50 and 100 sones per octave band; this corresponds to an intensity level between 90 and 100 dB for the octave of 600 to 1200 cps.

McGrath formulated another explanation. He connected the greater harmfulness of the higher octaves with the circumstance that "the number of cycles doubles each octave" and that "the effective sound pressure doubles every 6 dB". He assumed without further argument, that "the impairing effect is the same as if the pressure were actually doubled for each octave band".

We cannot agree with this conception. Probably his assumption is based on the idea that the traumatizing power is proportional to the maximum particle velocity at the entrance of the external meatus. As a matter of fact the maximum particle velocity of a given pure tone equals that of a tone one octave higher if this tone has half of its sound pressure, i. e. is 6 dB weaker. But the particle velocity will be changed in passing the outer and middle ear, dependent on the frequency.

A comparison of the criteria of Parrack, McGrath and

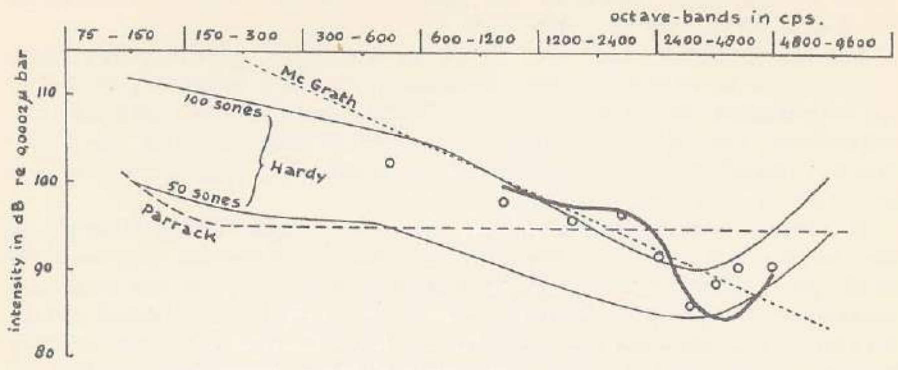

Figure 12

Comparative graph of the Deafness Risk Criteria proposed by Parrack, McGrath and Hardy (after van Leeuwen). These curves indicate the boundary between traumatizing and non-traumatizing intensity of the octave bands. In this graph the mean traumatizing thresholds of 2 test persons (oooo) and the mean tolerance-curve of 8 test persons (——) are plotted to show the inexactness of these theoreticalcriteria. The experimental findings will be described in § 3 of this chapter.

Hardy shows differences not only in their theoretical foundation, but also in the distinctly divergent curves (fig. 12) in the intensity-frequency diagram. They coincide in the 1200-2400 cps octave. In the 2400-4800 cps octave the "Deafness Risk Criterion" of Parrack exceeds both others by 5 dB only.

Van Leeuwen (1954) used the three abovementioned deafness risk criteria to compare the spectrum analysis of different department noises with the curve representing the average loss of the workers per department. As a whole the hearing losses proved to confirm the expectation based on the three deafness-risk criteria. This result can be explained by the partial coincidence of the three criteria. According to van Leeuwen Hardy's criterion, the total loudness in sones, satisfies best.

§ 3. Deafness-Risk Curve based on experiments

The above-discussed deafness-risk criteria are for the greater part based on theoretical considerations and calculations; with the exception of Hardy, who tried to correlate his curve with the audiograms of factory workers exposed to different kinds of noise.

In our opinion a curve based on experimental investigation is highly wanted. With the technique mentioned it is easy to determine the critical intensity that causes a 5 dB trauma for each frequency, viz. by stimulating during $2\frac{1}{2}$ minutes. This was done for 9 frequencies between 500 and 5000 cps. The

value found was called the critical intensity or the traumatizing threshold. Beginning well below this threshold and increasing with 5 dB steps, the effect was measured in the usual way over a frequency area of 300-8000 cps. These experiments were performed in 2 test persons and on each frequency two observations were made. The results never differed more than 5 dB. From the deafness-risk curve obtained (fig. 13) it appeared that in test person C.R. the 3000 cps area was the most damaging, and in test person G.M. the 3500 cps. There is also a difference between these 2 testees as to the critical intensity of 500 and 2000 cps.

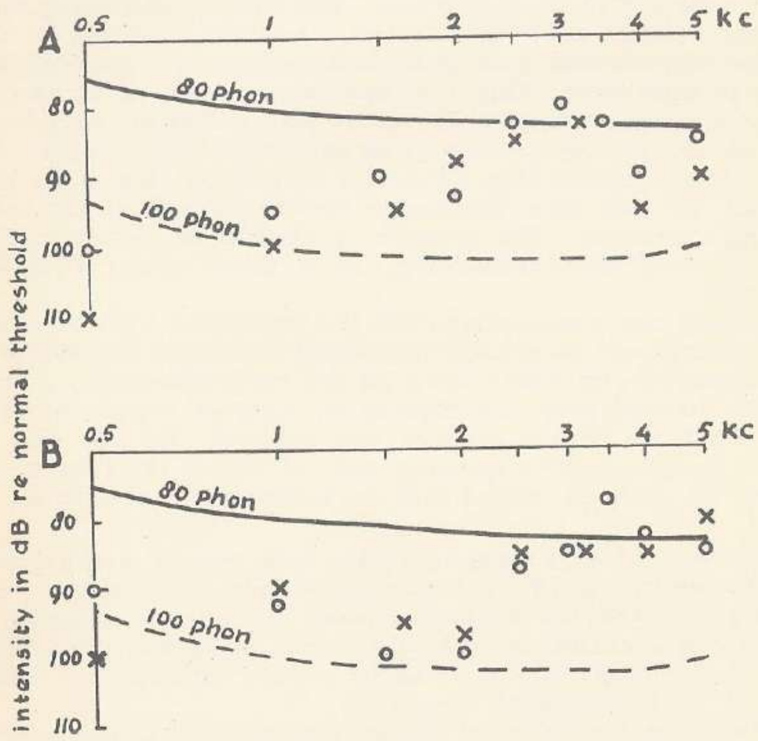

Figure 13

Minimal traumatizing intensities of pure tones (ooo) and 1/3 octave bands (xxxx) of a white noise, referred to normal threshold as determined in the test person C.R. (A) and G.M. (B). The curve connecting the values for pure tones is called the traumatizing threshold, and lies near the 100 dB-isophon for the lower frequencies and near the 80 dB-isophon for the higher frequencies.

In the same manner the critical traumatizing intensity of 1/3 octave bands of a thermal noise was determined. On comparing the values with those obtained for pure tones, it appears that the bands are tolerated a little better than the pure tones, on an average only 2 dB, but even 10 dB for 500 cps.

Plomp repeated our experiments with pure-tone and octave band stimuli and obtained nearly the same results.

According to the abovementioned theory of Hardy, stimuli of equal loudness should be of equal traumatizing power. This means that the traumatizing threshold should be an isophon. From fig. 13 it may be seen that this is not true. The values obtained for frequencies below 1000 cps approximate the isophon of 100 dB and for frequencies above 3000 cps the isophon of 80 dB.

If one increases the intensity of a tone to a certain value the tone gets an impure, sharp character possibly due to some distortion in the inner ear. The curve connecting these intensity-values may be called "tolerance curve". One gets the impression that this phenomenon is a warning that danger is imminent. This conception was proved by the results of our experiments; for there was a distinct agreement of the values for the traumatizing threshold (fig. 13A, B) and the tolerance curve (fig. 14 A, B). Based on this fact, it is tempting to use this tolerance curve instead of the traumatizing threshold. The former is simple to obtain and the latter is very time-consuming, as it needs about 45 determinations.

We made the assumption that the individual differences in traumatizing and tolerance threshold found are dependent on the resonance-characteristics of the external auditory meatus. We proved this assumption by special experiments in which the form of the meatus was altered. To this end we used an earpiece of a hearing aid, of which the lumen was widened to such an extent that the hearing threshold was not altered.

The result of these experiments was rather remarkable, as is shown by fig. 14. The tolerance curves are altered to a high degree, and the trauma caused by a thermal noise is displaced in accordance with this curve. Apparently the maximum of the noise dip is situated at less than half an octave above the most damaging frequency.

On studying the effect of thermal-noise stimulation on test persons, we found one remarkable dip in a Chinese student (fig. 14C). This led us to determine the tolerance curve of this test person in order to see if the abnormal pattern of the dip could be explained by an abnormal traumatizing threshold. This proved to be the case. From these experiments we may conclude that the tolerance curve and thus the deafness-risk criterion are dependent on the form of the external meatus. Moreover, the tolerance curve is not related to an isophon but probably related to the intensities causing distortion in the inner ear.

We studied our deafness-risk curve in relation to the criteria mentioned. For this purpose we calculated a mean curve

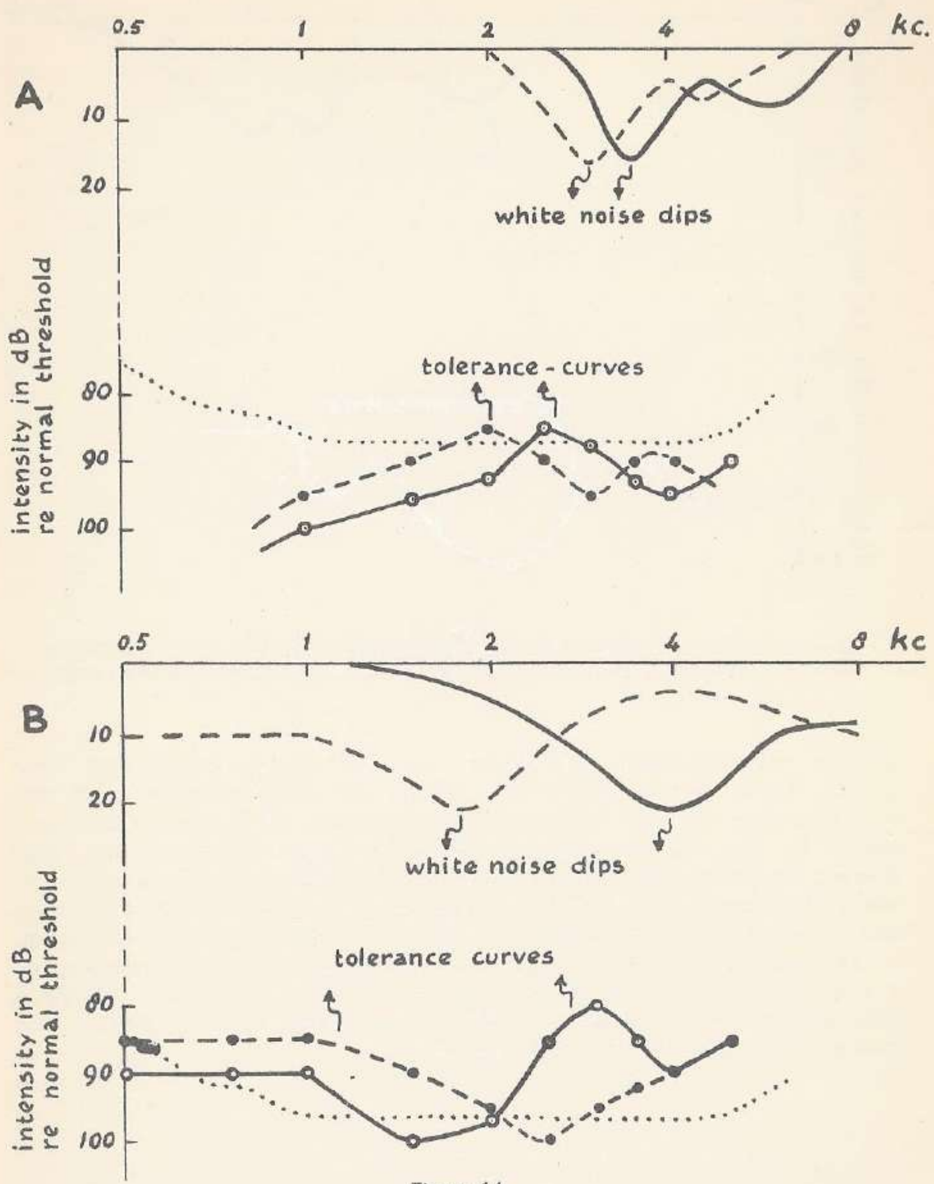

Figure 14

Tolerance-curves indicating the intensities above which a pure tone gets an impure, sharp character, and corresponding white noise-dips (——) of the same test persons as reported in fig.13A, B.

Note the parallelism between tolerance-curve and traumatizing threshold. The maximal hearing loss caused by a white noise is localized at somewhat less than $\frac{1}{2}$ octave above the maximum of these curves. The 1/3 octave band analysis of the white noise (......) shows a flat curve between 500 and 5000 cps.

By inserting into the external meatus a specially prepared earpiece of a hearing aid, which did not change the threshold audiogram, the tolerance-curve and the localization of the noise-dip (----) were altered to a high degree and in the same sense.

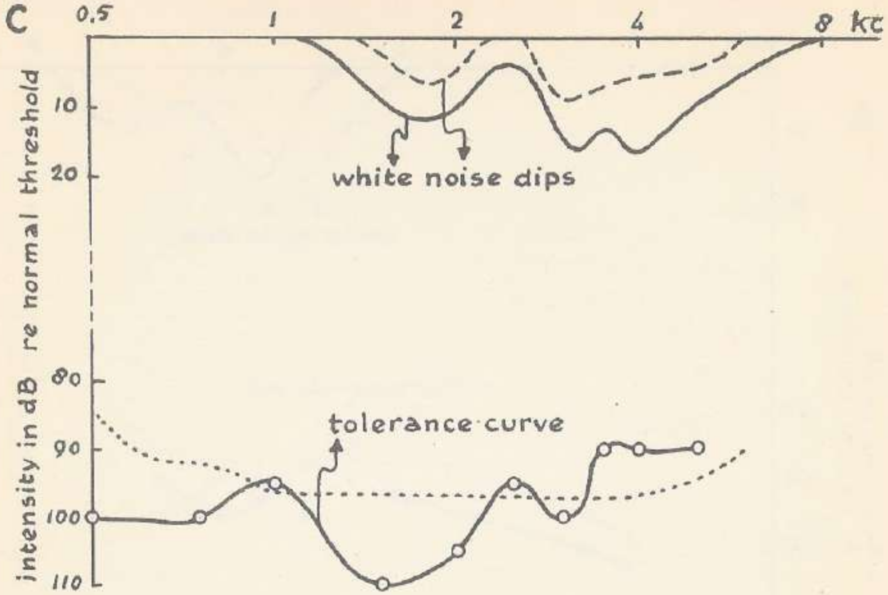

Figure 14
Dips of uncommon pattern and localization caused by a white noise in a Chinese student. These dips appeared to correspond to an also uncommon tolerance curve.

of the traumatizing thresholds of the test persons C. R. and G. M. This curve showed a close correspondance with the mean curve of the tolerance thresholds of 8 other test persons. In fig. 12 our experimentally determined curves are drawn between the theoretically calculated criteria of Parrack, McGrath and Hardy. It appears that for the mean curve the closest correspondence exists with the criterion of Hardy.

As was shown by our experiments (fig. 14) the recording of a tolerance curve enables one to predict the place where a dip will occur if a noise with equal intensity for bands between 1000 and 4000 cps is given.

Chapter VI

INFLUENCE OF INTENSITY ON THE TRAUMATIZING POWER

§ 1. Previous Reports

Davis (1950) studied for pure tones the size of the trauma by increasing the intensity from 110 to 120 and 130 dB. The duration of the stimulus ranged between 1 and 64 minutes. He concluded that the increase of the trauma for 500 cps was smaller and for 4000 cps greater than for 1000 and 2000 cps and that a linear relation between intensity and trauma did not exist.

Harris (1953) did the same for a 750 cps tone and an increase of intensity from 120 to 140 dB. The stimulation-time ranged from $\frac{1}{2}$ to 15 minutes. From his experiments he concluded that the relation between intensity and hearing loss was a linear one.

Plomp (1955) came to the same conclusion for other frequencies too.

§ 2. Experiments on the influence of an increase in intensity

In the experiments mentioned above the results were obtained by octave-audiometry. In our opinion better results can be expected with determinations by the continuous technique. Moreover, the results of the previous experiments are not conclusive, as Davis found a non-linear and Harris a linear correlation. Thus we decided to repeat these experiments by using a 2000 cps tone. This frequency was chosen because the trauma can be expected in a range wherein the threshold is easily indicated by the testee, and outside the range that is most important for speech-discrimination; thus the deafness risk is acceptable. Moreover, the same was recorded for a thermal noise. The intensities chosen were such that the minimum size of the resultant dip was 5 dB.

For our problem, viz. the effect of non-steady noise on the ear, it was desirable to determine the result of the increase of intensity for intermittent stimuli too.

1. A continuous pure tone of 2000 cps was used, the intensity being increased in 5 steps of 3 dB. The exposure time was 5 minutes (table IV A) and 15 minutes (table IV B), the number of testpersons four.

Table IV

Relation between intensity of a 2000 cps tone and hearing loss

A. Stimulation-time: 5 min.

intensity	G M	C R	L	v T	average
—	10	10	$12\frac{1}{2}$	$7\frac{1}{2}$	10
+ 3 dB	15	$17\frac{1}{2}$	15	10	14
+ 6 dB	25	20	20	15	20
+ 9 dB	35	25	$22\frac{1}{2}$	20	26
+ 12 dB	$37\frac{1}{2}$	30	$27\frac{1}{2}$	$22\frac{1}{2}$	29
+ 15 dB	45	$42\frac{1}{2}$	$32\frac{1}{2}$	25	36

B. Stimulation-time: 15 min.

intensity	G M	C R	S	d H	average
—	15	10	$12\frac{1}{2}$	10	12
+ 3 dB	20	15	15	15	16
+ 6 dB	$27\frac{1}{2}$	20	20	20	22
+ 9 dB	$27\frac{1}{2}$	25	25	25	26
+ 12 dB	35	30	30	30	31
+ 15 dB	55	$47\frac{1}{2}$	35	35	43

Tables representing the maximal hearing losses in dB for different stimulus-intensities. Increase of intensity by 3 dB corresponds to an increase of hearing loss by about 5 dB for both stimulation-times. The relation appears to be a linear one, except for dips greater than 35 dB.

From these tables we may conclude that increase of the stimulation-time makes a difference only in the size of the dips, but not in the degree of increase.

In both tables a nearly linear relation between intensity and size of the trauma exists. By increasing the intensity by 3 dB, the size of the trauma was increased by about 5 dB. The only exception exists for the greatest intensities of stimulation. Here in two test persons the increase is more than would be expected from a linear relation. Thus we may conclude that below a dip-size of approximately 30-35 dB the increase is linear, but that above this value a disproportional increase often occurs. This phenomenon will be discussed in the next §.

2. Two intermittent tone-stimuli of 2000 cps were used during 5 minutes: (a) 2 x 1/16" (table V A) and (b) 8 x 1/16" (table V B). The intensities of both stimuli were increased by 12 dB, that is for stimulus (a) from 99 to 111 dB and for stimulus (b) from 89 to 101 dB.

Table V

Relation between intensity of intermittent pure tones and hearing loss

A. Stimulus 2000 cps, 2 x 1/16", 5'

intensity	Sch	Fu	Br	CR	average
99 dB	$12\frac{1}{2}$	$7\frac{1}{2}$	$12\frac{1}{2}$	15	12
111 dB	30	$22\frac{1}{2}$	25	30	27

B. Stimulus 2000 cps, 8 x 1/16", 5'

intensity	GM	LR	Br	CR	average
89 dB	10	$7\frac{1}{2}$	5	$7\frac{1}{2}$	8
101 dB	$22\frac{1}{2}$	$22\frac{1}{2}$	$17\frac{1}{2}$	20	21

Tables representing the hearing losses for different stimulus-intensities. From these tables it appears that an increase of intensity by 12 dB results in a ca 14 dB greater dip.

From these tables it appears that an increase of intensity by 12 dB results in an increase of the hearing loss by 15 dB (table V A) or 13 dB (table V B). If it is assumed that both for intermittent and for continuous stimuli the relation is linear, these values mean that an intensity increase of 5 dB correlates with an increase of the maximum hearing loss of 3-4 dB. This is a little less than the relation found for a continuous tone.

3. A continuous white noise was used, the intensity being increased by 5 dB for a stimulation-time of 5 min. (table VI A) and by 3 dB for a stimulation-time of 15 min. (table VI B).

From table VI A it appears that an increase of intensity by 5 dB results in an increase of dip-size of $6\frac{1}{2}$ dB, whereas it appears from table VI B that this effect was 4 dB for an intensity-increase of 3 dB. This means that an increase of the stimulus-intensity by 3 dB corresponds to an increase of the maximum hearing loss of about 4 dB.

4. An intermittent thermal noise-stimulus of 2 x 1/32" was used, the intensity being increased from 110 to 119 dB. The stimulus-duration was 5 and 15 minutes (table VII).

Table VI
Relation of intensity of continuous white-noise stimuli and hearing loss

A. Stimulation-time: 5 min.

intensity	Kn	GM	Ge	Ja	average
-	5	20	15	5	11
+ 5 dB	10	30	20	10	17½

B. Stimulation-time: 15 min.

intensity	CR	KO	Vr	GM	average
-	22½	22½	17½	12½	19
+ 3 dB	22½	22½	30	17½	23

Tables representing the hearing losses for different stimulus-intensities. From these tables it appears that an increase of intensity by 3 dB results in a ca 4 dB greater dip.

Table VII
Relation of intensity of intermittent white noise stimuli and hearing loss

A. Stimulus: 2 x 1/32", 5'

intensity	MK	HO	CR_r	CR_l	average
103 dB	5	5	10	5	6
112 dB	15	15	17½	10	14

B. Stimulus: 2 x 1/32", 15'

intensity	MK	HO	CR_r	CR_l	average
103 dB	5	10	10	10	9
112 dB	17½	17½	25	17½	19

Tables representing the hearing losses for different stimulus-intensities. From these tables it appears that increasing the intensity by 3 dB results in a ca 3 dB greater dip.

From this table it appears that an increase in intensity of 9 dB results, for a stimulation-time of 5 minutes, in an 8 dB greater trauma, and for a stimulation-time of 15 minutes in a 10 dB greater trauma. Here too the effect of intensity increase is a little less than for the continuous stimuli.

From these different experiments it follows that probably the increase in the traumatizing effect of a pure tone is somewhat greater than that of a noise, and that the increase of the effect of a continuous sound is somewhat greater than that of an intermittent one. An increase of intensity by 3 dB results for a continuous tone in an about 5 dB greater dip; for an intermittent tone and a continuous white noise in an about 4 dB greater dip; and for an intermittent white noise in an about 3 dB greater dip.

§ 3. Application of the tables

In the next two chapters the traumatizing power of pulses of different character will be studied. As an example, the number of pulses per sec. will be increased. This will enlarge the size of the dip, but also the overall-intensity of the sound. With these tables we can now calculate the difference in traumatizing power between the various intermittent stimuli and the continuous stimuli of the same overall-intensity.

As already mentioned, the limit of a 35 dB-dip must be watched, since above this value the increase is abnormal. In our experience these large dips, which are associated with an often severe tinnitus, need several days to recover. This means that when a factory worker is exposed to a noise-intensity causing a dip of 30 dB or more in one working-day, this dip will not be recovered completely before the next day-exposure. Thus there will be a cumulation of hearing loss and permanent deafness must be feared very soon.

In order to prove that these disproportionally large dips are reproduceable, one test person was exposed to a series of intermittent 2000 cps stimuli (2 x 1/16") during 5 minutes. An intensity increase from 99 dB to 105 dB and to 111 dB increased the maximum hearing loss from 15 to 20 and to 30 dB respectively. But another intensity-increase of 6 dB, viz. 117 dB, caused a dip of 55 dB. After a week a stimulus of 3 dB less, viz. 114 dB, was offered. The resulting dip now reached a value of 45 dB, which was midway between those of the two preceding dips. These experiments make it plausible that the disproportional increase above a dip-value of 30 to 35 dB is reproduceable. Moreover, the form of the large dips corresponded well to the form of the smaller dips.

Another example of exceeding the critical dip-size is given in the next chapter § 2, table IX B, test person He. In this case the difference in effect between the continuous stimulus and the intermittent stimulus 12 x 1/32" amounts to 20 dB, whereas this difference for the other two test persons is 10 and 5 dB only.

Presumably this phenomenon must be based on the special behaviour of the basilar membrane following stimuli of different harmfulness. Thus the skin will react to heat stimuli in clearly distinct degrees with great jumps in the healing-time.

Chapter VII

THE TRAUMATIZING POWER OF INTERMITTENT SOUNDS

In chapter IV is demonstrated that the non-steady noise we studied consists of a basic noise and peaks of higher intensity. From these experiments we concluded that it is permissible to imitate peaks in a factory-noise by artificial sound-pulses, produced in the laboratory.

In the following experiments, sounds consisting of pulses with traumatizing intensity, alternating with intervals of non-traumatizing intensity, are used. In the discussions they will be referred to as intermittent sounds. The traumatizing power of intermittent sounds is determined by 6 factors, viz. the frequency, the maximum intensity level, the duration of each pulse, the rate of repetition of the pulses and the rise- and decay-time.

The two most important factors, viz. the frequency and the maximum intensity-level, have already been discussed in the preceding chapters. It proved to be possible to keep the pattern of the pulse constant, namely on a rise- and decay-time of 5-6 m. sec. except in the special experiment described in chapter VIII, § 3.

The remaining two factors are the duration of each pulse and the rate of repetition. In a regular intermittent noise this means the frequency of the sound-pulses. However, one should not confuse this frequency with the frequency of the sound used in the pulses. In the paragraphs 1-4 the pulses were derived from a pure tone of 2000 cps. The reason why this frequency was chosen has already been discussed in the foregoing chapter. The conclusions derived from the experiments with the 2000 cps tone were compared with the results obtained with pulses consisting of a thermal noise. This was done to be sure that these findings hold true for different kinds of sound.

As there are no reports of any investigation on this subject, a discussion of previous experiments cannot be given.

§ 1. Experiments on the influence of the duration of the single tone-pulse

The influence of the pulse-duration on the traumatizing power is studied in two series of experiments. In the first series experiments are done with a slow pulse-rate, viz. 2

Table VIII

Relation of the pulse-duration of intermittent 2000 cps stimuli and hearing loss, the pulse-rate being constant

A. Pulse-rate: 2 per second. Stimulation-time: 5 min.

pulse-duration	AG	GM	CR	Po	average	overall-intensity (calculated)
1/16"	10	15	$7\frac{1}{2}$	$12\frac{1}{2}$	11 dB	- 9
2/16"	15	10	10	$17\frac{1}{2}$	13 dB	- 6
4/16"	$17\frac{1}{2}$	15	15	20	17 dB	- 3
6/16"	$22\frac{1}{2}$	20	20	20	21 dB	- 1,2
7/16"	$22\frac{1}{2}$	25	20	$32\frac{1}{2}$	25 dB	- 0,5
cont.	$27\frac{1}{2}$	35	30	$42\frac{1}{2}$	33 dB	0

B. Pulse-rate: 12 per second. Stimulation-time: 5 min.

pulse-duration	AW	D	GM	CR	Po	average	overall-intensity (calculated)
2/96"	$7\frac{1}{2}$	$12\frac{1}{2}$	10	10	25	13 dB	- 6
4/96"	$7\frac{1}{2}$	$12\frac{1}{2}$	15	15	30	16 dB	- 3
6/96"	$12\frac{1}{2}$	$22\frac{1}{2}$	20	25	$27\frac{1}{2}$	22 dB	- 1,2
cont.	$17\frac{1}{2}$	$27\frac{1}{2}$	35	30	$42\frac{1}{2}$	31 dB	0

Each table represents the hearing losses for a series of intermittent stimuli with different pulse-durations and a continuous stimulus of the same intensity.
By increasing the duration of the single pulse both the dip and the calculated overall-intensity increase, but in a different manner (see fig. 15).

per sec., and in the second series with a pulse-rate of 12 per sec.

It must be understood that the factor that was changed in these experiments was the duration of the single pulse. The results of the two series are given in the tables VIII A and B. From these experiments it appears that the traumatizing power increases with the duration of the pulse. This is to be expected because if the duration of a single pulse is increased, the consequence will be that the interval becomes shorter, for otherwise it would not be possible to have the same rate of repetition. Thus the total exposure-time to sound increases.

Now the results obtained in this way were compared with those of continuous sound stimuli. We decided to base this comparison on the traumata resulting from stimuli of the same stimulation-time and the same overall-intensity. Thus if an intermittent sound of 5 minutes duration and 100 dB overall-intensity has a lesser effect than the corresponding continuous sound, we may conclude that the intermittent sound is less traumatizing.

As it is impossible, as stated in chapter IV, to get a reliable reading from a level meter especially in pulses with a slow rate, the only and most reliable method is to calculate the overall-intensities of such intermittent sounds.

From previous experiments with continuous tones, reported in table IV, we know that a 3 dB smaller intensity causes an about 5 dB smaller hearing loss. Thus with the aid of the value determined for one continuous stimulus we can calculate the probable values for the other continuous stimuli which have the same overall-intensity as the different intermittent sounds. These values are plotted together in the curves of fig. 15.

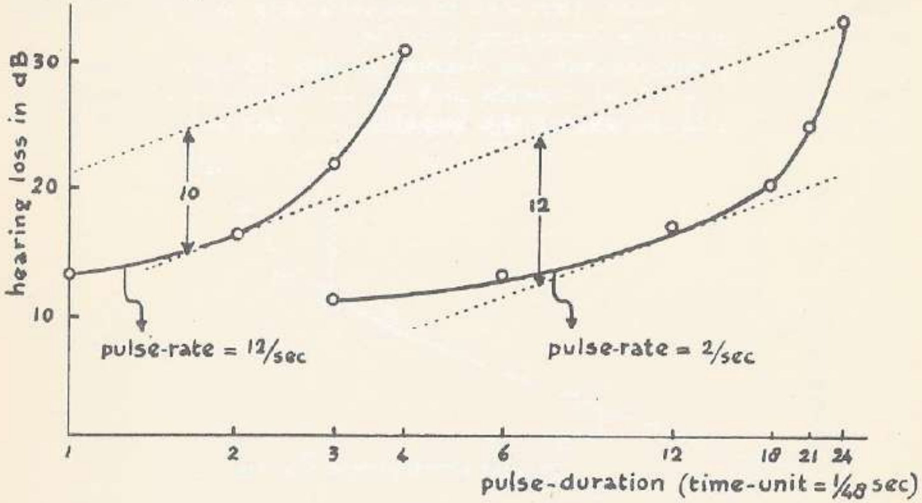

Figure 15

Curves based on the data of the tables VIII A and B, showing the hearing losses caused by intermittent 2000 cps stimuli with pulse-rates of 2 and 12 per sec. The dotted lines indicate the calculated hearing losses corresponding to the continuous stimuli of the same overall-intensities. The intermittent tones are less traumatizing, the difference being maximal, viz. 12 and 10 dB, for a pulse-interval ratio of 1 : 1.

These curves show that on the whole the intermittent sounds are less traumatizing than the continuous sounds. By increasing the duration of the single pulse, the character of the sound and its traumatizing power approach that of a continuous sound. If the duration of the single pulse is shortened, and the interval consequently becomes longer, the traumatizing effect also increases in proportion to the overall-intensity. The greatest difference between the traumatizing power of the continuous and of the intermittent sound of the same overall-intensity exists if the pulse-interval ratio is 1 : 1. Here the difference is, for slow-rate pulses, 12 dB, and for fast-rate, 10 dB.

§ 2. Experiments on the influence of the rate of repetition of the tone-pulses

With the same set-up we determined the traumatizing power of intermittent tones with different pulse-rates, that is with different numbers of single pulses per sec. The duration of the single pulse was in one series 1/16 sec. (table IX A), and in another series 1/32 sec. (table IX B). Thus, the greater the number of pulses per second, the smaller the interval. The exposure-time was 5 minutes.

As might be expected in these experiments too, the increase in pulse-rate resulted in an increase in traumatizing power, the intervals becoming smaller.

A similar comparison as shown in fig. 15 was made between these trains of sounds and the corresponding continuous sounds. Fig. 16 shows the results only for series IX A.

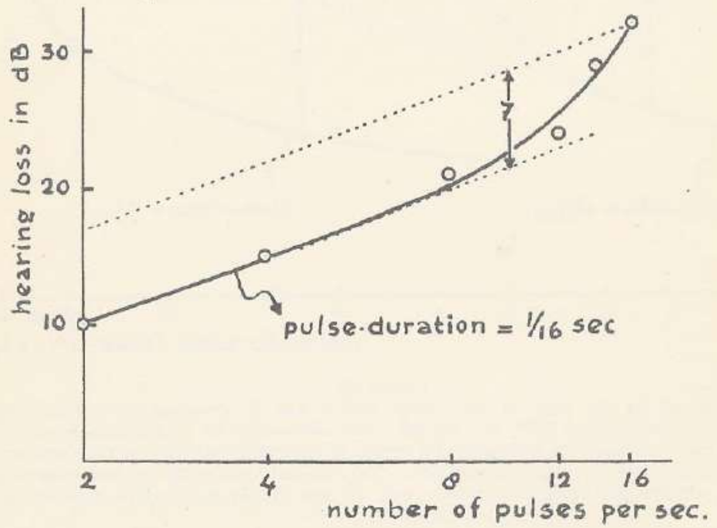

Figure 16
Curve based on the data of table IX A, showing the hearing losses caused by intermittent 2000 cps stimuli with a pulse-duration of 1/16 sec. The dotted line indicates the calculated hearing losses corresponding to the continuous stimuli of the same overall-intensities. Here too, the intermittent tones are less traumatizing, the difference being maximally 7 dB.

Table IX
Relation of the pulse-rate of intermittent 2000 cps stimuli and hearing loss, the pulse-duration being constant

A. Pulse-duration: 1/16 second. Stimulation time: 5 min.

pulse-rate	v L	dB	GM	CR	Po	average	overall-intensity
2x/sec.	10	10	10	7½	12½	10	- 9
4x/sec.	12½	15	12½	10	25	15	- 6
8x/sec.	20	22½	15	20	25	21	- 3
12x/sec.	22½	25	20	25	27½	24	- 1,2
14x/sec.	22½	30	25	30	35	29	- 0,5
cont.	22½	35	30	30	42½	32	0

B. Pulse-duration: 1/32 second. Stimulation time: 5 min.

pulse-rate	GM	v R	He	average	overall-intensity
2x/sec.	10	12½	22½	15	- 12
4x/sec.	15	17½	22½	18	- 9
8x/sec.	15	17½	27½	20	- 6
12x/sec.	20	22½	32½	25	- 4,2
16x/sec.	25	22½	40	29	- 3
cont.	30	27½	52½	37	0

Each table represents the hearing losses for a series of intermittent stimuli with different pulse-rates and a continuous stimulus of the same intensity.
By increasing the pulse-rate both the dip and the calculated overall-intensity increase, but in a different manner (see fig.16).
In test-person He, table B, the critical dip-size of 35 dB was surpassed (see chapter VI, § 3).

This curve shows that, here too, the intermittent sounds are less traumatizing than the continuous sounds. The greatest difference, viz. 7 dB, exists for intermittent sounds with a pulse-interval ratio of 1 : 1 or less.

The remarkable fact, therefore, is that the same optimal ratio, namely 1 : 1, of pulse duration and interval is found, whether the pulse duration is changed or the rate of repetition of the pulses is changed. Possibly the pulse-interval ratio is of great importance.

3. Experiments with constant pulse-interval ratio

In order to verify this assumption, 3 series of experiments were made, in which the pulse-rate was varied, but the pulse-interval ratio remained constant. The number of pulses per sec. was varied from 1 in 4 sec. to 16 per sec., while the duration of the single pulse and duration of the interval were the same in one series, in another series 1 : 3 and in the third series 3 : 1 (table X). All these experiments were done in 3 test persons.

Table X

Relation of the pulse-rate of an intermittent 2000 cps tone and hearing loss, the pulse-interval ratio being constant

	pulse-interval ratio											
	1 : 3			mean	1 : 1			mean	3 : 1			mean
pulse-rate	GM	CR	Po		GM	CR	Po		GM	CR	Po	
1x/4 sec.	15	10	12½	13	17½	20	22½	20	25	25	30	27
1x/2 sec.	10	12½	12½	12	10	10	17½	13	25	22½	32½	27
1x/sec.	10	15	17½	14	15	17½	20	18	20	17½	20	19
2x/sec.	10	10	17½	13	15	15	20	17	20	20	20	20
4x/sec.	12½	10	25	16	12½	20	27½	20	20	20	27½	23
8x/sec.	15	12½	25	18	15	20	25	20	20	25	27½	24
12x/sec.	10	10	25	15	15	15	30	20	20	25	27½	24
16x/sec.	10	12½	22½	15	12½	20	25	19	15	25	25	22

Table representing the hearing losses for intermittent 2000 cps stimuli with different pulse-rates. The average values found, are plotted together in fig.17.

The results of these experiments may be studied from fig. 17, where the average maximal hearing loss is plotted against the number of pulses per sec.

In this figure there is a fair accordance between the curves for pulse-rates between 2 and 16 per sec. They show a maximum for a rate of approximately 8 per sec., which is about 4 dB above the values for 2 pulses per sec. and about 2 dB above the values for 16 pulses per sec. For slower pulse-rates there appears to be a sec. rise when the pulse-duration gets longer than 1 sec. As this study does not deal with such slow rhythms, this side of the curves will receive no further consideration.

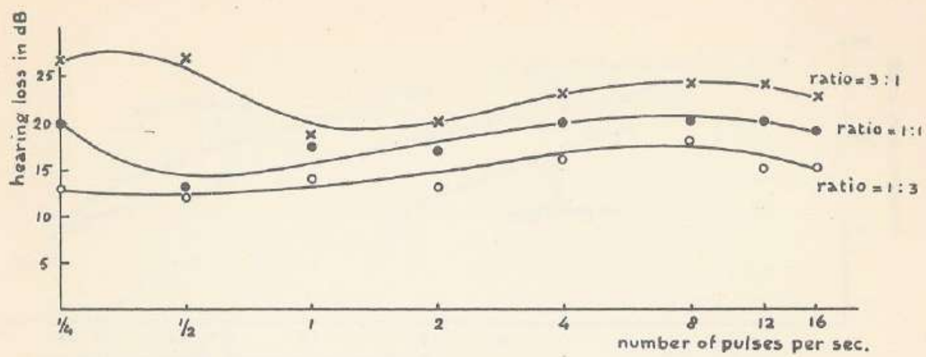

Figure 17

Curves based on the data of table X, showing the hearing losses caused by intermittent 2000 cps stimuli with a pulse-interval ratio of 3 : 1, 1 : 1 and 1 : 3. For pulse-rates exceeding 1 per sec. there is a maximum of approximately 8 per second. For smaller pulse-rates the traumatizing power seems to increase, if the duration of the single pulse exceeds 1 second.

On considering the data given in fig. 15 it will be seen that, in comparison to the overall-intensity, the damaging effect of stimuli with a pulse-interval ratio of 1/3, 1 and 3 is less when given 2 x per sec. than when given 12 x per sec. In fig. 16 the difference between the hearing loss caused by the stimulus 8 x 1/16" and the calculated hearing loss of the corresponding continuous tone is remarkable small, viz. 7 dB. This curve has no distinct minimum, presumably because the less traumatizing pulse-interval ratio coincides with the most traumatizing pulse-rate.

§ 4. Some considerations on the results obtained with 2000 cps stimuli

The experiments with intermittent stimuli mentioned above reveal the great importance of even very small intervals in diminishing the traumatizing power, though they scarcely affect the calculated or measured overall-intensity level. An interval of 9 m.sec. between pulses of 1/16" lessens the effect of a 2000 cps tone by 3 dB relatively to a continuous tone. In fig. 18 this beneficial effect, as shown already in fig. 15 and 16, is drawn in another way.

The relation between the logarithm of the interval duration and the hearing loss seems to be linear for the tone-stimuli used.

To summarize the results described we may conclude as follows:

a. intermittent stimuli with a pulse-interval ratio of less

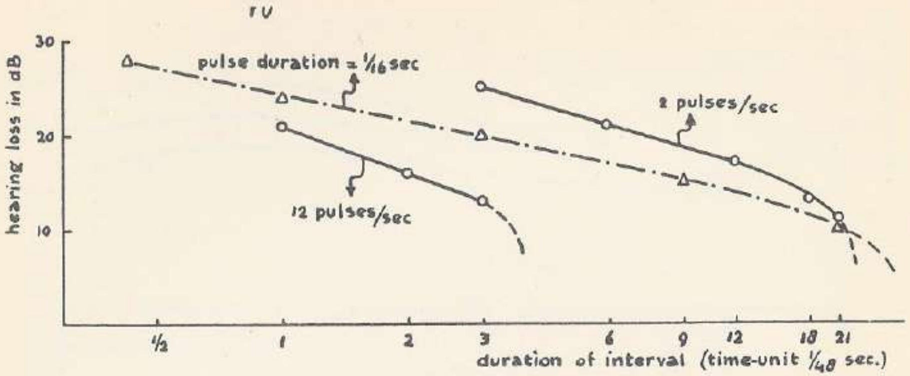

Figure 18
Curves, showing the hearing losses reported in fig. 15 and 16 as a function of the interval-duration. For the intermittent stimuli used, the relation between hearing loss and interval appears to be a nearly linear one, provided the interval is plotted on a logarithmic scale.

than 3 have a traumatizing power that corresponds to that of a continuous tone with an intensity that amounts to ca. 5 dB less than the calculated overall-intensity; for the mean dip-size of these intermittent stimuli is 8 dB less than would have been produced by the continuous stimuli of the same overall-intensity. To get an equal dip-size the intensity of the continuous stimuli must be 3/5 x 8 dB = 5 dB less.

b. intermittent stimuli of the same pulse-interval ratio are about 3 dB more traumatizing when given with a pulse-rate of 8 per sec. than with a pulse-rate of 2 per sec.

c. the most favourable pulse-interval ratio seems to be the ratio 1 : 1.

d. if the pulse-interval ratio becomes greater than 3, the traumatizing power increases rapidly to that of the continuous tone.

§ 5. Isotraumatic intermittent thermal noise-stimuli

It must be proved that the abovementioned results, obtained with 2000 cps stimuli of 5 minutes duration, are of general validity. For this purpose 4 test persons were exposed to a pulsating thermal noise, and, in order to make a comparison, also to a continuous thermal noise. The exposure-time was 15 minutes, and the pulse-interval ratio 1 or less. The intensities were chosen so that the expected values of the dip did not exceed 35 dB (table XI).

The effect of all intermittent white noise-stimuli was compared with the effect of the steady white noise of 107 dB. This comparison consisted in the calculation of isotraumatic

Table XI
Traumatizing power of intermittent white noise stimuli.
Stimulation-time: 15 min.

stimulus	GM	Vr	Ko	CR	average	overall-intensity (calculated)
2x 1/32" 122 dB	7½	20	20	25	18	
8x 1/32" 116 dB	12½	25	20	17½	19	110 dB
16x 1/32" 113 dB	15	25	17½	22½	20	
2x 1/16" 116 dB	7½	17½	15	20	15	107 dB
8x 1/16" 110 dB	12½	22½	15	20	18	
2x 1/8" 110 dB	7½	15	10	10	11	104 dB
2x 1/4" 104 dB	7½	10	7½	15	10	101 dB
cont. 107 dB	17½	30	22½	22½	23	107 dB
cont. 104 dB	12½	17½	22½	22½	19	104 dB

Table representing the hearing losses produced by different white-noise stimuli of different pulse-intensities. The isotraumatic intensities, given in table XII, were calculated by comparing the mean values for the intermittent stimuli with the value found for the continuous stimulus of 107 dB.

Table XII
Isotraumatic white-noise stimuli

2 x 1/32" 127 dB (115)	8 x 1/32" 120 dB (114) (109)	16 x 1/32" 116 dB (113) (110)
2 x 1/16" 124 dB (115)	8 x 1/16" 115 dB (112) (110)	
2 x 1/8 " 122 dB (116)	Continuous 107 dB	
2 x 1/4 " 117 dB (114)		

Table representing the calculated intensities of the intermittent stimuli of table XI, that will be needed for giving the same hearing loss as the continuous stimulus of 107 dB. The first number in parentheses indicates the calculated overall-intensity, the second the measured overall-intensity.
From this table it appears that on the average the intermittent stimuli are 7 dB less traumatizing than the continuous stimulus and that stimuli with a pulse-rate of 8 per sec. are somewhat more traumatizing than stimuli with a pulse-rate of 2 per second.

stimuli by using the procedure mentioned in chapter VI, § 3. For instance, if an intermittent stimulus causes a hearing loss of 18 dB, and the effect of the steady noise amounts to 23 dB, the maximum pulse level of the intermittent noise must be increased by about 5 dB to equalize the traumatizing powers. The exactness of the value for the continuous stimulus was augmented by adding a continuous stimulus of 104 dB to the series. In table XII the result of this calculation is given.

From this table it appears that the traumatizing power of the intermittent noise-stimuli is on the average 7 dB less than that of the continuous noise. This value is in the same order of magnitude as that found in the experiments with 2000 cps stimuli. Moreover, in considering the influence of the pulse-rate, the same order of harmfulness is found as for 2000 cps stimuli, being 8 per sec. more traumatizing than 16 per sec., and the latter more than 2 per sec. Only the differences are smaller. In considering the influence of the pulse-duration, there is no accordance with the 2000 cps stimuli. The isotraumatic overall-intensity of the noise-stimulus 2 x $\frac{1}{4}$" should be greater than the value found. A plausible explanation for this discrepancy is the extraordinary small dip caused by the intensity used.

Chapter VIII

THE TRAUMATIZING POWER OF COMPLEX SOUNDS

The previous chapters dealt with the traumatizing power of intermittent stimuli of a 2000 cps tone and of a white noise, characterized by intervals of non-traumatizing intensity. In most factory noises, however, not only the peaks but also the basic noise intensity may be above the traumatizing threshold, so that both components contribute to the traumatizing power of the total noise. In the peaks high frequencies are preponderant, whereas the basic noise for the greater part may consist of lower frequencies. For instance, the peaks of the pneumatic drill noise, represented in fig. 8 and 9, proved to consist to a high degree of frequencies in the range of 2230-3570 cps. Thus the intensity changes not only with time, but also with frequency. The question is now, what kind of dip occurs, when two sounds of different frequency are acting simultaneously.

We could not find any previous experiments on this subject in the literature.

§ 1. Dips obtained with two pure tones acting simultaneously

Together with van der Waal we made experiments with a tone of 1000 cps and a tone somewhat higher than 2000 cps, in order to avoid beats with the first overtone of the 1000 cps tone. The problem we wished to study was whether a difference exists between the effect of the tones acting independently and those acting simultaneously. In 12 test persons we compared the values found for the maximum of the dip, using the continuous audiometry technique. The intensity of the 1000 cps tone was 100 dB, and that of the 2050 cps tone 5 dB less in order to avoid too great traumata. The stimulus-duration was always 5 min. The averaged results are given in table XIII, representing the maximum hearing loss in the first octaves above the two stimulus-frequencies.

From this table it appears that the effect of the two tones acting simultaneously, consists of the combination of the two single dips. The size of the two maxima is, in general, not greater for the combination than for the single tones. The hearing loss between 1200 and 1800 cps seems to be $2\frac{1}{2}$ dB less when stimulating with the two tones. However this slight difference might be explained by a difference in determination-time.

Table XIII

Traumatizing power of two pure tones, acting simultaneously. Stimulation-time: 5 min.

stimulus		hearing loss in dB	
		1200 - 1800 cps	2400 - 3600 cps
a. 1000 cps	100 dB	12	$5\frac{1}{2}$
b. 2050 cps	95 dB	0	$15\frac{1}{2}$
a + b		$9\frac{1}{2}$	$15\frac{1}{2}$

This table represents the mean values for 12 test persons. The effect of the combined tones for the frequency-range of 2400 - 3600 cps is the same as that of the single 2050 cps tone.
For the frequency-range of 1200 - 1800 cps the effect of the combined tones is somewhat less than for the single 1000 cps tone. However, the latter effect was determined half a minute after the stimulation, whereas the effect of the combined tones was measured about 3 minutes later.

§ 2. Dips obtained with an intermittent pure tone and a white noise, acting simultaneously

Now in order to realize the possibilities which may be encountered in factory noises, a basic white noise was combined with intermittent tone-pulses of different frequencies. As in the former experiments, not only the combination was studied, but also the effect of the single components. In this way we could distinguish the attribution of the components in the dip caused by the combined sound. In these experiments the threshold shift had to be measured in more than one frequency-area. We took care that the threshold for a certain frequency was determined after equal intervals following stimulation with the single component and with the combined sound. The values given in table XIV are the hearing losses obtained in different frequency-ranges chosen in such a way, that the dip-maxima were situated in these ranges.

Generally no influence of the two components exists if the resulting dips occur in different parts of the tonal range. If they act together on the same part of the basilar membrane, the effect will of course not be the sum of the numbers dB of hearing loss, but a hearing loss resulting from the summation of the two traumatizing powers.

Table XIV

Traumatizing power of a white noise and intermittent pure tones, acting simultaneously. Stimulation-time: 5 min.

ubj.	stimulus		hearing loss in dB				
			500 - 800 cps	1200 - 1800 cps	2700 - 3200 cps	3500 - 4000 cps	4200 - 5000 cps
R1	a. 500 cps $2 \times \frac{1}{4}$"	125 dB	10		5	$7\frac{1}{2}$	
	b. white noise	90 dB			$7\frac{1}{2}$	$7\frac{1}{2}$	5
	a + b		10		15(10)	$7\frac{1}{2}(11\frac{1}{2})$	0
R1	a. 500 cps $2 \times \frac{7}{16}$"	125 dB	10		$7\frac{1}{2}$	$7\frac{1}{2}$	
	b. white noise	90 dB			$7\frac{1}{2}$	$7\frac{1}{2}$	5
	a + b		10		$15(11\frac{1}{2})$	$7\frac{1}{2}(11\frac{1}{2})$	5
THD	a. 500 cps $2 \times \frac{1}{4}$"	125 dB	10	5			
	b. white noise	90 dB		5	$7\frac{1}{2}$	5	
	a + b		10	10 (9)	$7\frac{1}{2}$	5	
THD	a. 500 cps $2 \times \frac{7}{16}$"	125 dB	10	10	10	5	
	b. white noise	90 dB		5	$7\frac{1}{2}$	5	
	a + b		15	15(12)	$15(12\frac{1}{2})$	$12\frac{1}{2}$ (9)	10
GM	a. 1000 cps $3 \times \frac{1}{6}$"	117 dB		15			
	b. white noise	97 dB				10	
	a + b			15		5	
vH	a. 1000 cps $3 \times \frac{1}{6}$"	107 dB		5	15		
	b. white noise	87 dB					
	a + b			5	$12\frac{1}{2}$	5	
dB	a. 1000 cps $3 \times \frac{1}{6}$"	107 dB			5		
	b. white noise	92 dB			5		
	a + b				10 (9)		
Ho	a. 2000 cps $3 \times \frac{1}{6}$"	102 dB			10		
	b. white noise	87 dB					15
	a + b				10		$17\frac{1}{2}$
Kn	a. 2000 cps $3 \times \frac{1}{6}$"	107 dB			5		
	b. white noise	87 dB					5
	a + b				5		0
F	a. 3000 cps $3 \times \frac{1}{6}$"	107 dB					15
	b. white noise	102 dB			5	15	20
	a + b				5	$17\frac{1}{2}$	$17\frac{1}{2}(22)$
G	a. 3000 cps $3 \times \frac{1}{6}$"	107 dB				5	10
	b. white noise	87 dB					
	a + b					5	10
Sm	a. 3000 cps $3 \times \frac{1}{6}$"	112 dB				20	25
	b. white noise	97 dB				10	20
	a + b					20 (21)	25 (27)

Table representing the hearing losses in different frequency-areas containing the dip-maxima. The threshold of each area was determined after a constant interval following the stimulation.
In general, the areas, which are damaged by only one of the components, show the same loss after stimulation with the combined sound as after stimulation with the single component.
In areas, damaged by each of the components, a summation of hearing losses will occur. The values calculated by the method discussed in this §, are given in parantheses. As the sum of the calculated values is 166, and that of the values empirically found is 170, this method of summation appears to be in agreement with our findings.

For example, if each of the components causes the same hearing loss, one may imagine that the result of the combination will be equal to that of one of the components acting with a 3 dB greater intensity. As demonstrated in chapter VI for intermittent tone-stimuli and for steady noise stimuli, a 3 dB greater intensity results in a 4 dB greater trauma. So in this example a 4 dB greater dip may be expected for the combination.

However when the difference between the dips caused by the components amounts to 6 dB, one can imagine that the hearing losses are produced by two stimuli with intensities of I_1 and $I_2 = I_1 + 3/4 \times 6$ dB $= I_1 + 4\frac{1}{2}$ dB. Now we can add these two sound-pressures I_1 and I_2 the sum being about I_1 + 6 dB. The hearing loss caused by the same stimulus with an intensity of I_1 + 6 dB will be 8 dB greater than the smaller dip, or 2 dB greater than the greater dip. If the dip-sizes of the single components are D_1 dB and D_2 dB, and the intensity of the first component is I_1, the formula for the calculation of the hearing loss caused by acting of the components simultaneously, $D_{1,2}$, must be:

$$D_{1,2} = D_1 + 4/3 \left[\left\{ I_1 \boxplus \left[3/4\,(D_2 - D_1) \right] \right\} - I_1 \right] \text{ dB.}$$

+ means arythmetical summation.

$\boxplus$ means summation as usual for adding together intensity levels in dB.

The exactness of this calculation can be tested with table XIV. This table contains 12 specimens of summation. So we can compare 12 calculated values with 12 values found experimentally for the combined sounds. As the sum of the latter values is 170 and the sum of the calculated values is 166, we may conclude that this way of adding experimental hearing losses is in agreement with our findings.

§ 3. Dips obtained with the noise of a pneumatic drill

In chapter IV we constructed a synthetic noise similar to that of the noise of a pneumatic drill. The most traumatizing bands are those of 2500 and 3200 cps mean frequency. From the preceding paragraph we know that when giving the unfiltered noise, the frequency-range of 4200 - 5000 cps will be traumatized mainly by the 3200 cps band and in a lesser degree by the 2500 cps band. If this holds true, the effect of this 3200 band, acting with the same intensity as that measured for this band in the total noise, must be only a few dB less than that of the total actual noise. In table XV we see

that in 4 test persons the effect of this band was on an average 16 dB, whereas the effect of the total noise was 18 dB.

Now the effect of stimulating with the 3200 cps band of the actual noise, and the effect of the synthetic sound by which this band was imitated, can be compared. As table XV shows, there is a difference of only 1 dB. Consequently the assumption made in chapter IV, that the traumatizing power of both is equal, is confirmed.

In chapter I we emphasized the importance of knowing to what degree both peaks and basic noise contribute to the traumatizing power. For this reason both components of the synthetic sound, namely the short tone-pulses of 3000 cps and the white-noise band, were given separately. From table XV we see that in causing hearing loss the peaks are of somewhat greater importance than the basic noise. The calculation of the effect of the synthetic sound, as explained in the preceding paragraph, is $15\frac{1}{2}$ dB, that is $1\frac{1}{2}$ dB less than that found experimentally. From these experiments we may conclude that in noises like this expensive measures to lower the basic noise intensity will yield at most a diminution of the traumatizing power by only about 3 dB.

Table XV
Analysis of the traumatizing power of the noise produced by a pneumatic drill.
Stimulation-time: 15 min.

stimulus	Cl	Rl	Li	Bu	average
a. total noise 98 dB	20	$12\frac{1}{2}$	25	15	18
b. 3200 cps band 91 dB	$12\frac{1}{2}$	$12\frac{1}{2}$	25	$12\frac{1}{2}$	16
c. synthetic noise 91 dB	$17\frac{1}{2}$ (15)	10 (9)	30 (25)	10 ($12\frac{1}{2}$)	17 ($15\frac{1}{2}$)
d. "basic noise" 88 dB (1/3 octave of white noise)	10	5	20	$7\frac{1}{2}$	11
e. "peaks" (3000 cps 16 x $\frac{1}{180}$" 108 dB)	$12\frac{1}{2}$	5	$22\frac{1}{2}$	10	13

Table representing the hearing losses at 4500 cps caused by the drill noise and its 3200 cps band, and by the synthetic sound imitating this band, and its components.
The effect of the total noise is only 2 dB greater than the effect of the 1/3 octave band of 3200 cps. The traumatizing power of the synthetic sound has about the same value as this band and as can be calculated by summation of the traumatizing powers of its components.

Chapter IX

CONCLUSIONS

The object of this study was to determine the hitherto unknown traumatizing power of non-steady sounds as compared to the better known traumatizing power of steady sounds. It was considered that e.g., a factory noise of a pulsating character consists of a basic noise and peaks. The traumatizing power might depend either on one of these factors or on both.

The manner in which the traumatizing power is determined in practice consists in measuring the intensity by means of a sound-level meter. In recent years this procedure has been refined by the use of band filters. This became necessary because higher frequencies had proved to produce a hearing loss at a lower intensity than low frequencies. The thresholds of traumatizing intensities were expressed in curves derived from experience and calculation. These curves were called Deafness Risk Criteria. Thus with a sound-level meter and band analyzer, and by consulting these curves, one determines whether a given factory noise is traumatizing or not.

However, no experiments have been made about the possibility to measure exactly a non-steady, e.g. intermittent noise. Especially if the peaks are traumatizing not only the overall-intensity, but also the factors: duration of the single peak in relation to the interval between the peaks, and the rate of repetition of the peaks, may influence the traumatizing power. The same holds true for the possibility that in peaks and basic noise different frequencies are preponderant. In this case the effect of the two components, acting simultaneously, may be different from the effect of a noise in which this difference is not present.

In our opinion it is not correct to base the determination of a traumatizing power chiefly or exclusively on calculation. The only reliable way is to determine the traumatizing power by studying the effect on persons. In order to realize this, one could study the traumata present in persons who work in noise of different character. In fact, this was done by Rosenblith, van Leeuwen, Goldner and others. But it is not possible to study in this way all the different factors mentioned above.

The method of choice must be to study the auditory fatigue caused by experiments with different sounds. The fact that, for a sound of given intensity after sufficient long exposure, e.g. one hour, the dip-size does not increase led to the assumption, that this dip-size will be the resulting permanent hearing loss after prolonged exposure. This assumption was confirmed by van Leeuwen, who found that the temporary hearing loss acquired by young factory workers in one day's exposure, is equal to the permanent hearing loss acquired by the older workers of the same department, the presbyacusia factor being taken into account. In addition we demonstrated by experiments on 3 normal ears, that the relation between the traumatizing powers of very different stimuli was constant for exposure times of 5, 15 and 45 minutes. We may conclude from these considerations that it is correct to use auditory fatigue, following stimulation during some minutes, for the determination of the traumatizing power.

Usually auditory fatigue is determined by means of octave audiometry, some determinations being made in the frequency-range, where the threshold shift is expected. This is a rough method, chiefly for two reasons: (a) the maximum hearing loss will not always be recorded and (b) the method is time-consuming and thus inexact, because the pattern of the dip changes rapidly. Another method is therefore wanted.

By means of continuous, i.e. sweep-frequency audiometry, the exact pattern of dips can be established in a very short time. As a matter of fact by starting the measurement half a minute after the cessation of the stimulus the maximum of a dip can be found and measured in 15 seconds. Moreover, the test person can easily distinguish between the sweep-tone and possible tinnitus!

In order to make comparative studies it is necessary that the effect of a stimulus can be reproduced. By using a headphone with a rubber rim no satisfactory reproduceability could be obtained. But we succeeded in getting satisfactory results by using the headphone without rim in such a way that the sound-leakage is minimal.

The pattern of the dip is usually a typical one, with a steep slope to the lower frequencies and a gradual slope to the higher frequencies. Occasionally, without any known reason, abnormal dips occur, showing an abnormal size and pattern. These dips cannot be reproduced. In our comparative studies they were neglected.

When using the same stimulus frequency in the same test person, the size of the maximum of the dip measured half a minute after the stimulation, proved to characterize not only the pattern of the dip, but also its recovery-time. Thus we are justified in using the size of the maximum as a measure of the degree of auditory fatigue.

When stimulating with pure tones of 1000 and 2000 cps it was established that the greater the dip the nearer the maximum is localized to the stimulus frequency.

In using 500 cps stimuli several accessory dips were found as a rule, probably caused by subjective overtones. In stimuli of higher frequency they are not met with so often. By times these dips are as great or even greater than the typical dip. This finding might explain, why in animal experiments the lesion, caused by low tone stimulation, extends over a large area of the basilar membrane.

We mentioned the possibility that the intensity measuring of non-steady noise might be unreliable. In order to prove this assumption we studied a synthetic intermittent noise of which the intensity of the components could be measured exactly. Thus the overall-intensity could be calculated in the usual way, and this cipher could be compared with the value found with our sound-level meter. It appeared that the calculated value was 0 - 6 dB higher than the measured value, dependent on the pulse-interval ratio and the difference between peak and basic intensity. In factory noises a measuring error of approximately this order can be expected.

To set up a program for our study of the traumatizing factors of non-steady noise we started to study the actual noise of a pneumatic drill recorded on a magnetophone-tape and reproduced in the laboratory. Apart from the method described by Peterson, the best way to study a pulsating sound of some regularity is to use the cathode-ray oscilloscope. It appeared that in this noise peaks occurred having a great energy in the 1/3 octaves of 2500 and 3200 cps mean frequency, whereas in the basic noise all frequencies were present in a more equal intensity.

Now the question arises what the respective shares may be of peaks and basic noise in the traumatizing power. The answer is found by separating them. This was effected by constructing a synthetic noise similar in oscilloscopic picture and in intensity to the noise of the pneumatic drill. In this way it was established that the peak-intensity exceeded the intensity of the basic noise by 20 dB and that the pulse-interval ratio was about 1 : 10.

An illustration of the inexactness of readings by means of a level meter in the case of non-steady sounds, is that the peaks of this synthetic noise cause an increase of 3 dB above the basic noise level, though the calculated overall-intensity amounted to 10 dB more than the basic intensity. These values were needed for our further experiments, and they well characterize the noise in question. The fatiguing effect of these synthetic sounds and this actual noise will be discussed further on.

As we mentioned above, the difference in traumatizing power between low and high tones was the reason that deafness-risk criteria were introduced. With our technique we established an experimental deafness-risk curve by determining on two test persons the traumatizing threshold for 9 frequencies between 500 and 5000 cps. The averaged result was a line somewhat similar to the criterion of Hardy, i. e. the loudness in sones, and different from the deafness-risk criteria of Parrack and McGrath. However, we found that the individual traumatizing threshold does not coincide with an isophon. Consequently the traumatizing power is not a function of the loudness, as Hardy suggested. There is a considerable individual variability and it was experimentally demonstrated that the difference depends, inter alia, on the form of the external meatus. The importance of the resonance characteristics of the external meatus appears also from animal experiments made by Davis et al. (1953). They found that the minimal intensity, needed to produce a pathologic-anatomic lesion of the basilar membrane, was the same for all frequencies, provided the intensity was measured at 1 mm from the ear drum.

On studying 1/3 octave bands of a thermal noise a similar curve was obtained as for pure tones.

The relation was studied of this deafness-risk curve and the curve indicating the thresholds above which the hearing sensation of pure tones gets an impure, sharp character. This so-called "tolerance-curve" also proved to be different from an equal loudness line, being situated for the low tones on the 100 dB-isophon and for the high tones near the 80 dB-isophon. It was investigated if this easy obtainable curve might be used as a substitute for the individual traumatizing threshold. Indeed, below 4000 cps this tolerance curve and our deafness-risk curve run to a high degree parallel, although not on the same level. An explanation of this parallelism might be found in the assumption that the distortion of the basilar membrane between the place of adequate stimulation and the windows causes both the sensation of sharpness and the auditory fatigue. Moreover it was demonstrated that, from the form of the tolerance-curve the localization of the dip caused by a white noise can be predicted. This localization is of great importance in respect to the intelligibility of speech.

In order to investigate the relation between intensity and traumatizing power, several tables were composed each indicating the dip-values caused by one and the same sound of different intensities above the traumatizing threshold. These tables were composed for continuous and intermittent stimuli of a 2000 cps tone and a white noise. It appeared from these experiments that a linear relation exists between intensity and dip-size up to the critical dip-size of about 35 dB. Thus greater dips must be avoided for experimental reasons and because they are dangerous. Moreover, in most test persons dips of this size are not recovered completely within 24 hours. This implies that the young factory workers will soon get a permanent hearing loss, if their temporary hearing loss after one day's exposure is greater than 30 dB!

By means of these tables it was possible to predict the dip-size of a sound of a calculated intensity, when the dip-size corresponding to another intensity of the same sound was known. Furthermore it was possible to calculate the intensity corresponding to a certain dip-size, when the intensity causing another dip-size was known.

The traumatizing power of intermittent 2000 cps tones, characterized by intervals of non-traumatizing intensity, was compared to that of the continuous tone with the same calculated overall-intensity. It appeared from these experiments that intermittent stimuli are less traumatizing than the corresponding continuous tones. Increase of the pulse duration, the pulse-rate being constant, causes a greater increase of trauma than would be expected from the corresponding increase of the overall-intensity. In the same way it was established that increase of the pulse-rate, the pulse-duration being constant, has a greater influence on the traumatizing power than on the calculated overall-intensity of the tone. The difference was maximal, viz. 7-12 dB for a pulse-interval ratio of about 1 : 1. Even an interval of 10 m. sec. diminished the traumatizing power. When keeping the pulse-interval ratio constant, it appeared that a pulse-rate of 8 per sec. is more harmful than one of 2 per sec.

As shown by a series of experiments with white noise stimuli, the same conclusions are applicable for this sound; with the exception of the optimal pulse-interval ratio which could not be determined in this series. On the average the traumatizing power of intermittent noise stimuli is 7 dB less than that of the continuous noise with the same (calculated) overall-intensity.

If a factory noise consists of two traumatizing components of different frequency-ranges, the effect will depend on the part of the basilar membrane involved. By using 2 pure tones and by using a continuous white noise and tone-pulses it was proved that the traumatizing power of one component is not altered by the other. When the difference in frequency is great, two separate dips will appear; but when the difference is small, a hearing loss will occur, caused by the summation of the two traumatizing powers. The mode of summation is explained in chapter VIII, § 2.

As was shown, the noise of the pneumatic drill consisted of two adjacent 1/3 octave bands of traumatizing intensity. In accordance with our experiments with simultaneously acting sounds, the effect of one of these bands was only 2 dB less than that of the total noise. The traumatizing effect of this band is not only caused by the peaks, but also by the basic noise. This was proved by studying them separately. The peaks proved to be somewhat more traumatizing than the basic noise, notwithstanding their interrupted character. This is due to the relatively high intensity of the peaks.

From these laboratory experiments we may draw some conclusions that may be of use in an attempt to prevent occupational deafness.

The first conclusion must be that the overall-intensity of non-steady noises cannot be measured by sound-level meters (and the like). The measured intensity is much lower than the peak intensity and also lower than the real overall-intensity.

The traumatizing power of a non-steady noise is also less than indicated by the real overall-intensity. Both discrepancies mainly depend on the pulse-interval ratio and on the difference between peak- and basic intensity, but not in the same way.

If the rate of pulsation in a factory noise is fast, e.g. 8 per sec. this noise will be more traumatizing than if the pulsation-rate is 2 per sec., all other factors, even the overall-intensity, being the same.

If sound-pulses are produced in a workshop it is preferable to synchronize these pulses in such a way that the duration of the pulse and the interval are about equal. In this way the traumatizing power will be less than if by desynchronization the interval disappears. If it is possible to create an interval this must be done.

The last important conclusion is that, if the traumatizing power of the peaks equals or exceeds that of the basic noise, lowering the intensity of the basic noise, e.g. by treating the walls of the workshop, will scarcely alter the traumatizing power of the total noise if the peaks remain about the same.

SUMMARY

Unlike the traumatizing effect of continuous sounds, this effect of non-steady sounds has never been studied. In order to obtain experimental knowledge on this subject, intermittent pure tones, an intermittent white noise, synthetically constructed sounds, imitating factory noises, and a recorded noise of a pneumatic drill, were studied.

On comparing the measured overall-intensity and the calculated intensity of the synthetic sounds, it appeared that the common method of intensity measuring cannot be used. Thus the traumatizing power of non-steady sounds cannot be determined by measuring the intensity of the different frequency ranges and by comparing them with the Deafness Risk Criteria.

This inexactness was our reason for studying the problem in an experimental way, namely by provoking the fatigue effect in test persons. However, this method requires a rapid and accurate determination of the frequency and value of the resulting maximal hearing loss. Continuous audiometry, by means of which the hearing span is determined on different intensity levels, enables us to achieve this aim in $\frac{1}{4}$ minute. It was established that the values obtained were reproduceable and gave a good measure for the degree of fatigue. It was proved that from these experiments of short duration conclusions may be derived with respect to the genesis of occupational deafness.

By this method it was established that even for continuous pure tones and for 1/3 octave bands the empirically obtained traumatizing threshold deviates from the calculated Deafness Risk Criteria. Moreover, important individual differences in susceptibility for the different frequencies were found. It was proved that these differences depend on the resonance characteristics of the external auditory canal.

The empirical traumatizing thresholds do not run parallel with the lines of equal loudness, but they follow the curve connecting the intensities at which a pure tone acquires for a test person an impure and sharp character. The determination of this curve, the so-called tolerance-curve, can be easily and quickly made. The maximum of this curve indicates the frequency-span of the basilar membrane, that will be especially injured by a factory noise.

The traumatizing power of a pulsating noise may be determined by the intensity of a continuous basic noise, and also by the peaks superimposed on it. As our problem mainly consisted of the effect of these peaks, the traumatizing powers

of 2000 cps stimuli with an intermittent character, which was systematically varied, were studied. The results were compared with those of an intermittent white noise.

From these experiments it appeared that intermittent stimuli are less traumatizing than continuous ones of the same calculated overall-intensity. Provided the overall-intensity is the same, a fast pulse-rate of 8 per sec. is more damaging than a pulse-rate of 2 per sec.; and if the durations of the pulse and of the interval are about equal, the traumatizing power will be minimal.

If both noise and peaks are traumatizing, it appears that the traumatizing effect of the total noise is equal to the sum of the traumatizing powers of the components. For instance, if in a certain frequency-range two components of a noise have the same traumatizing power, the effect of the total noise will be equal to that of one of the components with a 3 dB greater intensity.

From these results the following conclusions may be drawn:

1. a sound-level meter whether or not combined with band filters, does not give exact values for the traumatizing power of pulsating sounds;
2. the "Deafness Risk Criteria" need correction based on experimental investigation;
3. if in a noise peaks and basic noise are about equally traumatizing, diminishing the intensity of the basic noise, e.g. by sound-treating the walls, will have a merely restricted effect, because the traumatizing power of the peaks acting directly on the workers is only very slightly lessened;
4. the traumatizing power of non-steady noise can be reduced by synchronization. In the case of a nearly continuous noise this may acquire a pulsating character. In the case of a pulsating noise the pulse-rate will diminish. The best results will be obtained if, in addition to a slow pulse-rate, the duration of peak and interval are made nearly the same.

RESUME

L'effet traumatisant des bruits à intensité variable fut étudié au moyen du phénomène de fatigue auditive, mesuré par la technique de l'audiometrie continue. Des tons purs et un "bruit blanc", interrompus périodiquement, et un bruit produit par un foret pneumatique ont été étudiés.

Il est permis de conclure:

1. qu'un appareil mesurant la pression sonore, éventuellement avec des filtres de bandes, n'indique pas la valeur exacte de l'effet traumatisant provoqué par les bruits pulsatifs;
2. que les "Deafness Risk Criteria" exigent une revision basée sur l'expérimentation;
3. que la diminution de l'intensité dans les intervalles entre les pics par exemple par l'atténuation de la réverbération n'aura qu'un effet restreint parce que le pouvoir traumatisant des pics reste important;
4. que l'effet traumatisant d'un bruit peut être diminué par synchronisation. Ce moyen fait acquérir à un bruit quasi continu un caractère pulsatif. Dans le cas d'un bruit pulsatif le rythme peut être ralenti. Un résultat optimum sera acquis si l'on obtient un rythme lent et pulsatif à des intervalles ayant une durée égalant celle du pic.

ZUSAMMENFASSUNG

Die gehörschädigende Wirkung eines Schalles mit Fluktuierender Intensität wurde mittels experimenteller Gehörermüdung untersucht. Zur Bestimmung dieses Phänomenes wurde die Methode der kontinuierlichen Audiometrie benutzt. Auf diese Weise wurde der Effekt intermittierender Reintöne, eines intermittierenden thermischen Geräusches und eines durch den pneumatischen Borer erzeugten Lärmes geprüft.

Die Schlussfolgerungen lauten zusammengefasst:

1. Der Schalldruckmesser ergibt keine exakte Werte für die Schädlichkeit pulsierender Lärme, auch wenn er mit einem Oktavsiebe versehen ist.
2. Die sogenannten "Deafness Risk Criteria" bedürfen einer experimentell gestützten Revision.
3. Massnahmen, die eine Abschwächung des Schalldruckes allein in den Perioden zwischen den Intensitätsspitzen bewirken – zum Beispiel Verminderung der Wandreflexion –, werden oft nur einen beschränkten Erfolg haben, weil die erheblich schädigende Wirkung der Intensitätsspitzen grösstenteils übrigbleibt.
4. In manchen Fällen wird es möglich sein, durch Synchronisierung eine Herabsetzung der gehörschädigende Wirkung zu erlangen. Durch eine derartige Massnahme dürfte ein beinahe kontinuierlicher Lärm einen mehr pulsierenden Charakter, und ein pulsierender Lärm eine Rhythmusverzögerung erhalten.
   Der grösste Erfolg wird dann erzielt, wenn ausser einem langsamen Rhythmus auch noch ein Ausgleich der Puls- und Intervalldauer zustande gebracht werden kann.

RESUMEN

Se ha hecho un estudio sobre la nocividad de sonidos de intensidad variable, midiendo el fenómeno de cansancio auditivo con ayuda de la audiometría continua.

Han sido examinados los sonidos puros, latientes, un ruido llamado "white noise" y el ruido producido pur una taladradora neumática.

Las conclusiones que resultaron fueron las siguientes:

1. que el contador de presión de sonido, combinado o no con analizadores de frecuencias, no indica el valor exacto de la nocividad de sonidos latientes;
2. que es necesario revisar los "Deafness Risk Criteria";
3. que la disminución de intensidad en los periodos entre los "picos", por ejemplo disminuyendo la reflexión, no producirá, a menudo, sino un efecto reducido, por permanecer en su mayor parte la influencia nociva de los picos;
4. que la nocividad del ruido se puede disminuir, en ciertos casos por medio de sincronización. Esto hará, por una parte, que un ruido casi contínuo llegue a tener un caracter latente, y por otra parte, vaya presentando un ritmo más lento. El mejor resultado se obtendrá teniendo cuidado de se produzca un ritmo lento de latido y un reparto uniforme entre latido e intérvalo.

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STELLINGEN

1. Het traumatiserend vermogen van een pulserend fabrieks-lawaai kan niet bepaald worden door meting met geluids-drukmeter en bandfilters.

2. De sterkte van de boventonen, die het binnenoor bereiken, kan bepaald worden door óf de gehoorvermoeidheid óf de adaptatie te meten.

3. Een normaal microphonisch effect kan gevonden worden bij een verminderde functie der haarcellen.

4. De sacculus-otoliet behoort functioneel bij het statische orgaan.

5. Het gebruik van Cortison-oogdruppels vereist specialistische contrôle.

6. β-stralen zijn gevaarlijk voor het oog.

7. Een wettelijke regeling van de revaccinatie tegen pokken is dringend gewenst.

8. Indien behandeling met Cortison binnen twee maanden na het begin van „Bell's Palsy" onvoldoende verbetering heeft gegeven, is decompressie van de nervus facialis aangewezen.

9. De diagnose: tuberculoma is zonder bacteriologisch onderzoek niet zeker.

10. Een zenuwdoofheid wordt gekenmerkt door het ontbreken van regressie bij de balance-test en een matig steil dynamogram.