DASA 1858

EFFECTS OF OVERPRESSURE ON THE EAR – A REVIEW

Frederic G. Hirsch, M. D.

Technical Progress Report
on
Contract No. DA-49-146-XZ-372

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Lovelace Foundation for Medical Education and Research
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FOREWORD

This report, which is primarily a review of published material concerning the effects of blast on the human and the mammalian ear, also incorporates some previously unpublished data concerning the impact of age on the vulnerability of the tympanic membrane to blast overpressures, and some further material on intraspecies scaling.

An attempt has been made to correlate such quantitative data as can be found in the literature, but this has not been found possible of accomplishment in a completely satisfactory way. By rescaling some previously published material in view of available data, and incorporating some unpublished material a value for the threshold of eardrum rupture in man is estimated to be 5 psi, and the "short"-rising overpressure required for rupture of human eardrums is 15 psi.

This information will be of use to those whose task it is to assess hazards and identify populations at risk, as well as those responsible for providing safe working environments and similar problems in the field of environmental health.

ABSTRACT

Information regarding blast effects on the ear has been reviewed in an attempt to gather quantitative information available for animals and man for help in the establishment of relationships between various levels of overpressure and the incidence of eardrum failure, the degree of damage to the middle and inner ear and other identifiable sequelae referable to cochlear or vestibular functions.

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EFFECTS OF OVERPRESSURE ON THE EAR - A REVIEW

1. INTRODUCTION

For many years physicians have been aware that the ears of humans and other mammals have an especial vulnerability to injury when exposed to overpressures generated by explosions and the muzzle blast of guns. By the year 1900 there appeared in the medical literature thirteen articles on the subject, beginning with the report of Greene in 1872.[1] The most comprehensive treatment was that of Castex in 1893.[2] Since that time, well over one hundred papers have been published on blast injury of the ear, their number increasing during periods when a major armed conflict was being waged and diminishing during peaceful times; although, whenever major explosions have occurred, renewed interest has followed.[3,4,5]

A review of that which has been written concerning blast injury of the ear reveals that, with some important exceptions, the reports deal mostly with clinical considerations, and that quantitative data relating overpressures to incidence or degree of injury are lacking. These exceptions date back quite a few years, however, to the work of Zalewski in 1906.[6] This study, which will be dealt with more fully later on, was for almost forty years the only one of its kind until the work of Zuckerman[7,8] and his colleagues during World War II was done. Also about this time, Perlman[9-11] published his studies which have contributed so much to an understanding of the response of the otic structures to blast waves.

In the recent past, the Comparative Environmental Biology Department of the Lovelace Foundation for Medical Education and Research has had an opportunity to obtain some quantitative data on a number of mammalian species during the full-scale weapons tests, its shock tube studies, and some of its other activities.[12-21] Recently, studies of the vulnerability of the ear to blast injury have been resumed in England by Golden and Clare.[22]

It would appear useful and timely to prepare a review of what is known about otic blast trauma in view of recent advances in explosives technology, the development of new types of ordnance which have higher muzzle velocities and consequently higher muzzle blast overpressures, and for purposes of Civil Defense planning. This communication represents such an undertaking.

2.0 PHYSICAL, ANATOMICAL AND PHYSIOLOGICAL CONSIDERATIONS

The vulnerability of the ear to blast overpressures is readily appreciated when one considers that a blast wave is physically the same phenomenon as a sound wave. It is generated when air molecules are rapidly and violently compressed such as occurs when a solid or liquid substance is suddenly changed into a gas. In an explosion, this change in physical state occurs in times of 1×10^{-5} seconds or less, depending on the chemical nature of the substance. The resultant compression can be of many hundreds or thousands of pounds to the square inch at the source. Near the source, the molecules are forced outward for some distance before commencing to oscillate. Once oscillation has occurred, a wave is propagated radially. As it is propagated through the air, the peak overpressure and its velocity fall off at a rate which is faster than an inverse square of the distance relationship, so that at distances of several hundreds of feet the overpressure will have diminished to a magnitude of several atmospheres. One definition of a shock pulse can be given as a sound wave of great initial condensation and great initial velocity.[11] It follows, therefore, that an organ system which is built especially for the reception of sound will receive blast overpressures equally well.

The ear has evolved as an organ system for the transduction of sound waves into nerve impulses which are electrical in nature. It has developed an ability to respond to a limited band of frequencies which for the human may be regarded as lying between 20 Hz and 20,000 Hz. It has developed a high order of sensitivity. It responds to signals which have an energy level as low as 10^{-16} Watts/cm^2, or whose pressure is about one five billionths of an atmosphere, or whose force causes an excursion of the eardrum - a distance which is less than the diameter of a single hydrogen molecule.[9-11, 23] The drumhead cannot respond faithfully to pulses which have periods of less than 0.3 milliseconds, but it attempts to do so by making a single large excursion which corresponds to that occasioned by a sound wave of high audible frequency.[9-11] It is this excursion which mediates the trauma to the ear.

The mammalian ear is divided anatomically and physiologically into the external, middle, and inner ears. Each of these plays a different role in the overall function of the auditory apparatus.

The external ear is a sound-gathering device which has two main functions: the first is that of amplification; and the second is as a direction-sensing device. From the standpoint of blast trauma, both functions are affected albeit in different ways.

Golden and Clare[22] have found in their studies that, when a shock pulse is generated in the air at a distance from an ear, there is an increase of about 0.2 percent in the overpressure at the site of the tympanic membrane over that which is measured in the air at the same distance from the source of the pulse. FIGURE 1 shows their experimental arrangement and a typical

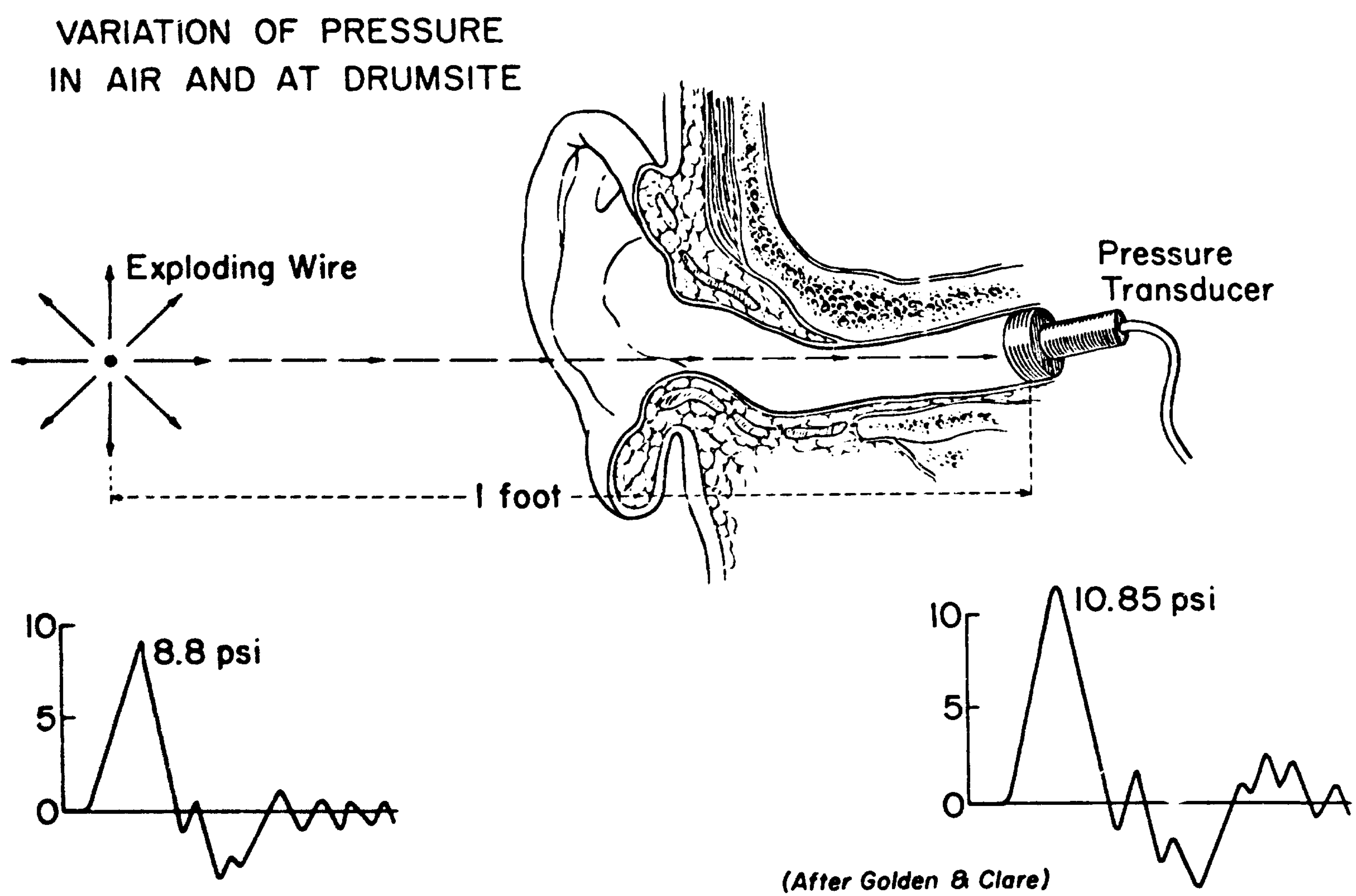

FIGURE 1.
A diagram of the experimental arrangement of Golden and Clare [22] showing the measured pressures in air and at the site of the tympanic membrane.

set of values for the respective overpressures.

When an ear has been significantly injured in such a way that a hearing loss results, there also occurs an interference with stereognosis, which is the ability of an animal to locate the origin of sounds in its environment.[11] Part of this ability depends on differential loudness in one ear as opposed to the other, and the rest depends on the reception of sounds at slightly different times in each ear, so that a phase difference between the two ears is occasioned. This phase difference is mediated and interpreted by the nervous system in a complex way, the details of which are not germane to the present consideration. Suffice it to say that when there is injury to an ear, both loudness and phase are affected, since an altered impedance has been introduced into one side of the system.

Before leaving the consideration of the external ear, something should be said about the influence of ceruminous, or wax, plugs on the response of an ear to blast waves. These are not always present in the external auditory canal, but their incidence is quite high. Most often a plug which has a diameter sufficient to occlude the cross section of the canal will not be sufficiently long to fill the length of it, so that an air space exists between it and the eardrum. Less frequently, one end of a plug will be impacted against the drum.

When a ceruminous plug of the first sort is present, it will diminish the gain function of the canal and will act as an attenuator of a blast wave because, being both compressible and displaceable, it absorbs some of the energy of the shock pulse. That plugs of this sort are effective in reducing trauma to the ear by blast has been remarked by several of the authors who have written on the subject.[9,24-26]

Sometimes, however, the presence of a ceruminous plug will behave in a manner which makes an ear injury worse. If the deep end of the plug is very close to the eardrum, or actually is in contact with it, and if the displacement of it by the shock pulse is sufficient, then the plug behaves as a ramrod causing not only an extensive rupture of the drum but also a displacement of the ear ossicles. Colledge[24] has remarked about this, and experience with dogs at the Nevada Test Site was confirmatory.[12]

In the latter case, a plug was placed in one ear of each experimental animal. It was made of cotton and liquid rubber which solidified after exposure to the air. These plugs completely filled the external auditory canals. The relatively "slow"-rising, but very "long"-duration overpressure, measured near the exposure locations inside underground shelters, apparently acted for sufficient time to push the plugs into the middle ear causing obliteration of the eardrums and dislocation of the ossicles.

Experience with exposure of animals to high-explosive detonations on the one hand, and overpressures generated in shock tubes on the other, has shown that for relatively "low" overpressures there is little displacement of a ceruminous plug when the duration of the overpressure is "short" as in the case of some high-explosive detonations. When the duration of an overpressure of similar magnitude is relatively "long," as in the case of some of the shock tube-generated pulses, the plugs are frequently displaced more deeply into the canal. So whether or not a ceruminous plug in the external auditory canal protects the drum or makes matters worse depends on a variety of things: the duration of the overpressure, whether there is a space between the plug and the eardrum, and the character of the plug; i.e., its density, mass, and composition.

The eardrum, or tympanic membrane, separates the external ear from the middle ear. It is this structure which has engaged most of the attention of the clinicians who have concerned themselves with blast injuries of the ear. This is due to the fact that it is frequently ruptured. It is not, however, the most important lesion associated with blast trauma. Indeed, as will be subsequently developed, it is probably better for the drum to give way to the overpressure than for it to remain intact.

The drum and its associated ossicles act in concert to transfer acoustical energy from the external ear to the inner ear, which is the site of the actual transduction of the mechanical energy to the electrical energy that constitutes a nerve impulse. This system functions as an impedance matching device, and as such contributes an amount of gain to the signals received at the tympanic membrane. It should be emphasized that frequency, wave form, and relative amplitude are not altered by middle ear structures; but that there is a concentration of sound pressure on the oval window.[23,27,28,29]

The adult human tympanic membrane has an area of about 70 sq. mm., which is some 22 times greater than the area of the oval window. This difference in area causes an increase in sound pressure at the oval window and serves to make up for the relative difference between the inertia of the air and that of a fluid - in this case, the endolymph of the inner ear. It is the motion of the endolymph which actually stimulates the sensing organ in the inner ear.

The natural resonant frequency of the middle ear structures is between 1200 and 1700 Hz; however, the ligaments and muscles attached to the ossicular chain serve to highly dampen the system.

There are two dampers in the middle ear, the most important of which is composed of the stapedius muscle and its ligaments. It is this one which acts to limit the vibration of the stapes when intense signals are being received. The other is the tensor tympani muscle and its ligaments, which serve to limit the vibration of the eardrum. It is of interest to note that, due to the manner of construction of the ligaments, the limitation of amplitude excursion is largely effective when positive pulses are placed on the eardrum and less on the negative excursions.

These musculo-tendinous dampers are controlled by an involuntary reflex arc. Its stimulus is an excessive amplitude of vibration striking the otic structures which generates feedback. The feedback, in turn, activates the reflex arc in an analgous manner to an electronic automatic volume control circuit. It requires about 5-10 milliseconds for the reflex to become operative and effectual. This is, of course, too long a time for the bracing action of the stapedius and tensor tympani muscles to provide any protection against any but a "slow"-rising, relatively weak blast wave. It does provide some help, however, when a "low"-intensity blast wave assaults the ear under conditions where high ambient noise levels have existed prior to its arrival. Perlman,[11] Ireland,[30] and other authors have noticed that rupture of the drum is more common when an explosion occurs in a quiet environment than it is in a noisy one. It seems that the middle ear is quite a different target under these two circumstances.

Because of the manner in which the malleus is linked to the incus, inward displacement is greater than outward displacement. The incudo-malleolar joint is so constructed that when the malleus is subjected to an inward force the two bones move forward as one. However, when the excursion of the bones is outward, a separation of the malleus from the incus occurs, thus allowing a greater movement of the malleus vis-a-vis the incus.[11]

This feature of the incudo-malleolar joint serves as a protective device to the inner ear. When one recalls that a blast wave is characterized by a "sharp"-rising, positive pressure peak of "short" duration which is followed by a "longer," negative phase, it becomes apparent that a longer excursion of the ossicular chain can result from the negative phase of the blast wave than from the positive one, depending on how "fast" an equalizing pressure can enter the middle ear via the eustachian tube. It also follows that the displacement of the endolymph can be of a "longer" duration during the negative phase, thus prolonging the stimulation of the hearing organ. Perlman[11] feels that in all probability the length of time that an overload is applied to this organ, the Organ of Corti, is of importance in the degree of damage that ensues. By permitting a longer excursion of the malleus, which is attached to the drum, without requiring the same excursion of the intermediate bone (the incus) the movement of the stapes, which transmits the motion of the endolymph, is diminished, thus affording some degree of protection. He is also of the opinion that if the excursion of the drum and ossicular system to the negative phase could be reduced further or even eliminated, a greater degree of protection to the inner ear would result. It is this sort of thing that occurs when the drum gives way in face of the positive overpressure of a blast wave. The drum having lost its integrity, there results a reduced ability for the conductive system to respond to the negative phase, sothat the overload and its duration as applied to the inner ear is less - how much less is dependent on the size of the perforation. It is this that was meant when it was pointed out earlier that rupture of the drum can be regarded as more helpful than catastrophic. However, since the maximum overpressure and its rise time govern the nature of the ensuing negative phase, the former must be regarded as of over-riding importance.

3.0 QUANTITATIVE CONSIDERATIONS OF EARDRUM RUPTURE

There are a number of factors, the interplay of which makes the vulnerability of the tympanic membrane to rupture a variable thing. These may be divided into physical and anatomico-physiological factors.

It has been established that there is a direct relationship between the percentage of ruptured eardrums and the maximum overpressure.[31] This has also been shown to be the case by the experiences of White et al.[14-20] during the several full-scale weapons tests, and by studies on experimental animals subjected to high-explosive detonations and shock tube-generated overpressures.[15]

Although extensive systematic studies remain yet to be done, enough data are at hand to show that there are additional parameters which are probably of some importance. These are the duration of the overpressure, its rate of rise, and perhaps the duration and magnitude of the negative phase which follows the positive wave.[9-20]

A higher percentage of ruptures will be associated with a given peak pressure if its rise time is "fast," than will be the case when it is relatively "slow." For example, it was found during the full-scale weapons tests in Nevada that 50 percent of dogs' eardrums ruptured when exposed to a "slow"-rising overpressure of 31.2 psi; whereas, a "fast"-rising pulse generated in a shock tube needed only to reach a level of 12 psi in order to produce the same percentage of ruptures.[15,20]

In the opinion of Perlman,[9] if the negative pressure which follows after the overpressure of a blast wave is relatively large and prolonged, a drum which has not been ruptured by the positive pressure may be ruptured during the negative phase, if its outward excursion is sufficiently large.

The vulnerability of an eardrum varies also with its age and whether or not it has been subjected to previous trauma or disease.[6,32]

Many years ago Zalewski[6] found that when a static overpressure was applied to the tympanic membranes of fresh cadavers, the pressure required to cause rupture varied over a range of from 5.4 to 44.1 psi; however, that there was an age dependence was shown by the fact that whereas an average of 33 psi was required to produce ruptures in cadavers from the first decade of life, the figure was only 20 psi for the older age groups.

The reason for this variation of vulnerability with age has not been carefully studied, but the assumption has been that it can be explained by regarding the young membrane as having more elasticity than an older one.[9,32] Some current studies are under way in the Lovelace Foundation Department of Pathology in which histological preparations are being made of tympanic membranes removed from both quite young and quite old animals and humans who come to autopsy. So far, only a few such preparations have been made and studied, but a very definite impression has emerged that the number and organization of the elastic fibers in the submucosal connective tissue in the material obtained from the young drum is quite different when compared with the old ones. In the young drum they are more abundant and organized; whereas, in the old drums they are more sparse and less well organized. It will require the evaluation of much more material than has yet become available, however, before a definite statement can be made.

The thickness and elasticity of a tympanic membrane can also be influenced by the aftereffects of previous disease or injury. Anything which leaves a scar in its wake will, of course, lessen the drum's resistance to blast. Conversely, those pathologic conditions, usually of a chronic nature, which result in a thickened membrane, will cause the drum to become more resistant according to Perlman.[10]

It has been known since Zalewski's work[6] work was published in 1905 and from that of Blake et al.[8] that the eardrums of the various mammalian species manifest differing degrees of vulnerability to rupture by overpressures. Zalewski found that in the case of the dog, the range of pressures required for rupture was between 9.1 and 22.8 psi with a mean of 14.9 psi. This was in contrast with the values obtained for the human cadavers he studied where the range was between 5.4 and 44.1 psi with a mean value for all ages of 22.9 psi.

An opportunity for interspecies comparison of this point has been afforded over the years to the Comparative Environmental Biology Department of the Lovelace Foundation and, although a comprehensive, systematic study has not yet been made, there are enough data at hand to make a few statements possible.

Exposure of young dogs to nuclear blast at the Nevada Test Site indicated that the maximal pressures for rupture of the eardrum ranged from 4.1 to 85.8 psi, with 31.2 psi being the statistically determined pressure required for 50 percent failure of the membrane.[15,20] The highest pressure without rupture was noted to be 66.6 psi. The differences between these values and those of Zalewski[6] possibly can be accounted for by recalling that his experiments were performed using a static overloading of the drum; whereas, the overpressures in the nuclear tests were the result of the detonation of an explosive.

FIGURE 2 illustrates what has been found in regard to species differences. Included are some data on monkeys derived from the studies of Blake, Douglas, Krohn and Zuckerman[8] and on swine from Richmond.[33] It appears that the ear of the monkey is the most blast resistant of the species studied, and that the ear of the goat is the most vulnerable.

It is not possible at this time to attribute the difference in vulnerability to any single feature of the ears of these different species, such as

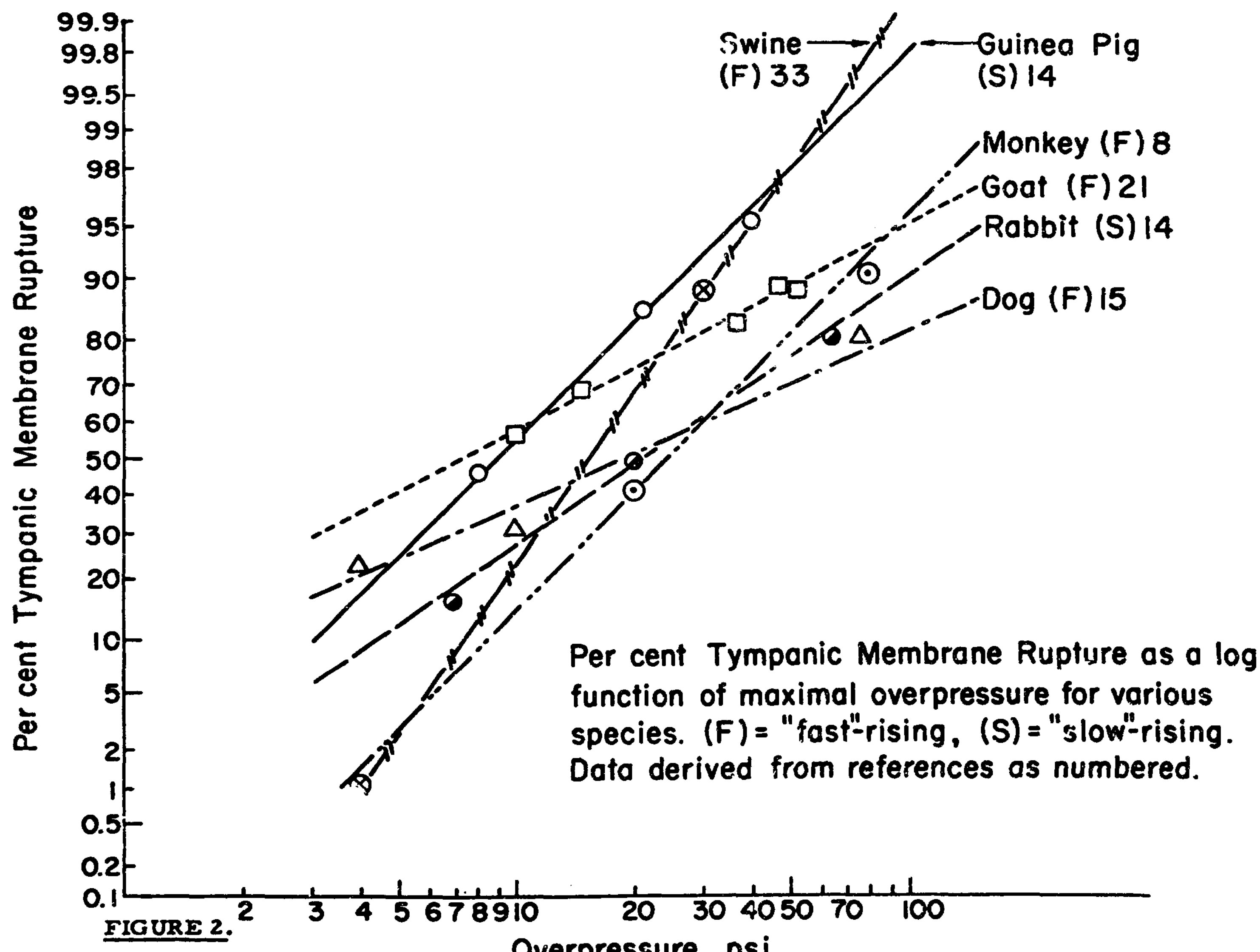

FIGURE 2.

A log-normal plot of overpressure versus percentage of tympanic membrane ruptures for various species. It can be seen that the 50-percent value is least for the goat (8.5 psi) and greatest for the monkey (22 psi).

the structure of the tympanic membrane, or the anatomy of the external ear, since no intensive comparative studies have been made. That there are wide variations in the anatomy of the ear among the mammals is obvious. Except for differences in the thickness of the stratified columnar epithelial layer, there has not been found any marked variation in the histology of the tympanic membranes from a number of species which have been examined. The middle connective tissue layer seems to be the same for all of the species examined. It is probable that some of the biophysical parameters, such as resonant frequency, elasticity, etc., might well show that the drums of the various species of mammals are very different in their dynamics, and they are different targets more because of this, than because of differences in histologic structure.

The mammal of chief interest is, of course, the human species; consequently, it is desirable to know where it fits into the scheme of things. Reference to the work of Zalewski has already been made.[6] This is the most systematic study which has been made, as well as the first. His experiments dealt with the resistance of cadaver ears to "slowly" rising overpressures. These he created by pumping air into the external auditory canal which had been sealed to prevent air escaping from the external auditory meatus. This is different than that of a "fast"-rising overpressure, such as a blast wave. He found that 11 percent of the cadaver eardrums ruptured at an overpressure which was less than 1 atmosphere (14.7 psi). At overpressures between 1 and 2 atmospheres 66 percent ruptured, and at pressures greater than 2 atmospheres the remaining 23 percent were ruptured.

Blake, Douglas, Krohn, and Zuckerman[8] also studied the problem using cadavers. Instead of using a "slowly"-rising overpressure, they generated a shock wave by the bursting-diaphragm technique such as is used on a larger scale in some shock tubes. They found that the pressure required to rupture 50 percent of the drums was about 1 atmosphere or 14.7 psi.

They also studied the incidence of ruptured tympanic membranes amongst air raid casualties. They found that the lowest pressure resulting in rupture of the eardrum was between 2 and 4 psi. In their sample, however, 37 percent of people exposed to blast pressures in excess of 100 psi showed no damage to their tympanic membranes. They concluded that the lower limit of pressure required to rupture 50 percent of eardrums was 15 psi and that the upper limit was 50 psi.

Zuckerman[7] in a later report concluded that over a range from 6 psi to 70 psi eardrum rupture may occur, but that the likelihood of such an event was much greater at the higher levels than at the lower.

Data such as we have just regarded leave something to be desired in the way of precision to those who have an interest in assessing casualty potentials. These people like to have numbers to use, such as the threshold pressure below which damage is not to be expected and a pressure value at which 50 percent of an exposed population can be expected to manifest the effect. It was regarded as a useful and interesting exercise to see if such numbers could not be culled from the literature. Accordingly, a literature search was undertaken with the result that a number of germane publications were found. Most of these were reports of the clinical experiences with blast injury to the ear, and no effort was made to equate overpressures with either the incidence or extent of damage. In some, however, reference was made to a particular type of ordnance, a particular type and weight of explosive, or a measured overpressure. By equating these things with other available data dealing with explosions, scaling values for various explosives, and the known characteristics of various types of ordnance, it was possible to make some approximations which when assembled seemed orderly and reasonable. In doing this the help of people knowledgeable in the field of explosion phenomenology, such as Mr. I. G. Bowen of the Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico; Mr. L. J. Vortman of Sandia Corporation, Albuquerque, New Mexico, and Mr. R. H. Reider of the Los Alamos Scientific Laboratory, Los Alamos, New Mexico, was needed. They all gave substantial assistance which is gratefully acknowledged.

The difficulties and uncertainties surrounding an approach of this kind were discussed by Zuckerman in 1941.[7] The peak overpressure and its scaling produced by any given explosive or type of ordnance can be very well determined for any given set of conditions, but since it is very difficult to determine exactly which set of conditions apply to a given case, some estimation is required. So, recognizing the inherent deficiencies of this sort of an approach, the following data are presented.

In the matter of the least overpressure which can be associated with eardrum rupture, Zalewski[6] found this number to be 5.4 psi. Perlman[10] found that a pressure of 3.9 psi was the lowest that produced rupture in his studies. Machle,[34] on the other hand, studied forty-five gunnery instructors who had frequent exposures to "fast"-rising overpressures of 4 psi and encountered failure of a drum at 6 psi. Shilling[35] found no case of rupture of the tympanic membrane to pressures less than 7 psi, but his subjects were subjected to a "slow"-rising overpressure. Corey[36] found 7 psi to be the rupture threshold in his study. It appears from these data that a "fast"-rising pressure pulse of about 5 psi is sufficient to rupture some human tympanic membranes and that this value can be regarded as the threshold.

When it comes to estimating the pressure required to rupture 50 percent of human drums, one is unable to find any report in the literature presenting data which permit making a categorical statement. However. there are some reports which do permit some estimation. Henry[37] on 292 men who sustained blast injuries to their ears. In these there were 152 perforations (or 52 percent). All these patients were injured when they were about 50 feet from an explosion of a land mine, 500-lb. aerial bomb, or a 3-in. mortar shell. Calculations indicate that the overpressure to which these people were subjected was probably about 17 psi.[38] Vadala[39] reports on his experience with 75 men who sustained ear injury as a result of exposure to the muzzle blast of a 37-mm. antiaricraft gun. From the studies of Murray and Reid[40] this gun has a muzzle blast overpressure of about 6 psi. In Vadala's material he encountered 6 cases of tympanic membrane rupture, or an incidence of 8 percent. Reider[41] at Los Alamos has some data from two recent industrial explosions which indicate that 85 percent of 22 exposed drums ruptured in one explosion where the peak overpressure was 30 psi. In the other explosion, where the overpressure reached 40 psi, all of the 6 exposed eardrums were ruptured.

If one plots these percentages versus their associated overpressure as a log-normal plot, one obtains a straight line best fit which is like those that have been obtained on experimental animals.[14-20] FIGURE 3 shows this plot compared with one prepared by White et al. for dogs exposed to "fast"-rising overpressures.[15] It would appear from this that the probable "fast"-rising overpressure required for rupture of 50 percent of human drums is about 15 psi.

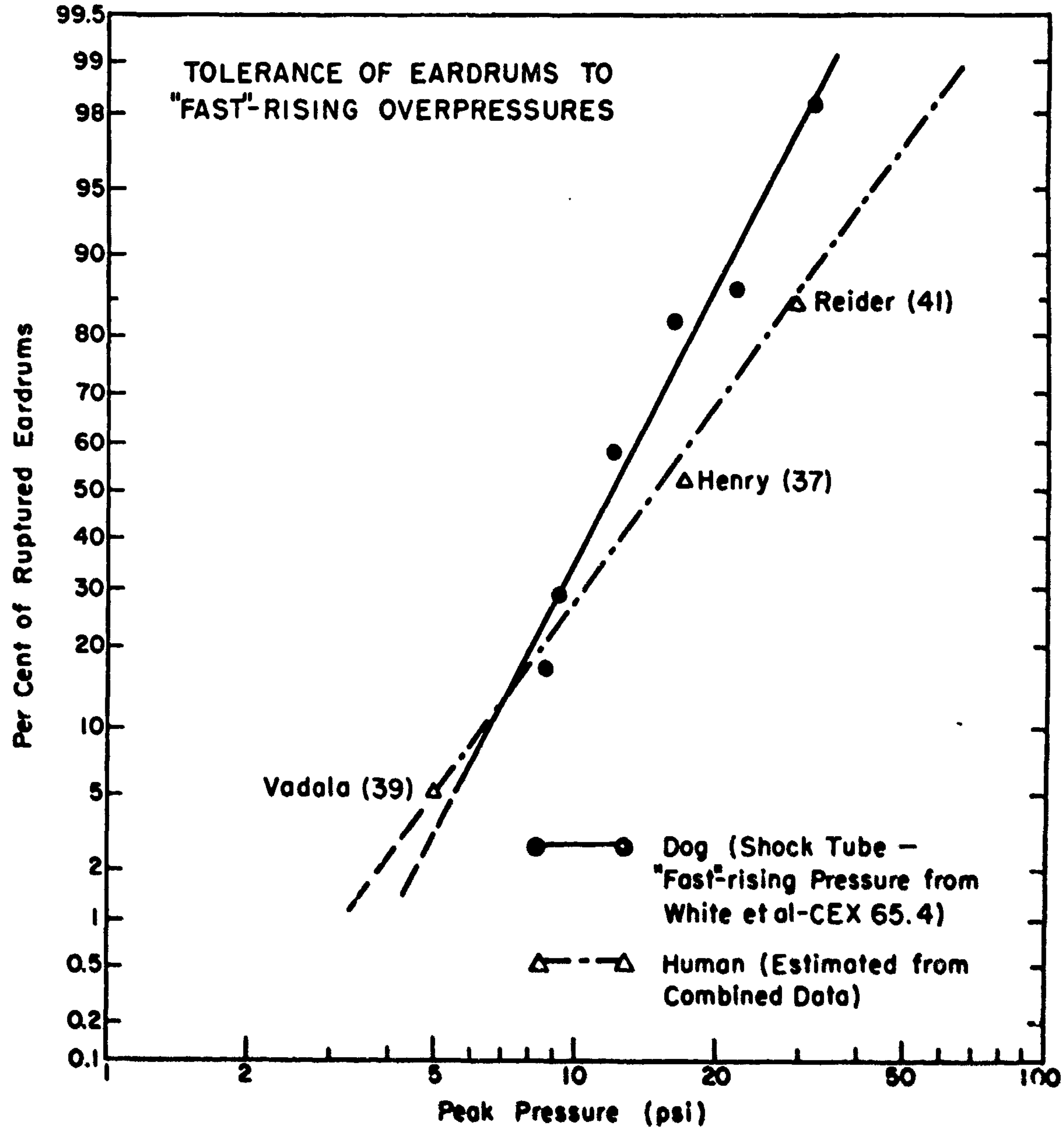

FIGURE 3.

A log-normal plot of the data on humans as derived from the references as shown. This is compared with the data on dogs as presented by White in CEX 65.4.[15]

4.0 HEARING LOSS CAUSED BY BLAST TRAUMA

One important result of blast injury to the ear is the amount of damage to the Organ of Corti in the inner ear caused by an excessive motion of the endolymph. Such damage can result in varying degrees of temporary or permanent deafness. That the hearing loss is related to whether or not the eardrum has ruptured has been remarked about in many of the reports which have been published in the literature. For example, Bourgeois[42] states categorically that when the eardrum ruptures the injury to the inner ear is less, and the consequent deafness is less grave in that it is less apt to be permanent. Concurrence with this opinion has been expressed by Henry,[37] Colledge,[24] Silcox and Schenck,[31] and others.

When a blast wave has caused the eardrum to rupture, the associated hearing loss will be of a mixed type; that is to say, there will be a loss of acuity for low tones as well as for high tones. Ordinarily the low-tone loss will be of the order of 10 to 30 db; whereas, the high-tone loss will be more in the nature of 40 to 80 db. This will be true providing there has been no dislocation of the ossicles associated with the rupture, because when this happens, there results a permanent and severe conductive deafness. From clinical reports it is apparently unusual for the ossicles to be displaced by a "fast"-rising, "short" duration overpressure unless the overpressure is very high. Ireland[30] found no incidence of ossicular fracture or dislocation in 317 cases of blast injury of the ear all due to high-explosive detonations; however, Barrow and Rhoads[43] encountered several in their study of 32 cases of blast injury of the ear. Henry[37] remarks in his study of 292 cases that dislocation of the ossicles was uncommon.

Henry also pointed out that he was unable to correlate the intensity of the immediate hearing loss with the size of the perforation, and other authors are found to be in agreement. Among the published reports studied, no one was found who disagreed with this opinion.

Boemer[44] in his study of 310 cases of acoustic trauma found that 78 percent of the cases of temporary deafness had not suffered a perforation of the drum and makes the point that these were the more severely deafened.

A number of studies of traumatic deafness, such as those of Murray and Reid,[40] Machle,[34] and Bunch[32] have emphasized that there is an accumulative effect on hearing when multiple acoustical insults are sustained by an individual. It is also apparent that the time interval between incidents is of importance in that when they occur with intervals shorter than the recovery period, the permanent hearing loss is more profound. Murray and Reid,[40] Silcox and Schenck,[31] and Perlman[9] have all pointed out that there is a marked individual variation in susceptibility to acoustic trauma. It appears that susceptibility to inner ear damage as evidenced by high-tone hearing loss and the time required for recovery from an acoustic insult go hand in hand; that is to say, the more susceptible inner ears require longer for recovery.[40]

There are three types of hearing loss due to blast injury. The first of these is a neurosensory type which involves audition of high tones, usually considered as those above 4000 Hz. This can be either temporary or permanent and can result whether or not there has been incurred any damage to the middle ear structures. If there has been only a single traumatic episode, or if the intervals between episodes have been long enough to permit recovery to the inner ear structures, then the high-tone loss is temporary. On the other hand if multiple traumata of the inner ear are experienced without adequate recovery intervals, the loss will be permanent.

A case in point is one taken from the comprehensive article on traumatic deafness written by C. C. Bunch[32] in 1937. It concerns a naval gunnery officer who had, in the course of his duties, experienced periods of time when his ears were exposed to muzzle blast overpressures from naval ordnance. He never suffered rupture of his eardrums so far as is known. The audiogram depicted in FIGURE 4 was taken on him at the age of 36 years. It shows a loss of auditory acuity beginning at 200 Hz and is most profound at 4000 Hz. This type of audiogram is regarded by otologists as characteristic of cochlear damage and also of senile degeneration of the inner ear. When one regards the age of this patient, it hardly seems likely that the hearing loss can be on the latter basis.

The second type of deafness associated with blast injury is that which is obtained when a rupture of the eardrum has occurred. Dr. D. E. Kilgore of the Lovelace Clinic has made available data on a 44-year old physicist who was involved in a hydrogen-oxygen explosion and as a result was exposed to a "fast"-rising overpressure estimated by Reider[41] to be near 30 psi. He suffered bilateral tympanic membrane ruptures which did not become infected and healed completely within several months. FIGURE 5 is an audiogram showing the auditory acuity for his right ear. The record for his left was virtually identical. The solid line is post-rupture, and the broken line is the record made following healing of the perforations. The mixed type of deafness is clearly apparent, as is the degree of recovery.

The third type of hearing loss is that which results when the middle ear structures are irreversibly damaged. This is illustrated by a case, also taken from Bunch,[32] concerning a soldier who was in a trench in World War I when a shell exploded less than thirty feet away from him. He suffered obliteration of his eardrums and dislocation of the middle ear ossicles as well. His audiogram, which is shown in FIGURE 6, was taken some twenty years after his injury which had occurred at the age of 25 years. The depressed acuity for all frequencies is characteristic for conductive deafness, and the fact that there has been no restoration in twenty years emphasizes the permanent nature of his disability.

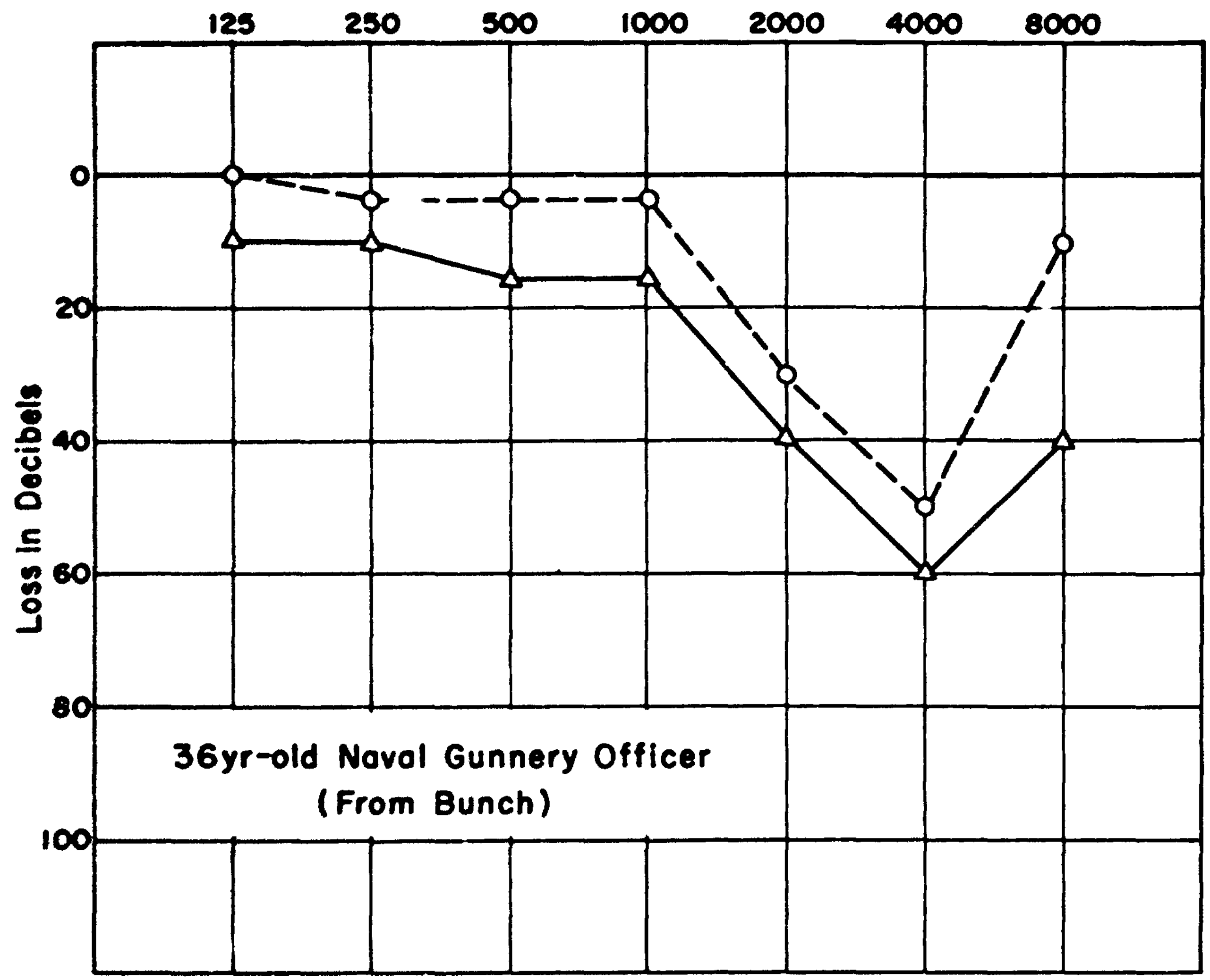

FIGURE 4.

The audiogram of a 36-year old Naval Gunnery Officer who had suffered repeated noise exposures, but had never had a rupture of an eardrum. The high-tone loss cannot be attributed to aging since he is yet a young man. Solid lines represent the right ear; dotted lines represent the left ear.

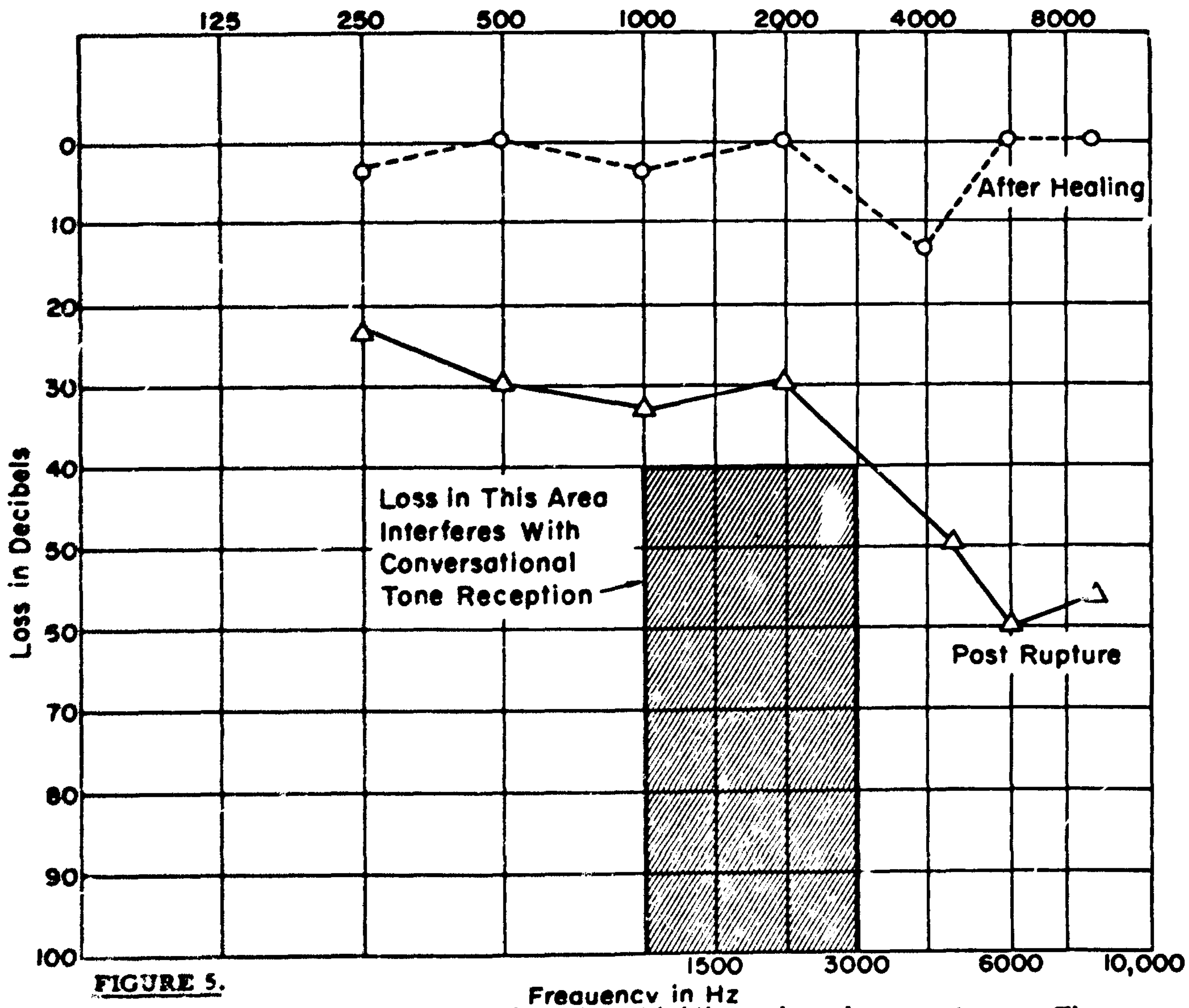

FIGURE 5.
The audiogram of a 44-year old physicist with bilateral eardrum ruptures. The solid line is post-rupture. The dotted line is following healing of the perforation. Data for right ear only.

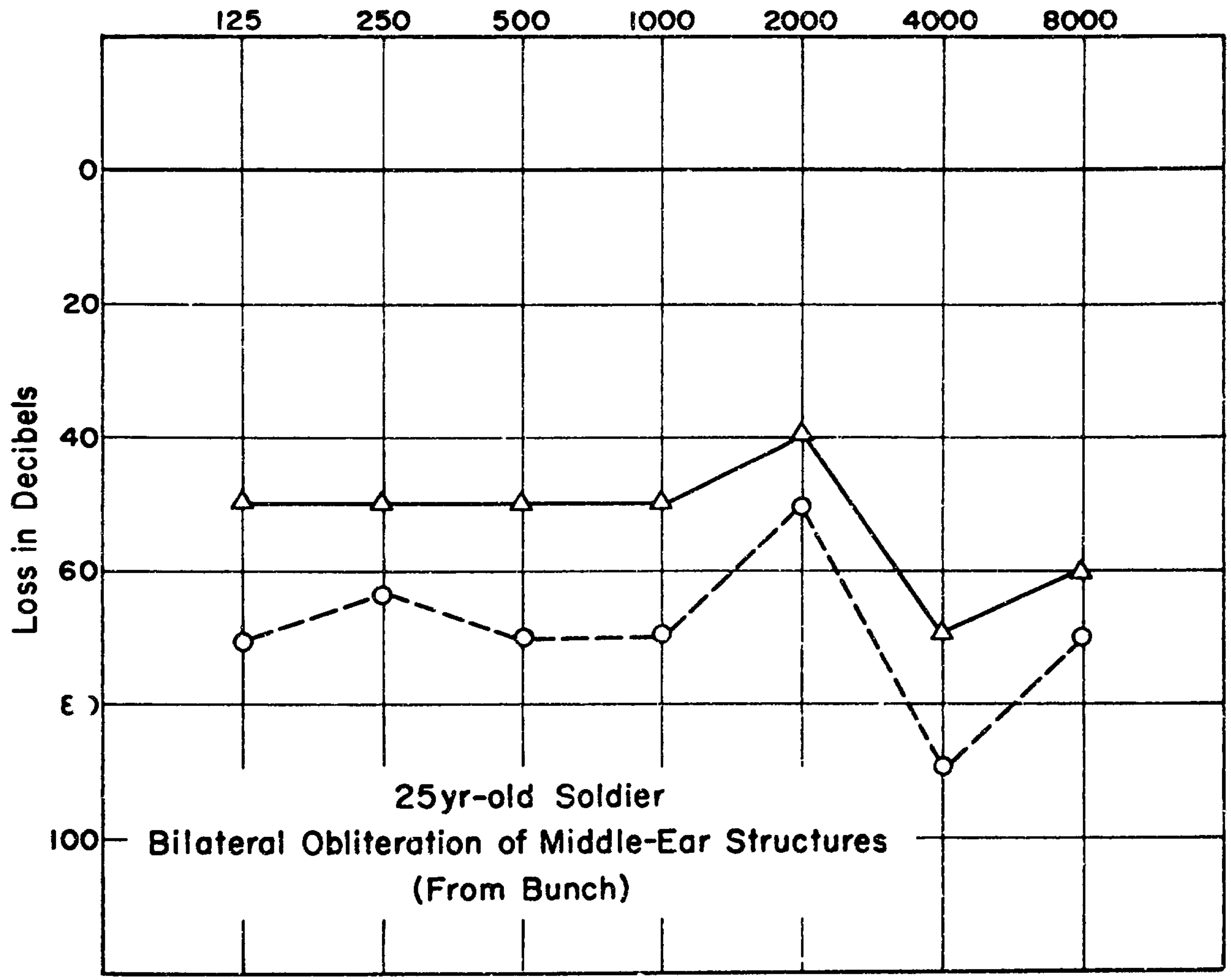

FIGURE 6.

The audiogram of a soldier who received severe blast injury to his ears at the age of 25. This record was obtained when he was 41 years old, some sixteen years after his injury. The blast injury obliterated the structures of his middle ears. Solid lines represent the right ear; dotted lines represent the left.

5.0 PREVENTION OF BLAST INJURY OF THE EAR

A search for a satisfactory method of preventing acoustic trauma has been conducted by many people for many years. The approach used by most of them has been to recommend the use of some type of ear plug which will attenuate a blast wave (or loud sound) and dissipate some of its energy.

All of the devices which have been designed will do these things and thus give their wearers substantial degrees of protection.[40, 44-46] They all have associated with their use, however, some degree of loss of auditory acuity which can be quite disadvantageous under certain circumstances.

As with all protective devices, such as "hard hats," safety shoes, safety glasses, and others, resistance to their use is perversely encountered in some of the population at risk.

Some otologists have regarded a simple cotton plug, constituting a protective device, as satisfactory as a more elaborate ear plug. Others, and they seem to be in the majority, decry the use of cotton plugs and point out with some merit the reasons for their objections.[45, 46] After reviewing a substantial amount of the pertinent literature, one is forced to conclude that the proper and faithful use of an ear defender in a traumatically noisy environment, or where a real hazard of blast injury exists, is wise and worthwhile.[32, 34, 40, 47]

The placement of gun crew members should certainly be made with the threat of muzzle blast in mind. Wherever the muzzle blast overpressure approaches 4 psi, the crew members should be protected by ear defenders.

6.0 DISCUSSION

From what has been said, it is easy to appreciate why the ear is especially vulnerable to blast overpressures. Indeed, it is remarkable that a structure possessed of delicacy and sensitivity such as the mammalian ear can present as much resistance to damage bv blast as it does. This must be due in part to the mitigative effect that rupture of the tympanic membrane frequently enters into the picture; although as has been pointed out, there are other important individual variables such as age, the previous health history of the ears, and the poorly understood differences in the susceptibility of individuals to acoustic trauma.

An entirely different set of variables are those associated with any given explosion - such as the maximum overpressure, the nature of its rise time, and its duration. To these must be added all of those things which collectively can be called "geometric positioning."

Where an individual happens to be when an explosion occurs, how he is oriented with respect to the direction of propagation of the blast wave, and whether environmental conditions are such as to afford shielding or reflections of the overpressure will cause marked differences in the magnitude of exposure in different individuals who may be quite close to one another at the time.

For all of these reasons, it is very difficult to derive quantitative data about the vulnerability of human ears from the study of what has occurred to an exposed population. Further, insofar as experimental studies of inner ear trauma are concerned, it has not been possible to equate overpressure versus damage due to the extraordinarily formidable difficulties associated with investigations of inner ear function. This has been pointed out by Wever and Bray[48] and more recently by Vartanyan and Maruseva.[49] The latter also emphasize that the frequency sensitivity range of the ear of an animal are highly species specific and that the mechanism of cochlear function and neural organization in the brain vary. For these reasons, extrapolations of data derived from one species to another are precarious.

Insofar as the middle ear structures are concerned, it can probably be safely said that the threshold pressure for damage to middle ear structures is about 5 psi and that overpressure near 15 psi will cause the rupture of 50 percent of the eardrums exposed to them. However, except when the ossicles have been displaced, damage to the middle ear is of secondary importance as compared with inner ear trauma, especially insofar as long-term and permanent disability are concerned. Thus, these numbers lose some of their significance and utility insofar as they can be applied helpfully to casualty assessment and identifying conditions of hazard. One can assume that obvious middle ear trauma is always associated with some significant degree of inner ear damage, but the converse is not a valid assumption. It has been shown by many, although perhaps no better than by Bunch,[32] that inner ear damage can very often occur in the absence of demonstrable injury to the middle ear.

Compared with the other types of blast trauma, such as that to the lung and to those organs affected by the presence of air emboli in their vascular elements, injury to the ears is distinctly a matter of secondary importance. Even though the body of information concerning otic blast trauma may leave something to be desired concerning some of its quantitative details, enough can be discerned from reading that which has been published on the subject to enable a fairly satisfactory understanding of what happens and how it happens. Enough certainly is at hand to appropriately guide those who are concerned with environmental health and safety insofar as ears are concerned.

7.0 SUMMARY

The literature concerning blast injury of the ear has been reviewed. In general, there is apparently little in the way of quantitative data to be found. An effort has been made to arrive at some quantitative estimates relating blast overpressure to ear injury. It appears that the threshold for rupture of the human eardrum by a "fast"-rising overpressure is about 5 psi and that the overpressure required for rupture of 50 percent of eardrums is near 15 psi. It has not been found possible to equate overpressure quantitatively with damage to the inner ear. Some of the anatomical and physiological factors involved in otic trauma due to blast have been discussed, and the utility of ear defenders has been considered.

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13. ABSTRACT

Information regarding blast effects on the ear has ~~been~~ reviewed in an attempt to gather quantitative information available for animals and man for help in the establishment of relationships between various levels of overpressure and the incidence of eardrum failure, the degree of damage to the middle and inner ear and other identifiable sequelae referable to cochlear or vestibular functions.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Blast Effects Ear Injury - Blast Overpressure and Eardrum failure Human ear injury Ear Injury Criteria						

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