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EFFECTS OF SOUND ON THE VESTIBULAR SYSTEM

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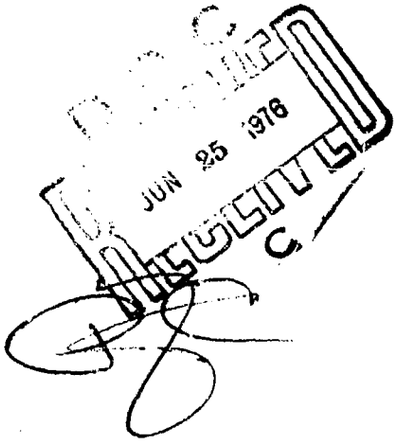

MARCH 1976

AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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The experiments reported herein were conducted according to the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

HENNING E. VON GIERKE
Director
Biodynamics and Bionics Division
Aerospace Medical Research Laboratory

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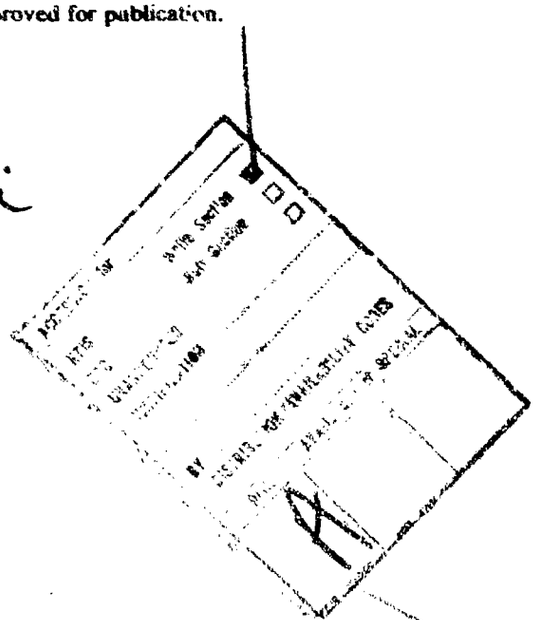

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Vestibular responses have been evoked from guinea pigs, monkeys, and human beings following stimulation with static pressure, infrasound, sustained audiofrequency sound, and repetitive audiofrequency transients. These observations lead to suggestions concerning the manner in which sound affects the vestibular receptors as well as to proposals concerning levels of sound exposure that might disturb human performance by influencing behaviors mediated at least in part by the vestibular system.

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PREFACE

The research described in this report was performed under Contract F 33 615-73-C-4002 between the United States Air Force and Miami University, Oxford, Ohio. This research was accomplished both in the laboratory of the first author at Miami University and in facilities of the Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base.

Much of the data described in this report have been published elsewhere and the methods are only briefly considered here; in those cases where unpublished observations are described (particularly Section II, p. 39), methods are presented in greater detail.

We thank our colleagues who have contributed to this effort, particularly H. E. von Gierke, C. S. Harris, and the staff of the Veterinary Medical Division at Wright-Patterson Air Force Base.

SECTION I

INTRODUCTION

Sound exposure may evoke several types of responses from a human being in addition to those directly related to hearing. Among these nonauditory effects of sound are responses that result from activation of vestibular system receptors.

PURPOSE

We are interested in describing the biomechanical and physiological mechanisms whereby sound affects the receptors of the vestibular system. The primary purpose of this report is to review acoustical vestibular stimulation performed with human observers and laboratory animals. Animal experimentation has been pursued to further our understanding of the effects of sound on the vestibular system that have been observed in human beings. Primary attention is devoted to experiments conducted in our laboratory; however, current work from other laboratories is also considered.

THE VESTIBULAR SYSTEM

The vestibular system has two distinct, yet interrelated functions. First, the vestibular system coordinates with other sensory systems in maintaining the spatial orientation of the body, including the head and eyes. Vestibular influences can be observed in several orientation reflexes (e.g., the counter-rolling of the eyeball when the head is tilted). The vestibular system is often presented as a postural control system because it makes important contributions to motor control of the body. This classification is not completely correct because the vestibular system also has a significant influence upon our

spatial orientation perceptual system. This second function is associated with subjective awareness of (1) body orientation with respect to gravity, and (2) body movement (within limits). Vestibular receptors contribute to perception of orientation and motion because they respond to linear and angular acceleration (gravity can be described as linear acceleration). Obviously, many senses, including the visual system, the auditory system, and the skin, contribute to perception of spatial orientation. The contribution of the vestibular system to spatial orientation perception is clearly illustrated when signals from vestibular receptors are modified by disease or unusual stimulation.

One of the difficulties that we encounter in dealing with the vestibular system relates to the unusual nature of the sensations evoked by stimulation of vestibular receptors. We can think of no sensation that is uniquely correlated with vestibular stimulation in the way visual sensations are correlated with stimulation of the eye or auditory sensations are associated with stimulation of the ear. For example, strong motion sensations may result from strictly visual inputs, as most of us have noticed while watching a "chase scene" in a motion picture theater. Similarly, we encounter difficulties when we attempt to uniquely relate particular sensations to vestibular disturbances. To illustrate, the symptoms of motion sickness can be evoked by unusual or intense vestibular stimulation; however, similar sensations can be evoked under many other conditions (e.g., alcoholic intoxication). Unless we have reason to believe that vestibular receptors are somehow stimulated, we are unable to attribute particular unpleasant sensations to the vestibular system.

Further information on the general nature of the vestibular system is available in Howard and Templeton (ref 20).

BACKGROUND

Historically, acoustical stimulation of vestibular receptors has been a topic of confusion and controversy. Early research and theory concerning acoustical vestibular stimulation were obscured by failure to differentiate between the functions of the cochlear and vestibular portions of the labyrinth. Through the haze of conflicting observation and opinion, two main lines of development can be detected. One group of investigators proposed that the ability to localize sounds in space was associated with stimulation of the semicircular canals. This sound localization view of semicircular canal function was supported during the present century by the work of Tullio. Another group of investigators advocated Flourens' position that the vestibular receptors were concerned with movement rather than with detection of acoustical signals. This second group of investigators recognized that sound can stimulate the vestibular receptors but noted that the responses elicited by sound stimuli were analogous to those produced by motion stimuli. In other words, the investigators who followed Flourens believed that sound can be considered an inadequate stimulus for the vestibular receptors. A summary of early work concerning acoustical vestibular stimulation can be found in Camis (ref 7).

During the period from 1930 to the present time, several investigators have reported responses indicative of vestibular stimulation following exposure of human beings to high intensity acoustical stimulation. Nystagmus (involuntary oscillation of the eyeball clearly related to vestibular stimulation) has been observed following exposure to pure tones ranging from 200- to 2500-Hz at intensities from 120- to 160-dB SPL. Observers report sudden shifts or displacements of the visual field following stimulation at intensities of 115- to 130-dB with pure tones that have rapid onset rates. These visual field displacements are also thought to result directly from vestibular stimulation.

Dizziness, nausea, and disturbances of postural equilibrium have been correlated with sound stimulation at intensities and frequencies lower than those which are required to evoke nystagmus or reports of visual field displacement. These responses are believed to reflect activation of vestibular receptors; however, the possibility that dizziness, nausea, and equilibrium disturbance result from acoustical stimulation of physiological systems in addition to the one associated with vestibular receptors cannot be discounted. References for recent acoustical vestibular stimulation research can be found in Parker et al (ref 28) and Harris (ref 18).

ANATOMY AND PHYSIOLOGY

It is convenient to think about the mechanisms between acoustical stimulation and physiological or behavioral vestibular responses in terms of three basic blocks, as illustrated in Fig. 1. Environmental sound enters the body primarily at the tympanic membrane of the middle ear (due to the mechanical impedance match between body fluids and air at this point). Sound energy is transformed into tympanic membrane oscillation, and an oscillatory motion of the middle ear bones (ossicular chain) is evoked by tympanic membrane motion. The ossicular chain terminates with the footplate of the stapes at the oval window of the labyrinth.

The bony labyrinth refers to the fluid-filled cavities of the temporal bone. The membranous labyrinth is located within the bony labyrinth. The perimeter of the bony labyrinth is filled with perilymph and roughly defines the shape of the vestibule, cochlea, and semicircular canals (see Fig. 2). Figure 3 illustrates the endolymph-filled series of sacks and tubes that comprises the membranous labyrinth. The sensory receptors for the auditory system are located in the cochlea; the utricle, saccule, and semicircular canals contain the vestibular receptors.

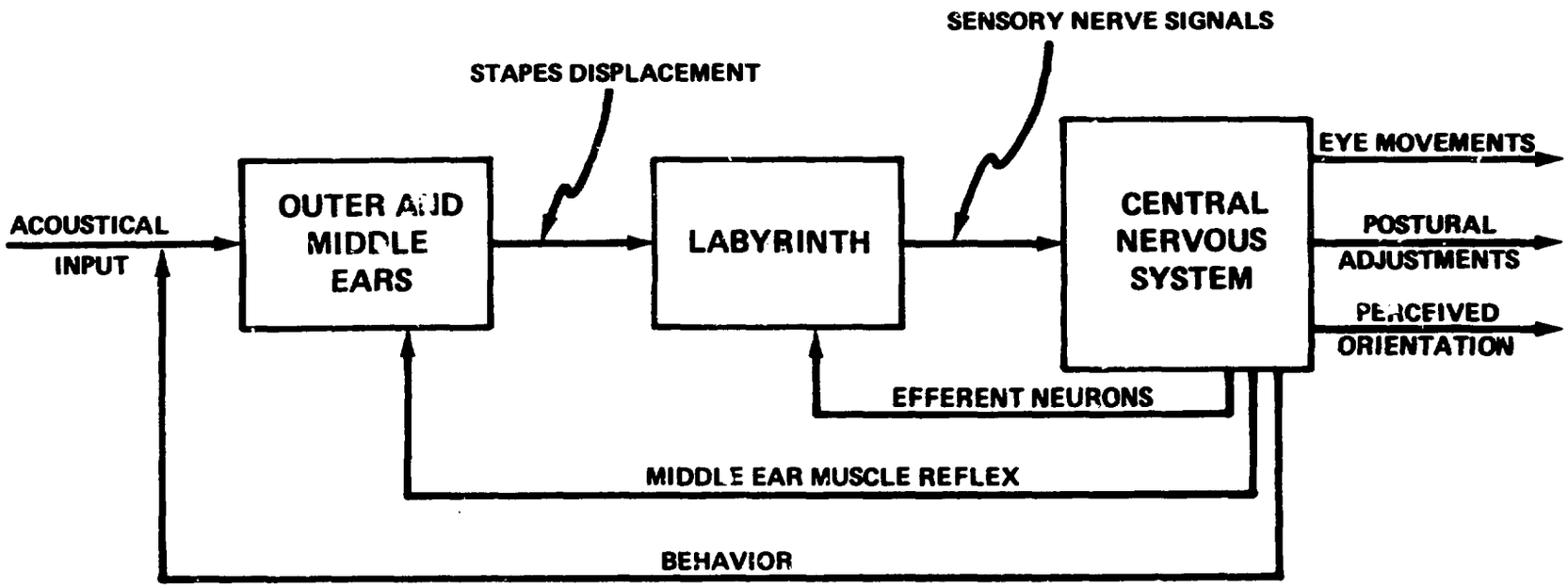


Figure 1. Acoustical vestibular stimulation, including three feedback pathways. See text.

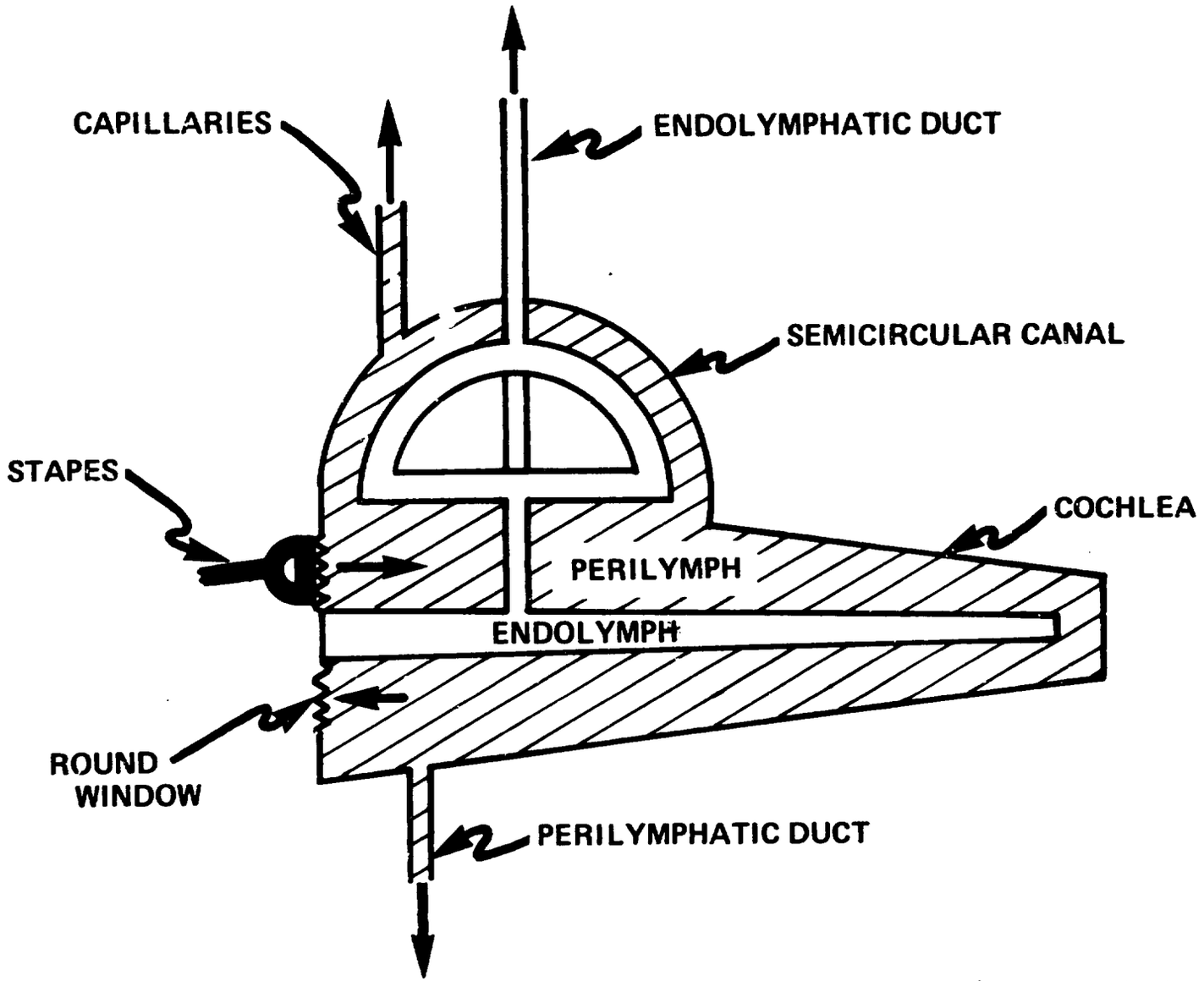


Figure 2. Bony labyrinth and membranous labyrinth (endolymph-filled space). Arrows indicate elastic release points for fluid displacement when stapes moves inward (from von Békésy, ref 5).

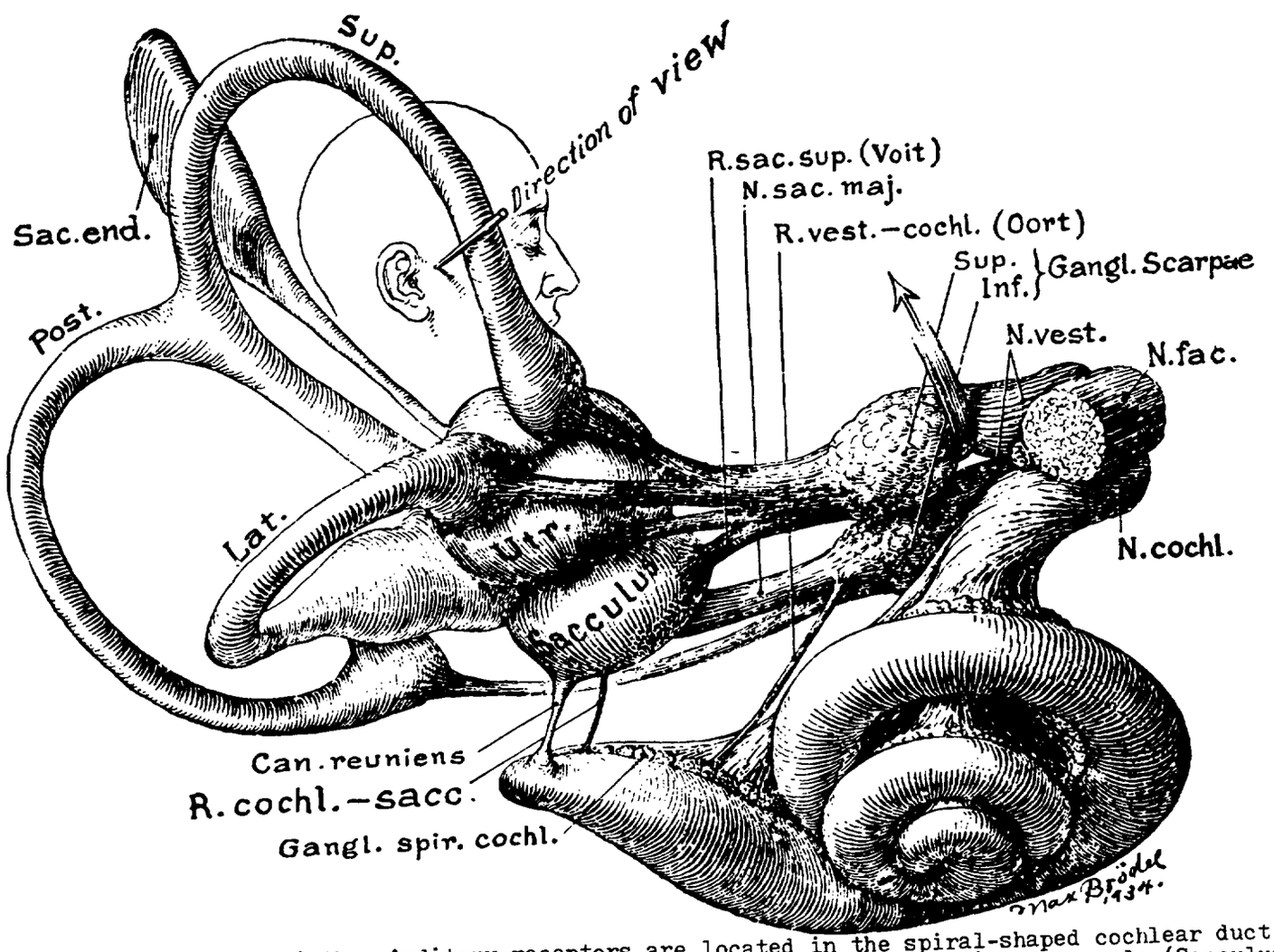


Figure 3. Membranous labyrinth. Auditory receptors are located in the spiral-shaped cochlear duct at lower right. Statolith organs are located in the utricle (Utr.) and saccule (Sacculus), and crista organs are found in each of the three semicircular canals (Lat., Sup., and Post.). The endolymphatic duct terminates in the endolymphatic sack (Sac. end.) at the upper lef The nerve supply to the auditory and vestibular receptors is also shown (from Hard , ref 16).

The sensory apparatus of the vestibular system is morphologically differentiated into two types of receptors: one for detection of linear acceleration (statolith organs in the utricle and saccule) and the other for detection of angular acceleration (crista organs in the three semicircular canals). Both types of receptors are activated by deformation of sensory hair cells as a result of inertial displacement of accessory components. However, the mechanism of accessory structure inertial displacement differs significantly for the two types of vestibular receptors.

Displacement of the statolith mass stimulates the sensory hair cells of the utricle and saccule. The statolith is displaced relative to the hair cells during linear acceleration exposure because the statolith has a higher specific mass than the surrounding medium. The hair cells of the semicircular canal crista organs are stimulated by displacement of a gelatinous flap (cupula) which extends into the membranous semicircular canal. The cupula, in turn, is displaced during angular acceleration by inertial movement of endolymph in the membranous ring contained within the bony semicircular canal. Both the statolith and cupula behave as though they contained a weak spring and return to a neutral position after termination of acceleration (see ref 20).

Differences in the nature of fluid displacement associated with stimulation of the two types of vestibular receptors may be important for our purposes. Displacement of the statolith mass is not directly dependent upon movement of labyrinth fluids; the fluid displacement resulting from a change in position of the statolith mass should be relatively small and localized. Conversely, displacement of the semicircular canal cupula is directly dependent upon volume displacement of fluid within the membranous ring.

Ossicular chain motion results in displacement of perilymph

and endolymph through the labyrinth. This labyrinth fluid displacement is dependent upon elastic "release points" in the nonelastic bony labyrinth wall. The major labyrinth release point is the round window; three additional openings in the labyrinth wall include the perilymphatic and endolymphatic ducts, which connect the labyrinth to the cranial cavity, and the capillaries. Labyrinth fluid displacement associated with inward (medial) displacement of the stapes is indicated by the arrows in Fig. 2.

The block diagram presented in Fig. 1 suggests that we consider sound-induced vestibular responses at three levels: biomechanical, physiological, and behavioral. Biomechanical responses to acoustical stimulation include ossicular chain and labyrinth fluid displacement that may result in physiological responses beginning with sensory hair cell activation. We include eye movements, postural adjustments, and other reflexive (unconditioned) responses to vestibular stimulation with neural activity under the heading of physiological responses. Goal-oriented activity of an organism and stimulus-induced perceptual changes can be considered under the heading of behavioral responses. Observations from our laboratory have been primarily concerned with biomechanical and physiological responses evoked by acoustical stimulation; however, our goal is to relate these biomechanical and physiological observations to reports of other investigators regarding behavioral responses.

Three possible feedback pathways are also illustrated in Fig. 1. The pathway labeled "behavior" indicates that an organism's overt actions can modify the acoustical stimulation that it receives. Potential physiological feedback could result from activation of the middle ear muscle (acoustic) reflex and the efferent portion of the vestibular nerve. The middle ear muscle reflex, which reduces the efficiency of sound energy transfer from air to labyrinth fluids, has a latency of 60- to 150-msec, and gradually adapts to continuous stimulation over a

period of minutes (ref 36 and 15). The efferent neural fibers, which terminate on vestibular sensory hair cells, appear similar to those of the cochlea (ref 29 and 35). Cochlear efferent neurons perform an inhibitory function (ref 12 and 39); the physiological activity of the vestibular efferents has not been clearly established.

SECTION II

VESTIBULAR RESPONSES TO ACOUSTICAL STIMULATION

We divide acoustical stimuli into four categories based on the temporal character of the pressure changes. Pressure transients, including pressure step functions and ramp functions, comprise one of these categories. The remaining three categories of acoustical stimulation that we employ consist of pressure oscillations. Infrasound refers to pressure oscillation at frequencies below 20 Hz, sustained audiofrequency sound denotes oscillations in the 20- to 20,000-Hz frequency range, and repetitive audiofrequency transients refer to trains of noise or tone bursts presented at various repetition rates. In addition to frequency, acoustical stimuli are specified by several other parameters: intensity, duration, phase, and onset rate. We specify the intensity of pressure transients in centimeters of mercury (cm Hg) of overpressure (pressure changes with respect to ambient air pressure). The intensity of oscillatory pressure is expressed in terms of the sound pressure level (SPL) scale in decibels (dB) with respect to 0.0002 microbar.

PRESSURE TRANSIENTS

One of our proposed mechanisms to account for acoustical vestibular stimulation is based on unidirectional (dc) flow of perilymph and endolymph through the labyrinth (see Section III, p. 62). We postulate that a dc labyrinth fluid flow results from static displacement of the stapes. One technique for producing static stapes displacement is exposure of an animal to transient pressure changes in the outer ear canal (external auditory meatus). Therefore, we undertook a series of experiments on biomechanical and physiological responses to external auditory meatus pressure transients.

Biomechanical Responses

Biomechanical responses to pressure transients have been examined with two techniques: (1) direct observation of the ossicular chain, and (2) labyrinth fluid pressure changes. These responses have been examined in anesthetized guinea pigs and monkeys (Macca mulatta) and in human cadavers.

Figure 4 illustrates longitudinal axis stapes displacement as a function of the intensity of a pressure step function at a guinea pig's tympanic membrane. The abscissa represents peak stimulus pressure with pressure increases to the right of the ordinate and pressure decreases to the left. Stapes displacement is indicated on the ordinate; points above the abscissa represent medial displacement (into the oval window) and points below the abscissa indicate lateral stapes displacement (out of the oval window). The stimulus source was a hypodermic syringe, which was connected to a hollow earbar with polyethylene tubing. Responses were recorded by direct observation with an operating microscope through an opening in the bulla. The curve illustrates that increased pressure at the tympanic membrane resulted in an initial medial stapes movement, followed, at higher stimulus intensities, by lateral stapes displacement. Tympanic membrane pressure decreases resulted in a lateral stapes displacement that increased unidirectionally as a function of stimulus magnitude. These observations confirmed our expectations that pressure transients would produce static stapes displacements; however, the bidirectional stapes response to pressure increases was unexpected.

Kobrak (ref 23) observed the rotation of the tympanic membrane as a function of pressure changes in the external auditory meatus. From the rotation observations, linear displacement of the umbo was calculated. The results of these observations, which are illustrated in Fig. 5, indicate that the middle ear response to static pressure decreases is approximately linear across the range of 0- to -6.0-cm H_2O; however, the

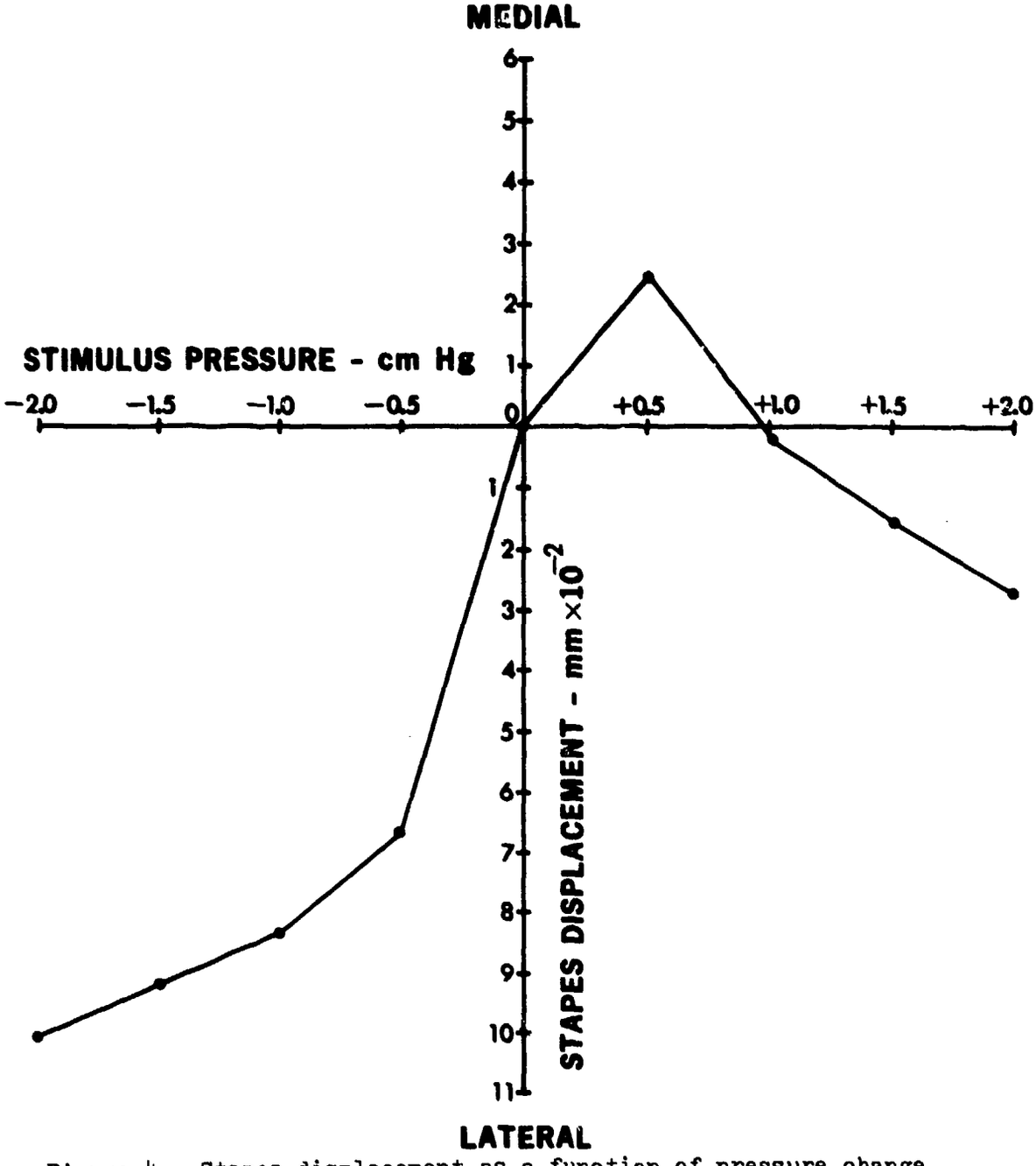


Figure 4. Stapes displacement as a function of pressure change at tympanic membrane of the guinea pig. Each point represents the average of 4 observations. Variation was negligible. A bidirectional response to pressure increases is illustrated (from Parker and Reschke, ref 26).

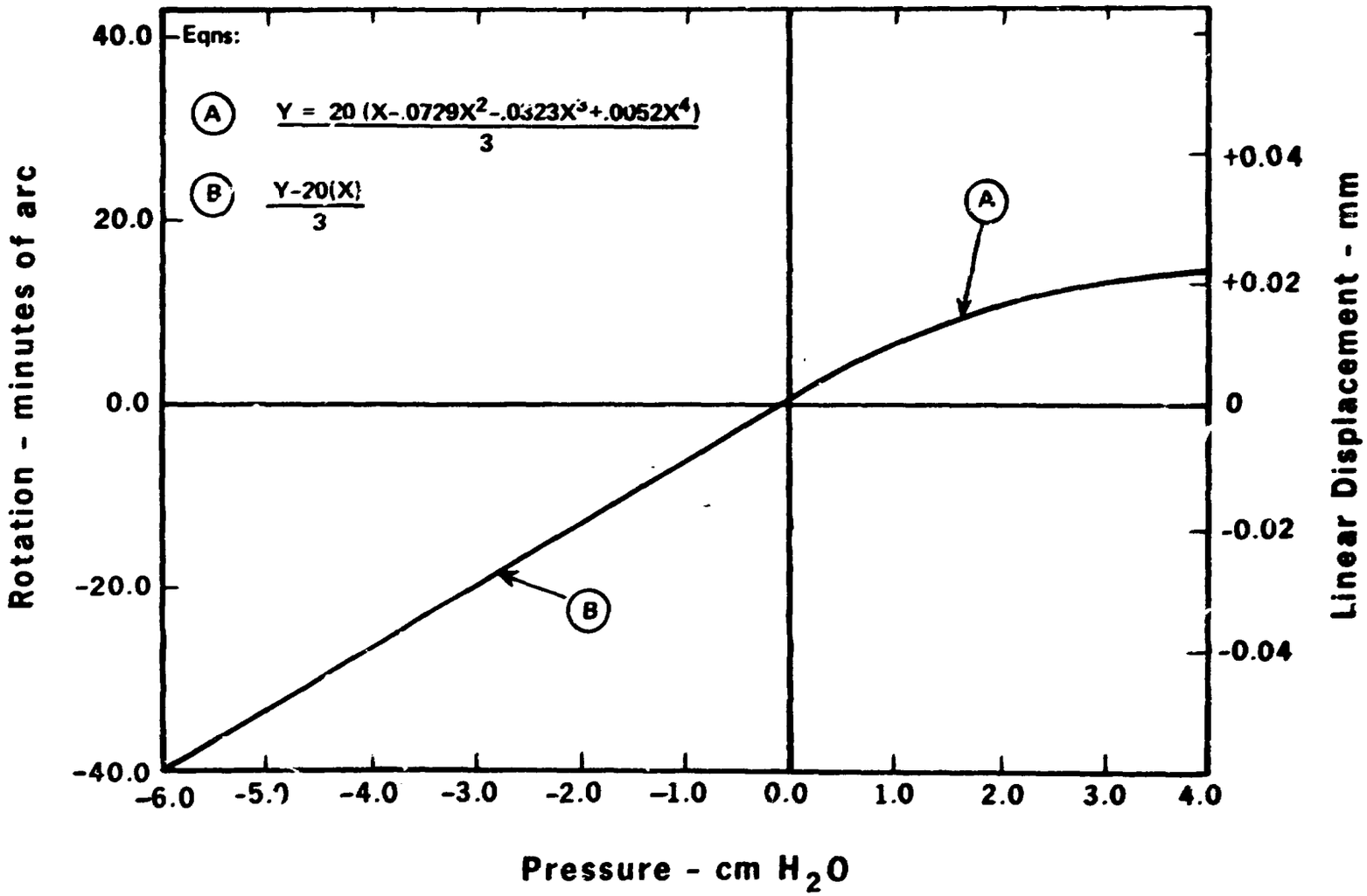


Figure 5. Tympanic membrane rotation (observed) and umbo linear displacement (calculated) as a function of pressure changes at tympanic membrane of human cadaver. Increased pressure produces nonlinear displacement; decreased pressure results in a linear response (from Kobrak ref 23).

response of the middle ear to static pressure increases is nonlinear.

Variation in perilymph pressure (top trace) as a function of transient pressure change at the tympanic membrane (bottom trace) is illustrated in Fig. 6. Downward deflection for both pressure traces indicates increased pressure. The middle trace in each oscillograph record indicates time in 1-sec intervals. Records A and B illustrate responses to ramp functions of increased pressure at the tympanic membrane; record C illustrates the response to a ramp function of decreased pressure. These responses were obtained by cementing a saline-filled glass pipette into a 1-mm hole in the superior semicircular canal of a guinea pig and connecting the pipette to a pressure transducer. The stimulus arrangement was the same as that employed for the stapes displacement observations. The perilymph pressure recordings provide essentially the same information as the direct stapes displacement observations: transient pressure increases at the tympanic membrane elicit a bidirectional response, whereas tympanic membrane pressure decreases result in a unidirectional perilymph pressure change or stapes displacement.

Perilymph pressure changes recorded from the horizontal semicircular canal of a monkey are presented in Fig. 7. Record A illustrates the response evoked by transient pressure increases and record B illustrates the responses evoked by transient pressure decreases at the monkey's tympanic membrane.

Figures 6 and 7 essentially describe the transfer characteristics relating perilymph pressure changes to transient pressure changes at the tympanic membranes of the guinea pig and the monkey. These transfer characteristics are presented in the form of oscillograph records because repeated stimulus exposures frequently resulted in a change in the form or amplitude of the response; therefore, presentation of average response curves

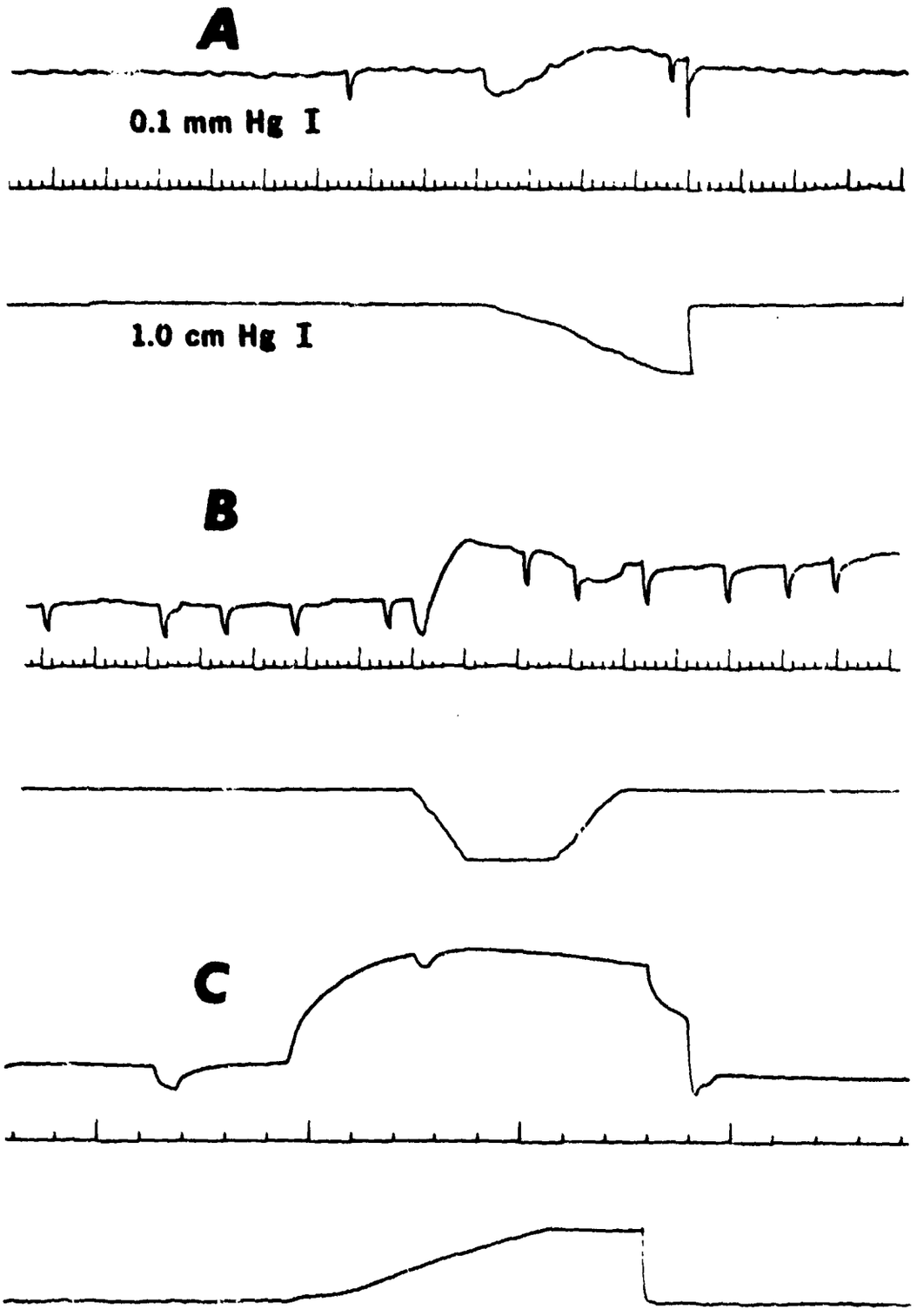


Figure 6. Guinea pig perilymph pressure changes in response to increased (records A and B) and decreased (record C) pressure at the tympanic membrane. See text (from Parker and Reschke, ref 26).

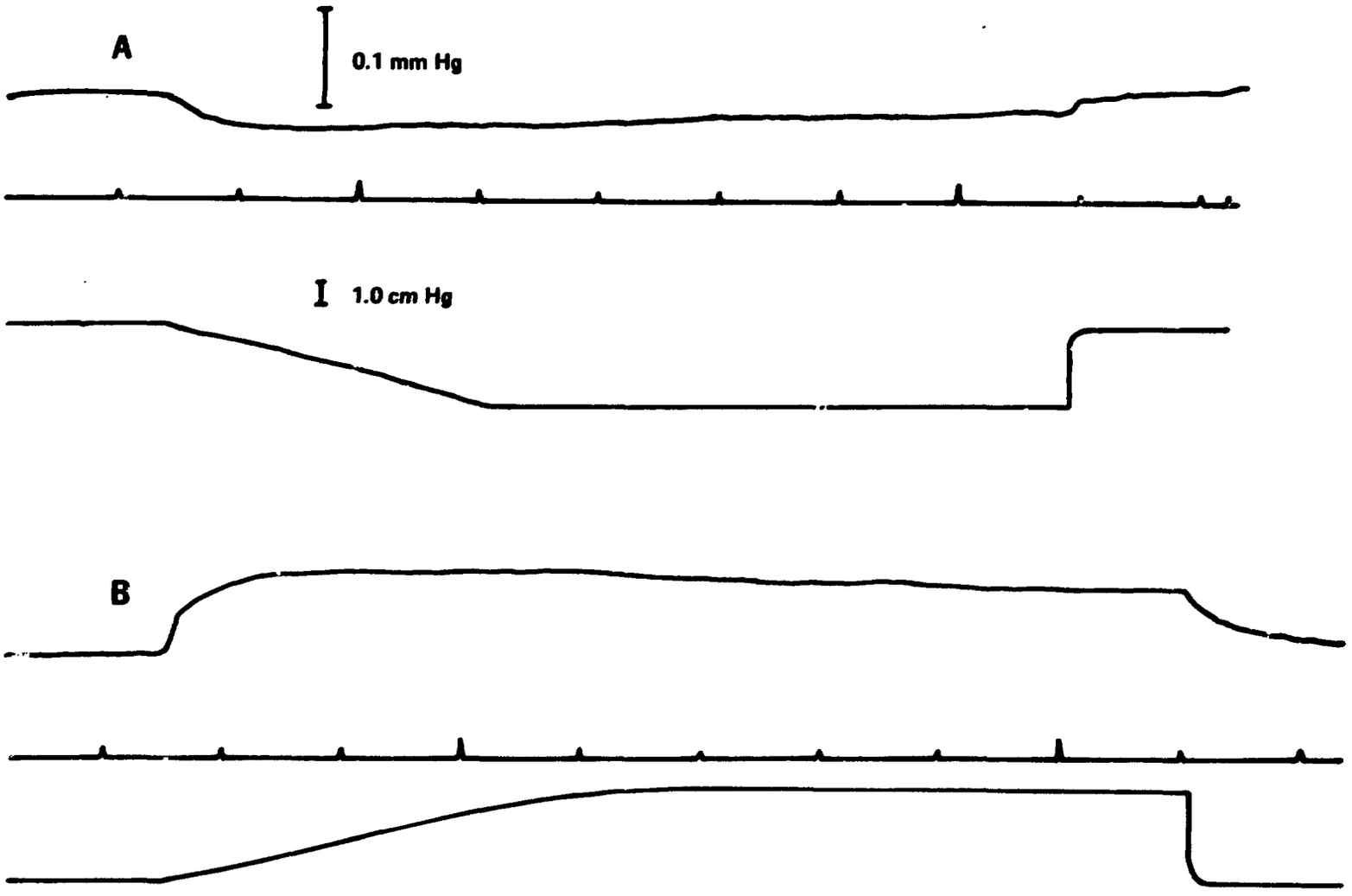


Figure 7. Monkey perilymph pressure changes in response to increased (record A) and decreased (record B) pressure at the tympanic membrane. Recording conventions as in Fig. 6.

appears inappropriate. Figures 6 and 7 illustrate three consistent differences between guinea pigs and monkeys. First, monkeys yielded unidirectional responses to both transient pressure increases and decreases while guinea pigs exhibited a bidirectional response to transient pressure increases at the tympanic membrane. Second, the maximum perilymph pressure change obtained from monkeys was invariably in the region of 0.1-mm Hg or less, whereas guinea pigs demonstrated maximum perilymph pressure changes of several times this value. Third, monkey perilymph pressure changes saturated (reached maximum value) at stimulus intensities of 1.0-cm Hg or less; guinea pigs' responses saturated at somewhat higher stimulus intensities.

Physiological Responses

Two types of physiological responses to pressure transients have been examined: (1) primary vestibular nerve activity, and (2) reflexive head and eye movements.

Responses from single vestibular ganglion neurons were obtained from 3M KCl-filled micropipettes (2-microns tip diameter) that were located at the mouth of the internal vestibular meatus in anesthetized guinea pigs (see ref 27). Figure 8 illustrates changes in action potential rate that were observed in 1 of 11 neurons from which responses to pressure transients could be obtained (out of a total of 32 neurons that were isolated). The average action potential rate (pulses per second) associated with 4 presentations of pressure increases (top record) and 2 presentations of pressure decreases (bottom record) is plotted in the figure. The temporal location of the stimuli is indicated by the black horizontal bars. Pressure increases of 1- to 2-cm Hg resulted in a decrement in neural response rate, and pressure decreases of approximately 1.5-cm Hg elicited a pulse rate increment. The response latencies indicated by the curves in Fig. 8 are relatively short (less than 1-sec); however, other neurons that were sampled exhibited

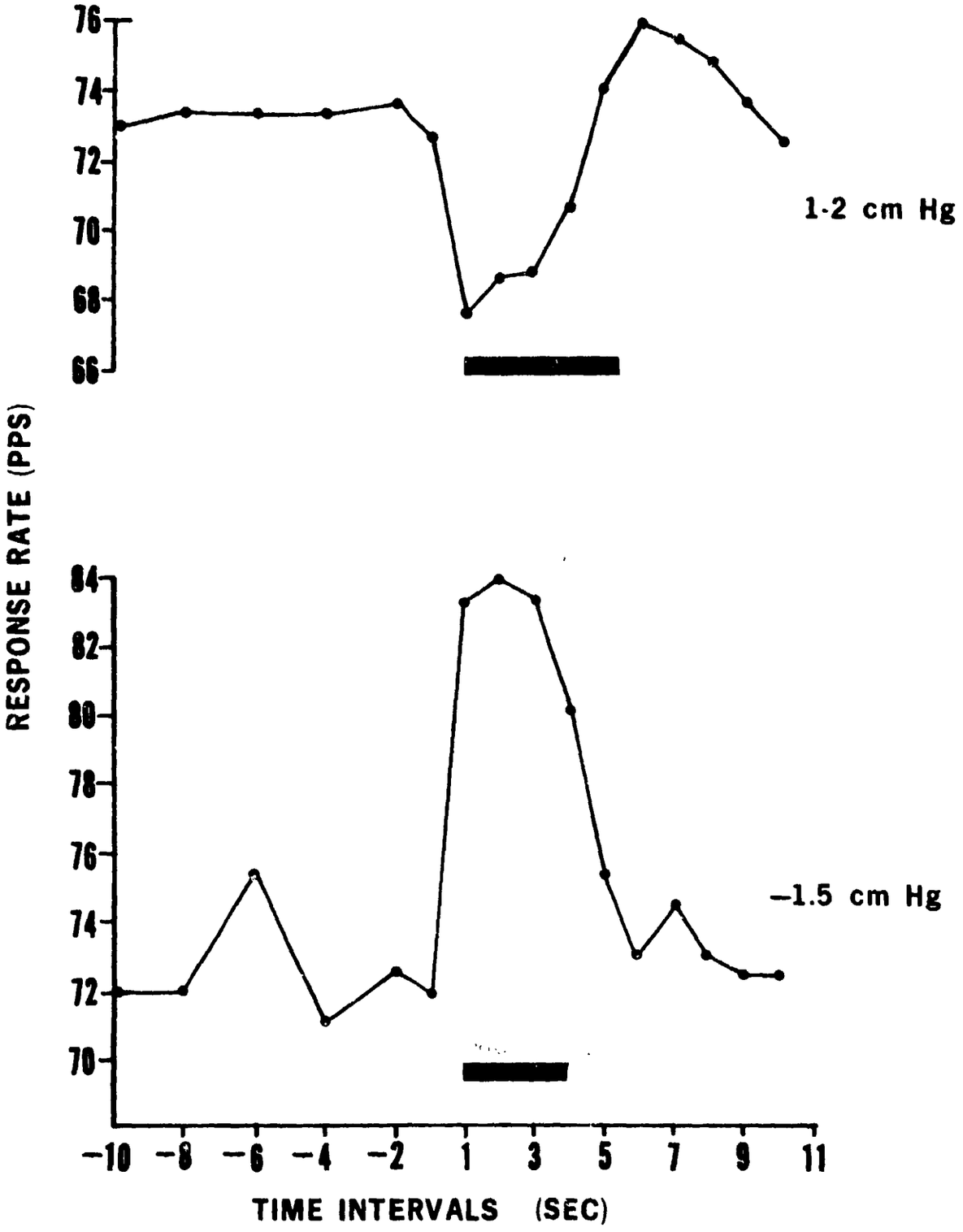


Figure 8. Changes in action potential rate from a single vestibular neuron as a function of increased (top curve) or decreased (bottom curve) pressure at the tympanic membrane. Temporal location of the stimulus is indicated by the horizontal bar under each curve (from Parker and von Gierke, ref 27).

response latencies of up to 5-sec. Response latencies are of interest when we compare neural pulse rate data to head and eye movement observations.

These neural response data are important because they clearly demonstrate that vestibular receptors in the guinea pig can be physiologically activated by pressure transients. The vestibular ganglion contains cells from the horizontal and superior semicircular canals as well as the utricle and saccule. The observation that 11 of 32 isolated neurons exhibited changes in response rate to pressure transients is consistent with the suggestion that only the semicircular canal vestibular receptors are stimulated by sound energy.

An oscillograph record of head and eye movements elicited from an unanesthetized guinea pig by a pressure increment step function is illustrated in Fig. 9. Head movements were recorded with a force transducer following a technique described by Parker (ref 24). The animal's head was restrained by a head holder that was attached to the force transducer, and the output of the force transducer indicated the attempts by the animal to change its head position in response to stimulation. Among the interesting features of this recording technique is the fact that one of the feedback loops providing the animal with information concerning the consequences of head movement commands is opened. Eye movements were recorded from electrodes that were located subcutaneously above and below the eye following ordinary electronystagmographic procedures.

The upper trace in Fig. 9 indicates the pressure transient that was delivered to the tympanic membrane; the second trace is the output of the force transducer; the third trace is a record of eye movements; and the bottom trace is the time marker (1-sec intervals). Peak stimulus intensity (excluding overshoot) was 4.3-cm Hg, and the stimulus duration was about 19-sec. The force transducer output trace shows that the animal attempted to

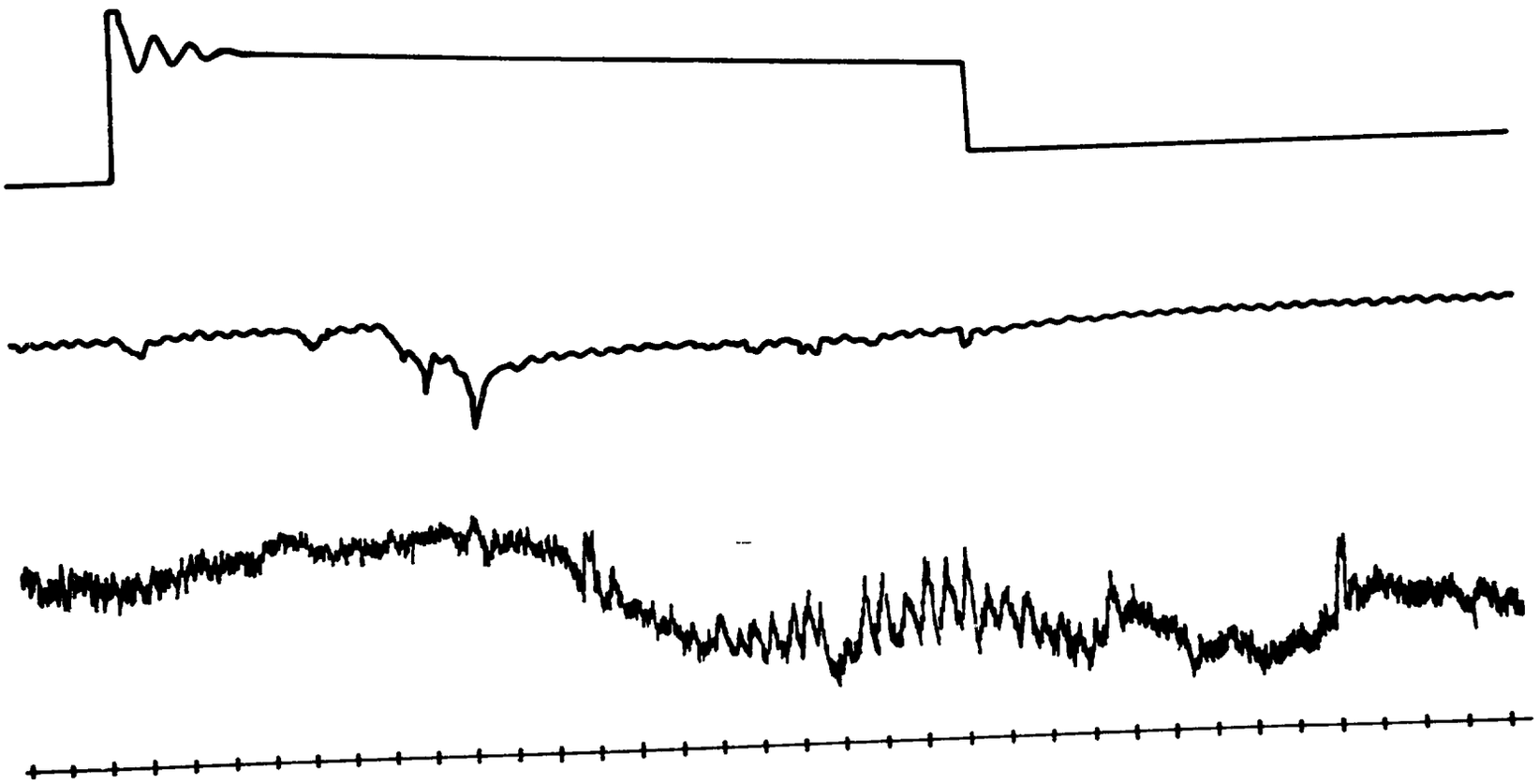


Figure 9. Pressure increase at tympanic membrane (first trace) elicited head movements (second trace) and eye movements (third trace). See text (from Reschke, Parker, and von Gierke, ref 32).

turn its head toward the side of stimulation about 6-sec after stimulus onset. The eye movements evoked by this stimulus were complex, and the full nature of these movements cannot be revealed by electronystagmography. Approximately 9-sec after stimulus onset, the eyeball exhibited a slow downward deflection followed by nystagmus in approximately the vertical plane which continued beyond the termination of the stimulus.

The data presented in Fig. 9 are important because they demonstrate that responses analogous to those elicited by "normal" vestibular stimulation can be produced by stimulation with pressure transients. The very long response latencies illustrated by these data are also of interest.

We have made numerous attempts to elicit eye movements from unanesthetized monkeys in response to pressure transients. We have not been able to record eye movements from monkeys in response to pressure transients up to 40-cm Hg. Several stimulation arrangements were employed to ascertain that the stimuli were freely conducted to the tympanic membrane with the same result: no response. Rotary nystagmus in response to intense audiofrequency sound could be elicited from the same ears with the same earbar placements as those that failed to exhibit a response to pressure transients (see Section II, p. 38). The implications of this failure to replicate physiological vestibular responses to pressure transients across species are discussed in Section III.

There has been little systematic investigation of human response to pressure transients although anecdotal reports of disorientation during static pressure change are widely cited (see ref 22). The best information available derives from a study by Ingelstedt, Ivarsson, and Tjernstrom (ref 21) in which vertigo was elicited from 5 out of 79 otologically healthy observers during simulated ascents from underwater dives. Nystagmus was observed concurrent with the reported vertigo.

Figure 10, which is taken from ref 21, illustrates the relationship between subjective vertigo, nystagmus, volume displacements of the right and left eardrums, and the stimulus pressure.

INFRASOUND

Based on our observations of responses to pressure transients, we deduced that appropriate frequencies and intensities of infrasound should elicit vestibular responses (in the guinea pig). Moreover, infrasound allowed us to estimate the frequency response of the ossicular chain-perilymph pressure system.

Biomechanical Responses

Pressure changes in the semicircular canal perilymph were examined as a function of exposure to infrasound with anesthetized guinea pigs and monkeys. A piston phone generated acoustical stimuli at intensities from 112- to 150-dB SPL and frequencies from 0.5- to 50-Hz.

Perilymph pressure changes in response to intense infrasound are complex and difficult to interpret. Part of the difficulty results from the observation that the perilymph pressure response can exhibit at least two different response components when stimulated by infrasound; we use the labels "primary response component" and "secondary response component." Either response component may appear alone, or both may appear simultaneously, depending upon stimulus parameters. Variation in response, both within and across species also introduces interpretation difficulties. Fortunately, differences between monkeys and guinea pigs are considerably greater than differences within either of these species.

The response of the ossicular chain-perilymph pressure system appears to be linear in the low infrasound frequency range (0.5- to 2-Hz) and the low audiofrequency range (50- to 70-Hz); that is, the perilymph pressure output waveform nearly

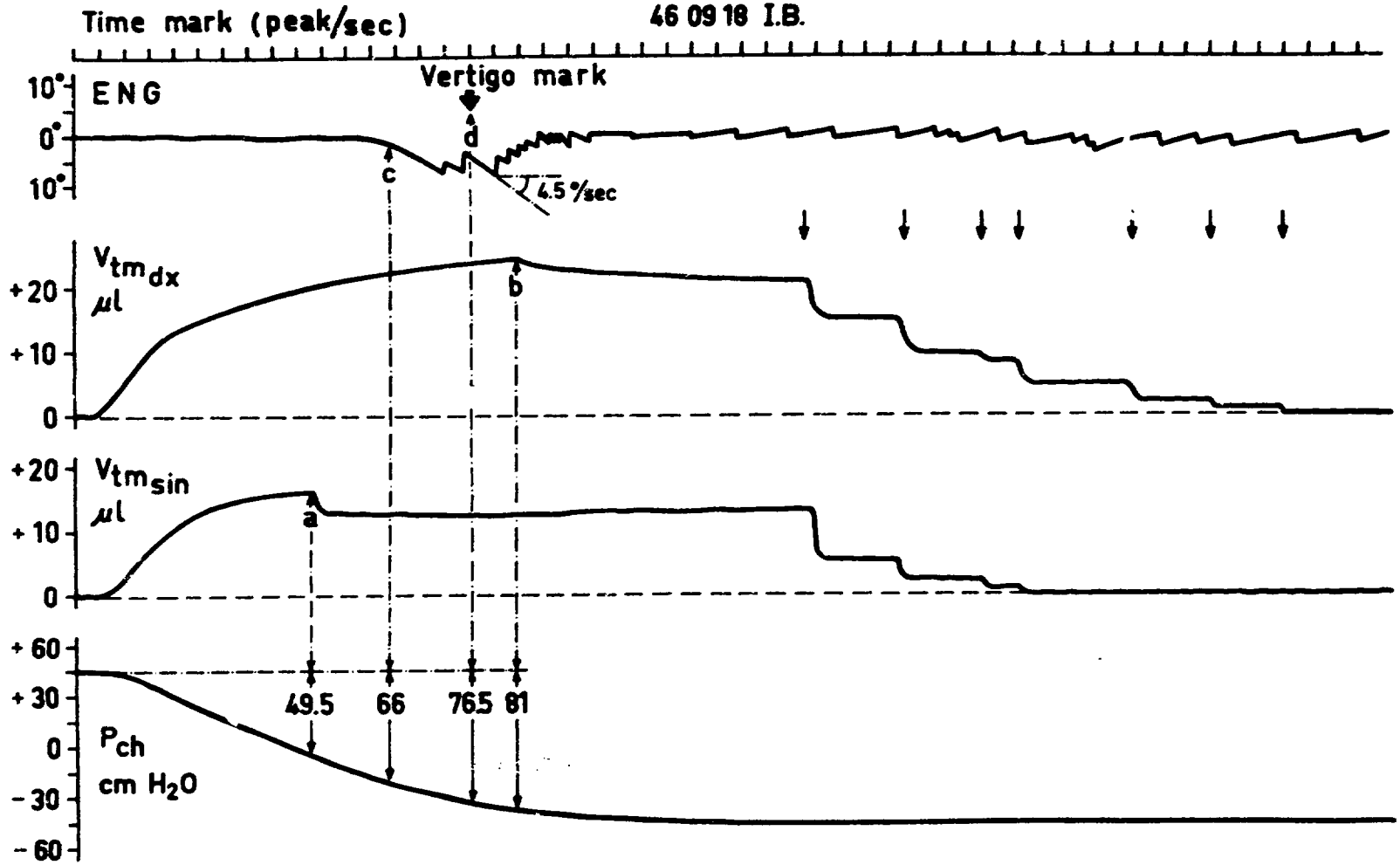


Figure 10. Electronystagmogram (ENG--top trace) and volume displacement of the right (second trace) and left (third trace) tympanic membranes during whole body pressure changes (bottom trace). Passive clearing of the left and right ears occurred at times (a) and (b) respectively. Nystagmus onset was at time (c) and the observer reported vertigo at time (d) (from Ingelstedt et al., ref 21).

replicates the acoustical input waveform. At stimulus frequencies intermediate between these values the perilymph pressure output may be complex. Figure 11 illustrates an oscillograph record of perilymph pressure changes evoked by 5.7-Hz infrasound at 150-dB SPL (record A) and 112-dB SPL (record B). The top trace in each record illustrates perilymph pressure changes, and the bottom trace shows the pressure changes at the tympanic membrane produced by the infrasound stimulus. The response elicited by the high intensity stimulus is clearly complex, whereas the response to the low intensity stimulus approximates the input waveform. The perilymph pressure change of record B illustrates what we call the primary response component.

Employing particular stimulus parameters, it was possible to determine the transfer characteristics for the primary response component of perilymph pressure change as a function of stimulus frequency. Transfer characteristics for the guinea pig and the monkey are illustrated in Fig. 12. These curves indicate two major differences between guinea pigs and monkeys. First, the amplitude of the perilymph pressure response evoked from the guinea pig was an order of magnitude greater than the perilymph pressure response evoked from the monkey by the same infrasound intensity. Second, the upper limit of the natural frequency range was greater for the guinea pig than the monkey by about three octaves.

The secondary response component was much smaller in magnitude than the primary response component. At frequencies where the secondary response component initially appears alone (as frequency is increased, +20-Hz for the monkey, +40-Hz for the guinea pig) the output invariably exhibited a phase lead with respect to the input by at least 30 deg.

Physiological Responses

Restrained, awake guinea pigs and monkeys as well as human

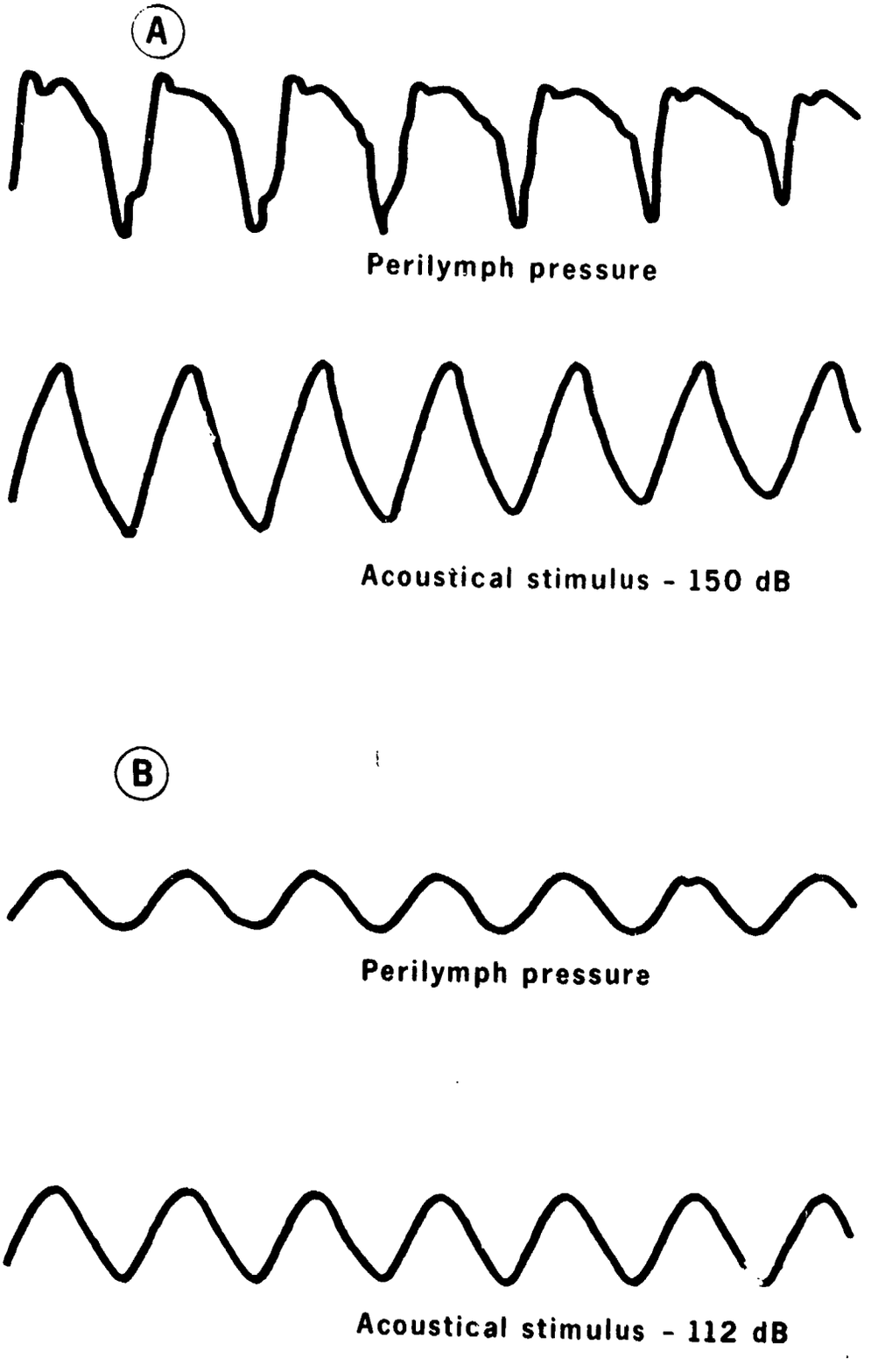


Figure 11. Perilymph pressure changes evoked by high intensity (A) and low intensity (B) infrasound stimulation. See text.

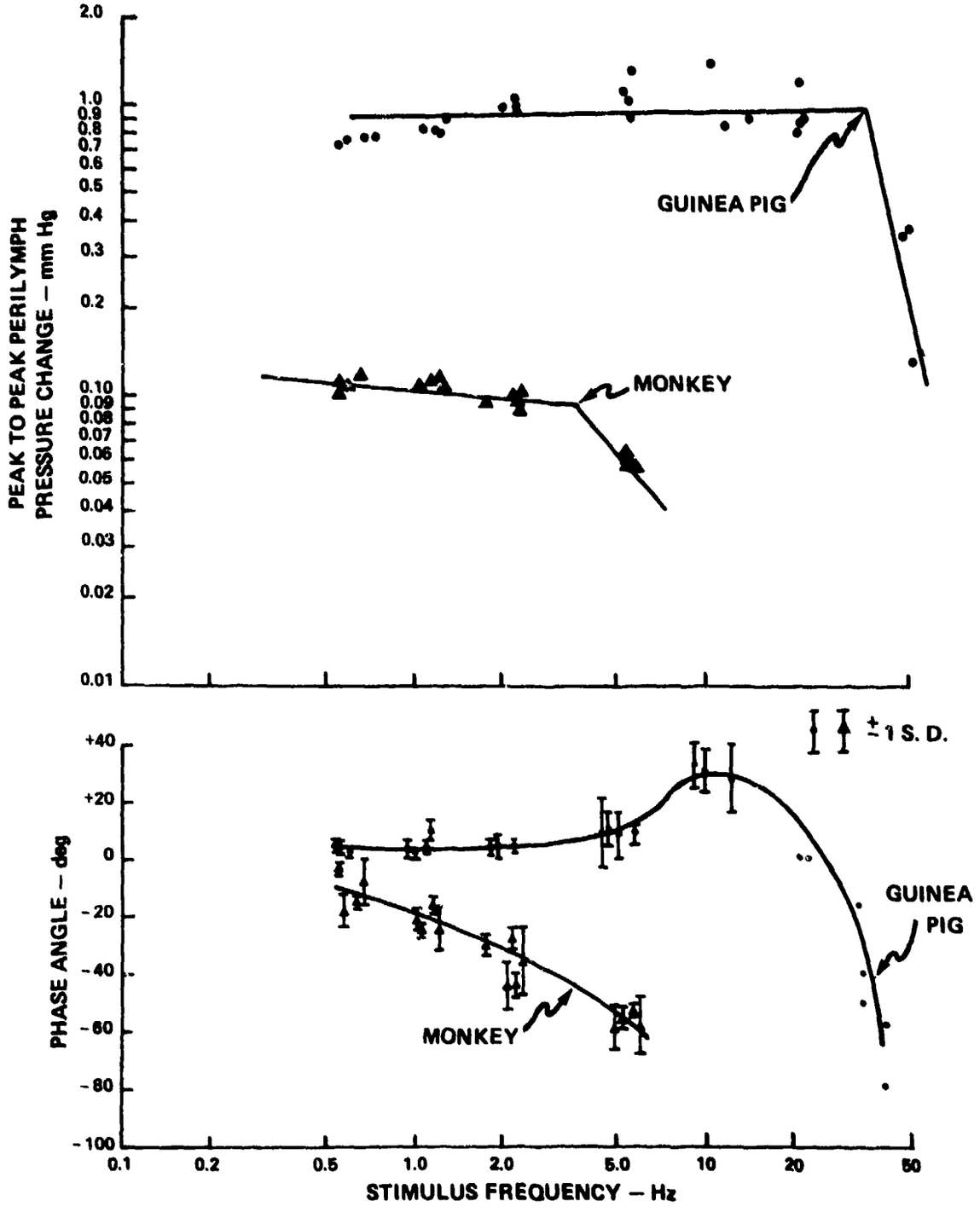


Figure 12. Amplitude (top) and phase angle (bottom) of perilymph pressure response as a function of infrasound frequency.

observers were exposed to intense infrasound (172-dB SPL at 1-, 2-, and 4-Hz; 169-dB SPL at 10-Hz; 162-dB SPL at 20-Hz; and 158-dB SPL at 30-Hz) that was generated by the "dynamic pressure chamber" located at Wright-Patterson Air Force Base, Ohio. Whole-body exposures were performed with the subjects located inside the dynamic pressure chamber. Two whole-body exposures of guinea pigs were performed after the external auditory meatus on one side had been sealed with bone wax. When the subjects were located outside the chamber, infrasound was presented to one ear through a hollow earbar that was sealed in the external auditory meatus and connected to the dynamic pressure chamber with plastic tubing. Responses from 5 guinea pigs and 4 monkeys were examined.

Consistent, repeatable eye movements of the types that are ordinarily associated with vestibular stimulation (nystagmus and counterrolling) were <u>not</u> observed in response to infrasound. Two of the guinea pigs exhibited a few nystagmus beats during stimulation, but these observations were not repeatable. One of these animals also exhibited a very small oscillatory eye movement that was apparently in phase with the stimulus, but the response was too small to record with electrophysiological techniques. None of the monkeys demonstrated any evidence of vestibular-induced eye movements.

The failure to observe physiological vestibular responses to infrasound from guinea pigs was surprising in view of an earlier study (ref 28) in which we demonstrated nystagmus to pressure oscillations of about 166-dB SPL. In the earlier study, however, the pressure oscillation was generated by an animal respirator; the oscillations were between ambient pressure (0-cm Hg) and +3.8-cm Hg rather than being symmetrical around ambient pressure, as is the case with infrasound. Consequently, the response may have resulted from the static pressure component of the stimulus.

In studies with human beings, visual nystagmus and postural equilibrium were employed as measures of vestibular activation by infrasound stimulation. Visual nystagmus was monitored with recording electrodes, and postural equilibrium was determined with a rail task (ref 13). Infrasound was coupled from the dynamic pressure chamber via a large diameter flexible hose to short secondary hoses at the earmuff devices that enclosed the ears. Adjustment of the length of the coupling hose and of the secondary hoses allowed presentation to one or both ears and of phase differences in the signals to the two ears.

Visual nystagmus was studied on volunteers who experienced infrasound monaurally, bilaterally in-phase, and bilaterally 180° out-of-phase at levels of 142-dB to 155-dB. The results may be summarized by the statement that visual nystagmus was not observed for any of the conditions investigated.*

Postural equilibrium, as indicated by ability to stand on narrow rails, was evaluated for infrasound exposures at levels ranging from 110- to 140-dB. Exposure conditions were the same as those employed in the study on visual nystagmus. Statistical analysis of the data obtained in this experiment revealed no effects of infrasound on postural equilibrium for the conditions evaluated. While infrasound stimulation failed to elicit vestibular responses, audiofrequency stimulation employing the same methodology yielded clear vestibular effects beginning at exposure levels of 105 dB (ref 19).

In a recent nonsystematic observation, two investigators exposed themselves to infrasound at intensities up to 172-dB and frequencies of 2- to 8-Hz for periods up to 25 sec. The

*C. S. Harris, personal communication, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, August, 1972.

investigators were unable to detect disorientation or nystagmus at these exposure levels.*

The results of these investigations correlate with those of Alford et al (ref 4), who reported that only 1 of 21 observers exhibited transient, mild vertigo during exposure to 140-dB infrasound at 12-Hz. In contrast to the results from the Wright-Patterson investigators and those described by Alford et al, Evans (ref 10) and Evans and Tempest (ref 11) have reported that infrasound at 7-Hz applied for approximately 1-min can elicit nystagmus at intensities as low as 125-dB. Reconciliation of the discrepant observations concerning the effects of infrasound on the vestibular system is difficult without more complete information than we have available; however, the Evans and Tempest reports leave open two areas for examination. First, it is possible that the nystagmus was produced by audiofrequency sound that was a distortion product of the infrasound signal. Several observations place the threshold for nystagmus response to audiofrequency sound in the 130-dB range. Second, in the absence of adequate controls, including "blind" evaluation of the data, the evaluator's prior information may intrude excessively on his evaluation of the ambiguous nystagmus records.

SUSTAINED AUDIOFREQUENCY SOUND

The experiments presented in this section are essentially replications of the basic observations from other investigators (see Section I, p. 4). Our variations on the theme include the use of different species, extension of the stimulus range, and examination with the perilymph pressure recording technique.

Biomechanical Responses

The action of the guinea pig ossicular chain was observed

*D. L. Johnson, personal communication, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, May, 1973.

under stroboscopic illumination during intense audiofrequency sound stimulation. This technique allowed us to determine the displacement of the stapes at various points within the stimulus sinusoid. Figure 13 indicates magnitude of stapes displacement (ordinate) as a function of the phase angle between the stroboscope flash and the stimulus sinusoid (abscissa) for three intensity levels. At the lowest stimulus intensity, the motion of the stapes was approximately symmetrical around its resting position (zero on the ordinate). At higher stimulus intensities, the motion of the stapes was increasingly asymmetrical: the stapes moved farther in the lateral direction than in the medial direction. Examination of the output of a condenser microphone or pressure transducer probe located in the external auditory meatus indicated that the response asymmetry was not a function of stimulus asymmetry. These observations, which were obtained by Reschke (ref 30), confirm the reports of Guinan and Peake (ref 14) and Kobrak (ref 23).

The magnitude of stapes nonlinear displacement as a function of stimulus intensity can be calculated from the curves presented in Fig. 13. Each of the three points illustrated in Fig. 14 was derived from one of the curves of Fig. 13 and represents the area under a particular curve indicating lateral displacement divided by the total area enclosed by the curve. If the curves of Fig. 13 were perfectly symmetrical, this calculation would yield a value of 0.5; on the other hand, if all of the stapes motion were lateral to its normal resting position, the calculation would yield a value of 1.0. Admittedly, interpretation of a function based on three points is tenuous; nevertheless, Fig. 14 suggests that the magnitude of lateral shift of stapes average position is a logarithmic function of stimulus intensity. Further, extrapolation suggests that the onset of stapes nonlinearity occurs at approximately 134-dB SPL and that stapes oscillation completely lateral to the normal resting position would be evoked by stimulus intensities of about 160-dB SPL.

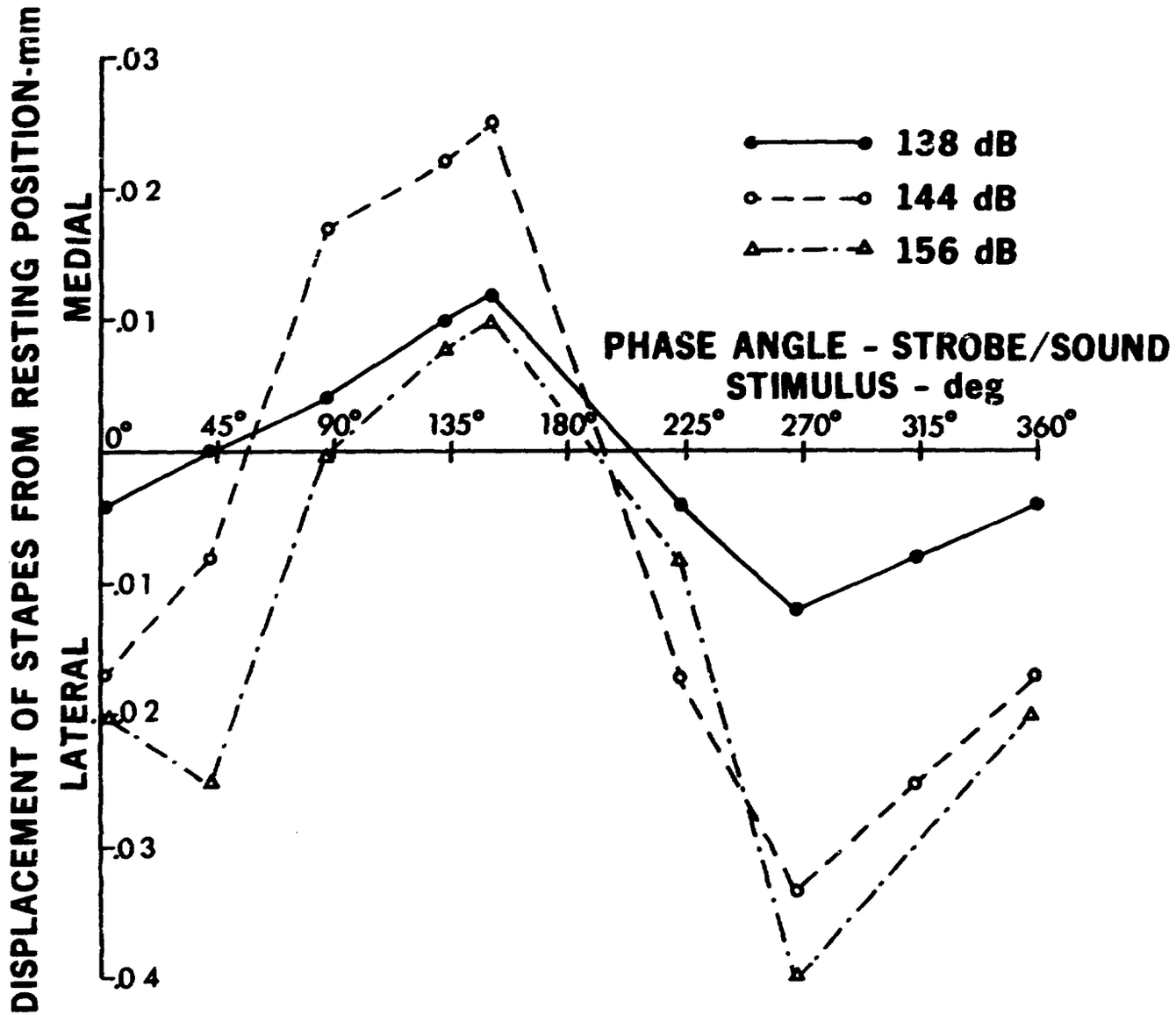


Figure 13. Displacement of stapes as a function of phase of sinusoidal acoustical stimulus at three intensities (from Parker and Reschke, ref 26).

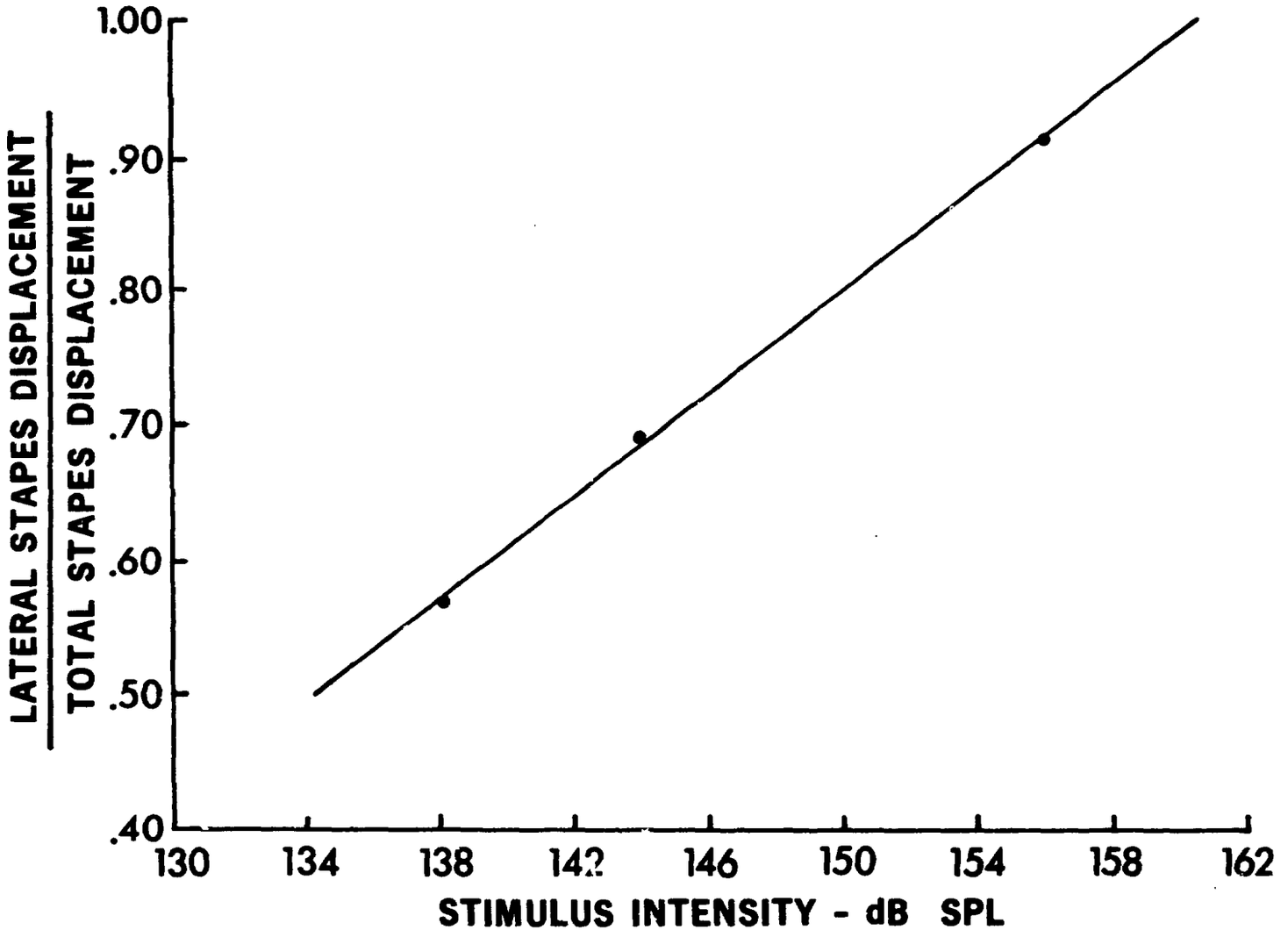


Figure 14. Stapes nonlinear displacement as a function of stimulus intensity. See text (from Parker and Reschke, ref 26).

Perilymph pressure change responses to intense audiofrequency sound have been recorded with the techniques previously described from anesthetized guinea pigs and monkeys. Audiofrequency sound usually elicits a perilymph pressure drop which is similar to the drop evoked by transient pressure decreases at the tympanic membrane (see Figs. 6 and 7). Peak perilymph pressure drops evoked by stimuli of 139- to 163-dB SPL at 800-Hz from a guinea pig and a monkey are illustrated in Fig. 15. The curves form power functions that have exponents of 1.65 for the guinea pig and 1.1 for the monkey. In other words, a 20-dB increase in stimulus intensity elicits a 33-dB perilymph pressure change from the guinea pig and a 22-dB perilymph pressure change from the monkey. Also, the magnitude of the guinea pig's perilymph pressure response is greater than the magnitude of the monkey's response for a given stimulus intensity level. Although responses vary across stimulus frequencies and among ears within a species, the magnitude and slope of the guinea pig's perilymph pressure responses were invariably greater than the monkey's responses. Observations of perilymph pressure drops are consistent with the ossicular chain data described in Figs. 13 and 14.

Perilymph pressure changes as a function of stimulus frequency variation are illustrated in Fig. 16. The upper trace of the oscillograph record illustrates perilymph pressure changes, with upward pen deflections indicating pressure decreases, and the lower trace shows one side of the sound stimulus envelope. The middle trace indicates time in 1-sec intervals; the marker on the time line indicates the points at which the frequency sweep reached particular values. Stimulus intensity varied irregularly from 159-dB to 168-dB SPL as a function of frequency. Large perilymph pressure drops are associated with stimulus frequencies in the 200- to 300-Hz, 500- to 600-Hz, and 800- to 900-Hz frequency ranges. Stimulation at 1000-Hz elicited a small perilymph pressure increment. The oscillation of the perilymph pressure trace in the 150- to 300-Hz range is an artifact. The

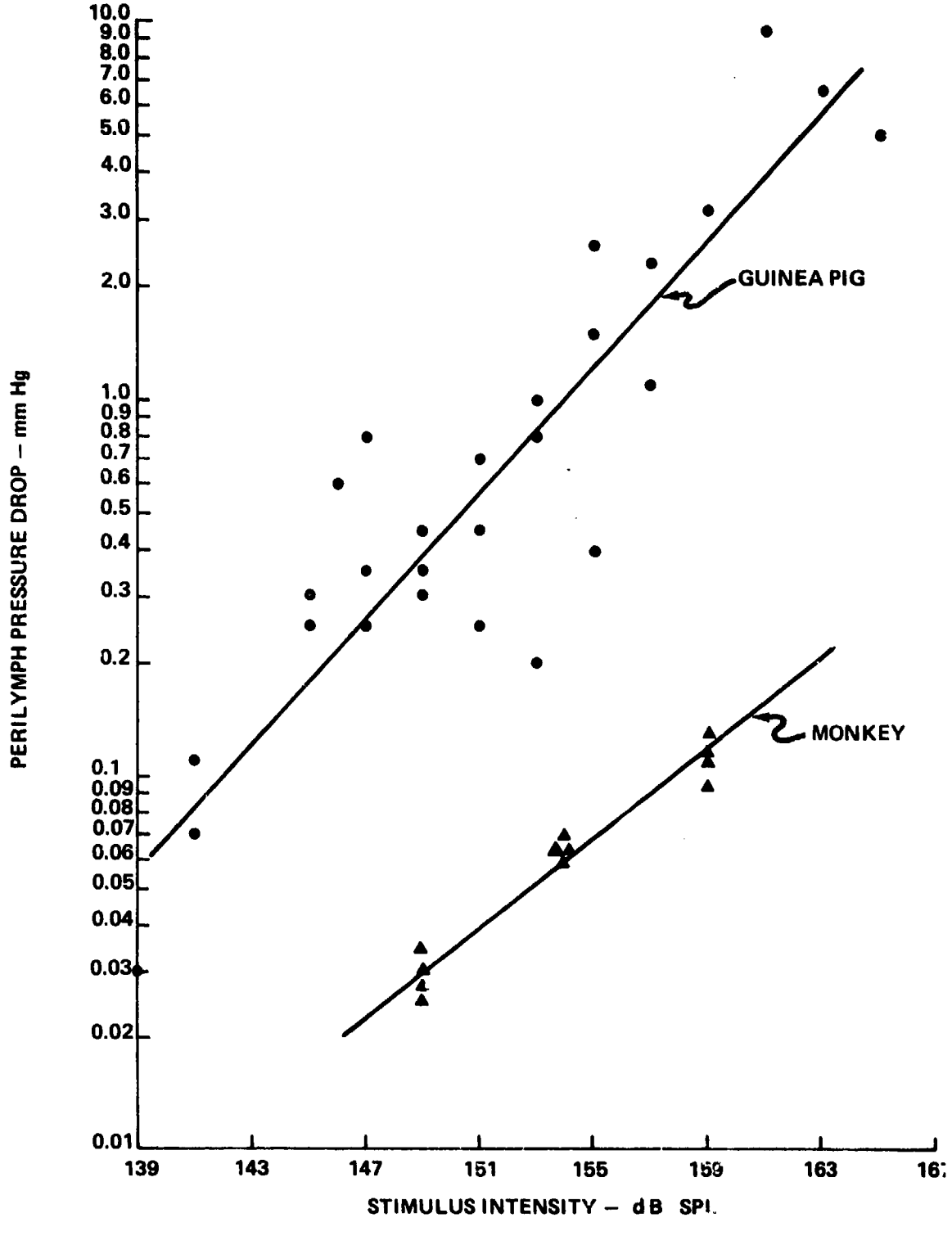


Figure 15. Perilymph pressure drop as a function of intensity of 800-Hz stimulus.

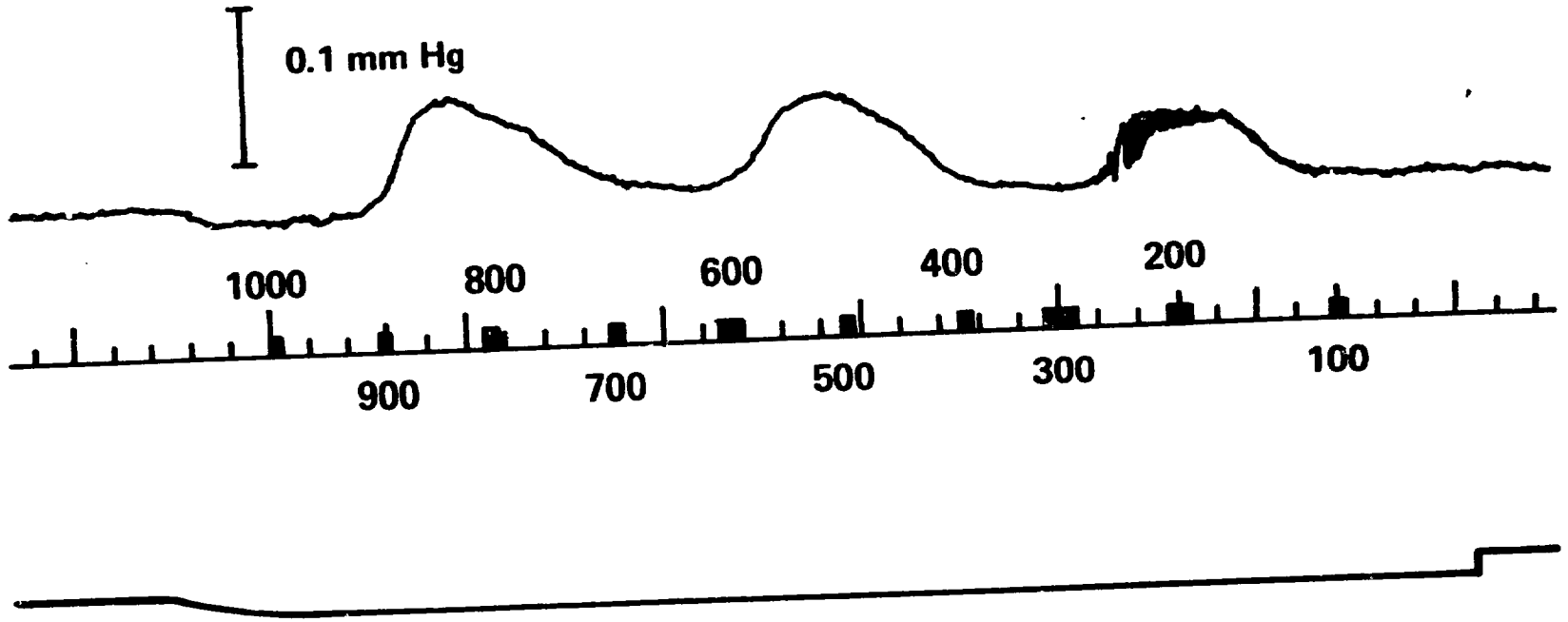


Figure 16. Perilymph pressure changes (top trace) as a function of stimulus frequency (indicated on time marker). See text.

location of the peak perilymph pressure changes varied to a small degree as a function of the direction of the frequency sweep. Examination of pressure changes in the tube connecting the speaker to the monkey's ear as well as observation of the output of a condenser microphone probe located in the hollow earbar indicated that the perilymph pressure changes illustrated in Fig. 16 were not a function of nonlinearities in the acoustical stimulation system. The oscillograph trace presented in Fig. 16 is interesting because it suggests that considerable variation in vestibular sensitivity to acoustical stimulation as a function of frequency should be observable.

Physiological Responses

Eye movement responses to audiofrequency sound in the 500- to 2000-Hz frequency range have been examined in guinea pigs by Reschke (ref 30). Intensity thresholds for eliciting nystagmus from unanesthetized guinea pigs vary as a function of stimulus frequency and duration. Stimulus durations of greater than 4-sec do not modify the intensity-frequency thresholds. Minimum threshold values that have been observed are as follows: 142-dB SPL at 500-Hz; 152-dB SPL at 600-Hz; 169-dB SPL at 700-, 800-, and 1000-Hz; 160-dB SPL at 2000-Hz; and 162-dB SPL for broad band noise. These observations are consistent with the perilymph pressure observations insofar as the 500-Hz stimuli are concerned. Unfortunately, Reschke was unable to perform eye movement threshold measures at 200-Hz and failed to do so for 900-Hz; therefore, we cannot confidently state that perilymph pressure changes are directly related to eye movement thresholds in an awake animal.

High intensity, audiofrequency sound stimulation elicited clear eye movements from monkeys. Ordinarily, these eye movements took the form of rotatory nystagmus, i.e., the eye rotated around the corneal-retinal axis exhibiting a slow turning in one direction followed by a quick jerk in the opposite direction.

At higher intensity levels, horizontal and vertical nystagmus were also elicited.

Threshold stimulus intensity for eye movements at particular frequencies varied across animals; the maximum difference noted for a particular frequency was 20-dB. Sensitive monkeys (those with low eye movement thresholds) exhibited only rotatory eye movements at threshold stimulus levels. Relatively insensitive monkeys (those with high eye movement thresholds) demonstrated rotatory, horizontal, or vertical nystagmus at nearly the same intensity levels. For some of the insensitive monkeys, rotatory nystagmus was not seen. Post-mortem examination of ears from two of the relatively insensitive monkeys failed to reveal any gross signs of middle ear abnormality or infection.

Thresholds for eye movements also varied as a function of "arousal" across trials within a particular animal. After a period of 45- to 60-min in the restraining chair, the monkeys appeared to become sleepy and withdrawn, and the eye movement threshold increased. The original threshold for responding could usually be restored if the experimenter tickled the monkeys or "made faces" at them just prior to stimulus presentation. In spite of our best efforts, the monkeys habituated to attempts to keep them alert, and experiments were terminated after a period not exceeding 2 hours. The average intensity-frequency eye movement threshold function for continuous sound, which was calculated across 19 monkey ears, is included in Fig. 17.

REPETITIVE AUDIOFREQUENCY TRANSIENTS

Following the reports by Evans and Tempest (refs 10 and 11) of nystagmus evoked by infrasound, we undertook a series of studies to examine this response employing guinea pigs, monkeys, and human beings. Repeated attempts to replicate the Evans and Tempest observations with any of these three species have been unsuccessful. The failure to replicate infrasound-evoked

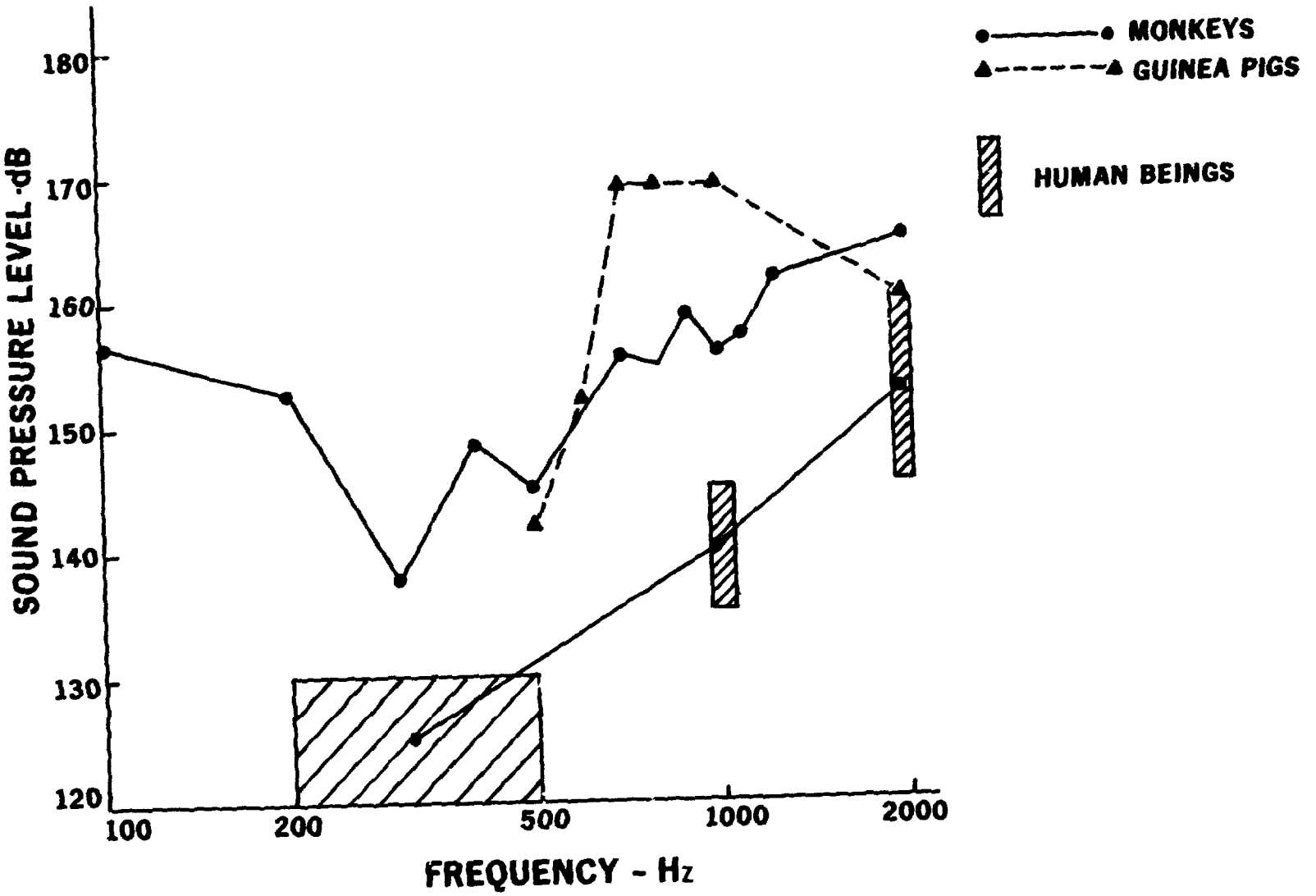


Figure 17. Thresholds for evoking rotatory nystagmus from monkeys. For comparison observations on guinea pigs (ref 30) and human beings (refs 2, 3, and 5) are included. In the case of the human observers, responses in addition to nystagmus were used.

nystagmus observations led us to the suggestion that Evans and Tempest may not have been investigating responses to pure tone infrasound; rather, they may actually have used an infrasound-modulated audiofrequency sound, and their results might be replicable using intermittent sound.

Observations with Guinea Pigs

Useful data were obtained from 13 young (300- to 350-grams), female guinea pigs.

The guinea pigs were restrained by taping their legs and wrapping them in newspaper. The animals were shaved around the ears and eyes to aid in the placement of earbars and electrodes. The skin at the base of the pinnae was injected with a local anesthetic (0.25-cc of lidocaine hydrochloride). After allowing a few minutes for the anesthesia to develop, the base of the pinnae was cut to facilitate earbar placement.

The animals were then placed in a modified stereotaxic instrument and held with hollow earbars, a nose bar, and tape. The animals were tested with static, positive pressure generated from a 1-cc syringe and transmitted through an earbar to determine if a proper seal had been made in the external auditory meatus. Counterrolling of the eye occurred if the earbar had been correctly placed (see ref 28). Subdermal electrodes, which were used to record eye movements, were placed above and below the eye ipsilateral to the ear that was stimulated.

Five stimulus dimensions (intensity, frequency, duration, onset/offset time, and repetition rate) were studied using the guinea pigs. Intensity was varied in 2-dB steps at 700-, 800-, 900-, 1000-, and 1100-Hz. Durations ranged from 10- to 300-msec and onset/offset times were 5-, 10-, 25-, 50-, and 100-msec. Repetition rates ranged from 2/sec to 50/sec. Each stimulus dimension was examined individually as the independent variable

with the other dimensions held constant. The order of presentation of particular stimulus values within a dimension was randomized.

The amplitude of the eye movement response, measured in millivolts, was the dependent variable. In a series of responses, the first two responses were ignored, in order to reduce transient effects, and the next eight responses were evaluated, when the amplitudes were calculated by the experimenter. In those cases when the computer was used to determine the average response, the first two responses were included in the calculation, and the number of responses used ranged from 5 to 25.

Intense, intermittent sound elicited large vertical eye movements from 13 guinea pigs. The magnitude of movement ranged up to 5-mm and was easily recorded with vertically placed subdural electrodes. Fig. 18 illustrates electrophysiologically recorded eye movements. In 18-A and 18-B the stimulus marker is on the top trace, time in seconds is indicated on the middle trace, and the bottom trace represents the eye movements. Unidirectional dorsal eye movements produced the record illustrated in 18-A. The electrical change illustrated in 18-B is bidirectional. Whether the eye movement that was associated with this record was also bidirectional could not be determined optically, and the initial electrophysiological change may have been the result of muscle potentials rather than eye movements.

Computer-generated averages of 14 and 10 responses to tone bursts are illustrated in Figs. 18-C and 18-D, respectively. In the case of Fig. 18-C the eye appeared to move unidirectionally and dorsally. The onset of this dorsal eye movement had a latency of about 79-msec. In the record of Fig. 18-D the trace is bidirectional; the downward trace deflection (indicating dorsal eye movement) had a latency of about 62-msec and the

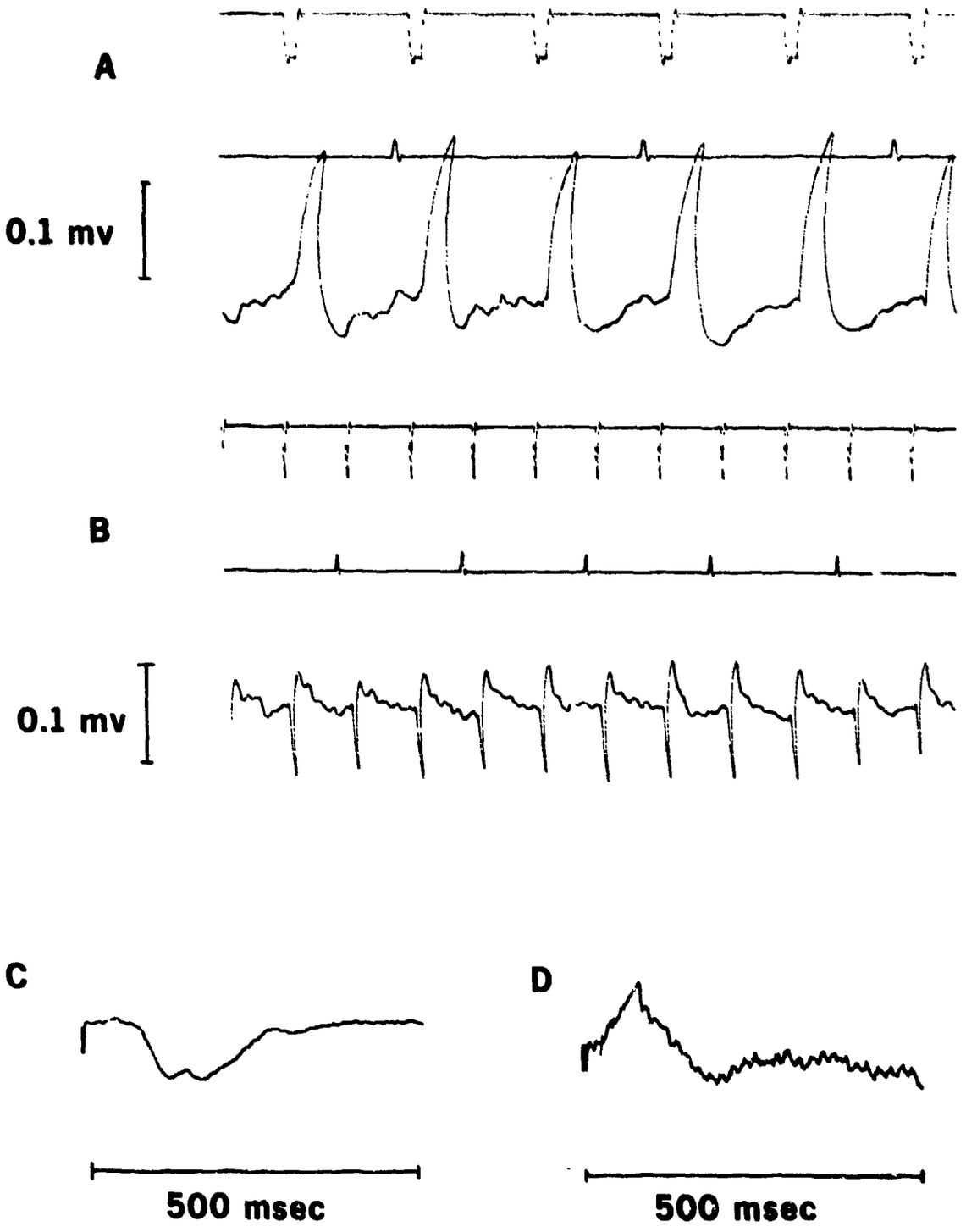


Figure 18. Eye movements evoked from guinea pigs by repetitive audiofrequency transients. See text.

upward portion of the trace deflection had a latency of about 20-msec. The form of response illustrated in Fig. 18-D was seen in approximately one-third of the computer averaged records. Eye movement latencies recorded from one animal averaged 64-msec (standard error of the mean = 4.7-msec); in those cases where the early component was recorded, the latencies averaged 23-msec (standard error of the mean = 2.0-msec). The stimuli that elicited these responses had a frequency of 800-Hz, onset/offset time of 5-msec, and varied in duration between 10- and 300-msec.

Response amplitude was an increasing monotonic function of stimulus intensity, as illustrated in Fig. 19. The filled circles indicate the response evoked by a 1000-Hz stimulus, and the open circles indicate responses evoked by a 500-Hz. Each point represents the average of 8 responses. The 1000-Hz response appears to saturate around 150-dB. The lines of best fit were determined by eye, and power functions were calculated from the lines following the equation $R = k\ S^n$, where R is response magnitude, S is stimulus intensity, k is a constant, and n is an exponent. The nonasymptotic portion of the 1000-Hz plot yielded a power function that has an exponent of 0.91 and the 500-Hz plot had an exponent of 1.27.

Response duration was an increasing monotonic function of stimulus duration up to 300-msec, which was the maximum stimulus duration examined in this study. Minimum response duration was about 50-msec. The response amplitude reached an asymptotic value for stimulus durations of 100- to 300-msec in several animals

The effects of varying onset/offset time were examined in nine animals. Onset/offset times of 5-, 10-, 25-, 50-, and 100-msec at durations of 15-, 20-, 30-, 50-, 100-, 200-, and 300-msec were employed. The repetition rate was held constant at 2/sec. The curves of response amplitude as a function of onset/offset time for the various durations revealed an inverse

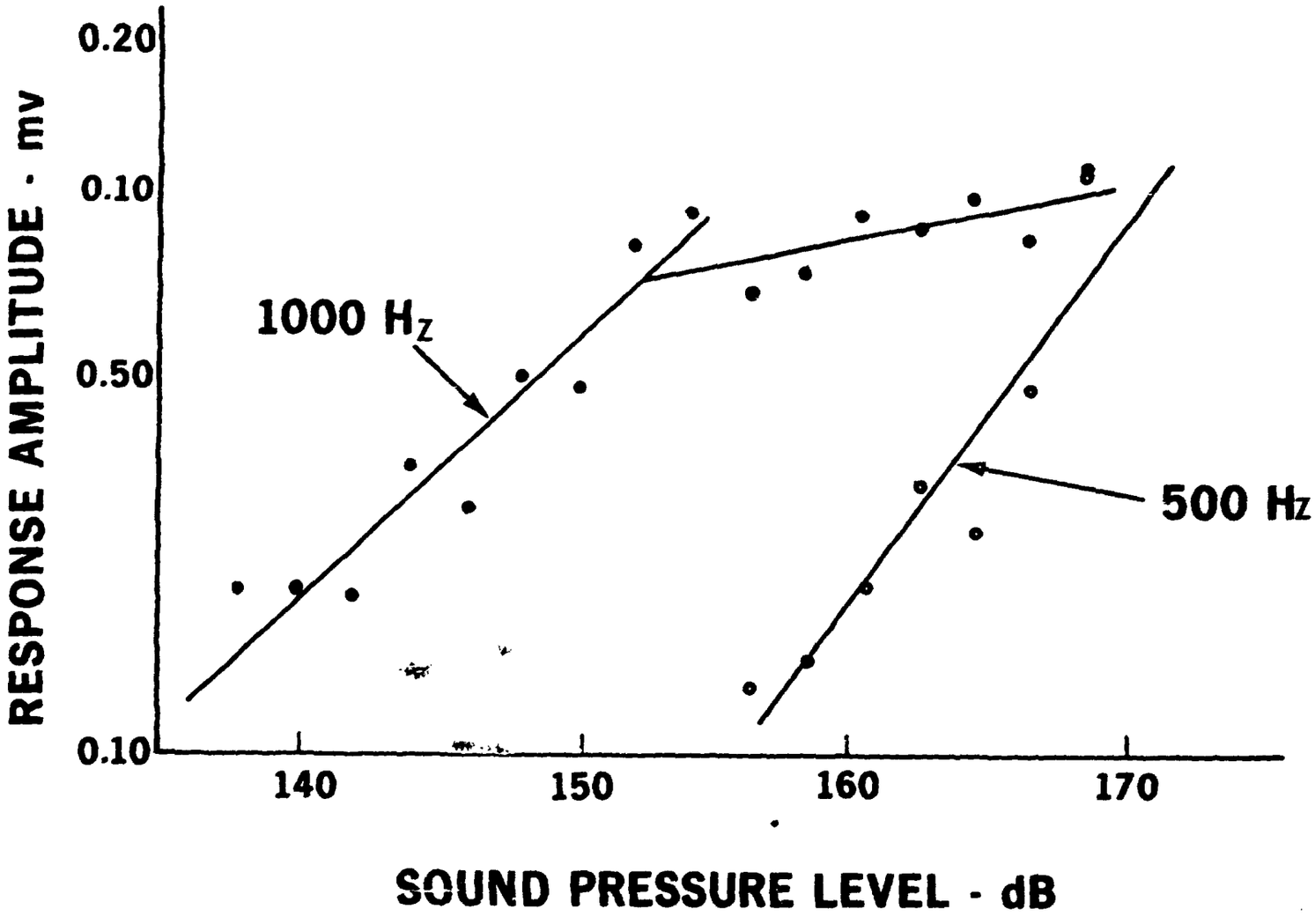


Figure 19. Average response amplitude of guinea pig eye movements evoked by tone bursts of 500- and 1000-Hz.

relationship between onset/offset time and response amplitude. Analysis of all possible pairs of onset/offset times within durations, within animals using a binomial test indicated that this relationship is statistically significant beyond the 0.001 probability level. The data from which the curves were derived are quite irregular; beyond the relationship between response amplitude and onset/offset time the curves yielded little information.

Complete data concerning the effects of varying stimulus repetition rate on eye movement amplitude were obtained from six ears. The curves from six animals of average response amplitude as a function of repetition rate are illustrated in Fig. 20. Each separate curve represents a different stimulus duration (the maximum stimulus duration was limited by the repetition rate). The standard error of the mean varied from 0.0006- to 0.010-mv for the points presented in Fig. 20. Generally, larger eye movements were produced by lower stimulus repetition rates.

Departures from the low repetition rate-large eye movement trend can be seen in the curves between the repetition rates of 10/sec and 5/sec. In 15 of 30 possible comparisons, 10/sec elicited larger eye movements than 5/sec; for 95 other possible comparisons in only 16 cases did the higher repetition rate elicit a larger response than the lower repetition. Employing a binomial expansion, the probability that the direction of eye movement magnitude changes for the 10/sec to 5/sec comparisons was drawn from the same population as for the other comparisons (50/sec to 33/sec, 33/sec to 20/sec, 20/sec to 10/sec, and 5/sec to 2/sec) is less than 0.02. In other words, stimuli at 10/sec elicit larger responses with respect to stimuli at 5/sec than would be expected on the basis of examination of the responses to the other repetition rates.

Observations with Monkeys

Useful observations were obtained from seven Rhesus monkeys.

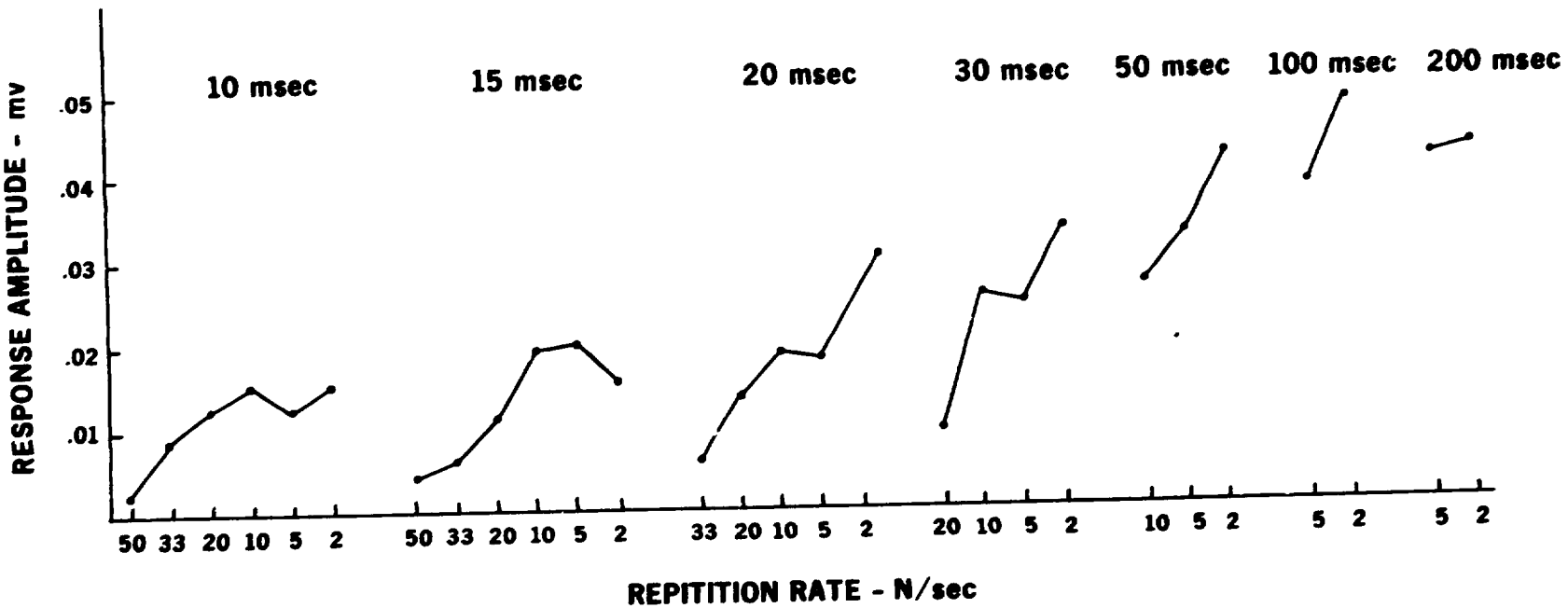


Figure 20. Average response amplitude of guinea pig eye movements evoked by repetitive acoustical transients at repetition rates varying from 50/sec to 2/sec.

Thresholds for rotatory nystagmus were determined by direct observation through an operating microscope during stimulation at frequencies ranging from 100- to 2000-Hz. The sound levels employed to study the effects of interruption were ordinarily set about 5-dB below the levels of sound that would elicit nystagmus when the stimulus was presented continuously.

During previous experiments we had noted that the monkey's responsiveness changed markedly over time. These responsiveness changes were apparently associated with several factors, including damage and degree of arousal. We were able to check possible gross damage by examining the external meatus and the tympanic membrane with the otoscope. We attempted to maintain arousal by tickling the monkeys, shaking their limbs, and "making faces" at them.

For the studies on the effects of intermittent sound, the stimulus intensities were set at a level that elicited clearly detectable eye movements. The observer's task was to observe the monkey's eye movement through the operating microscope and to estimate the magnitude of movement. The intensity levels that yielded clear eye movements varied across frequency. Because of these intensity differences, response variation as a function of frequency was confounded and therefore was not investigated systematically.

The initial repetitive sound observations were concerned with determination of the effects of variation in stimulus duration. Durations between 50- and 120-msec were used. During these initial observations it became apparent that the response changes produced by changes in the parameters of interrupted sound stimulation that we were employing were small and variable. In an attempt to obtain useful data, paired comparisons procedures were employed in the subsequent monkey experiments.

Two types of paired comparisons studies were performed with the monkeys. In the first type of paired comparisons study, three onset/offset times (10-, 25-, and 50-msec) were examined. Each onset/offset time was paired with the other two onset/offset times, and order was counterbalanced. The sequence of presentation of the six possible pairs was randomized. The onset/offset time paired comparisons were studied at three frequencies (300-, 1000-, and 3000-Hz) and three repetition rates (2/sec, 5/sec, and 10/sec). Only onset/offset time was varied within a pair of stimulus presentations. In the second type of paired comparisons study, three levels of repetition rate were systematically paired at each of the three frequencies and three onset/offset times.

Responses to the various stimuli were determined by direct observation through the operating microscope. Ordinarily a particular stimulus constellation (frequency, intensity, onset/offset time, duration, and repetition rate) was presented for a period of 5- to 10-sec. The observer's task was to state which of the pair of stimuli elicited a larger eye movement response.

Repetitive acoustical transients (trains of tone bursts) elicited brief, transient eye displacements (jerks) at the frequency of repetition. Under direct microscopic observation, these jerks appeared very quick (less than 0.1-sec duration) and the eye appeared to return to the original resting position between tone bursts. These eye jerks elicited by intermittent sound could be observed at stimulus intensity levels only slightly below (2- to 5-dB) those at which continuous sound would elicit nystagmus.

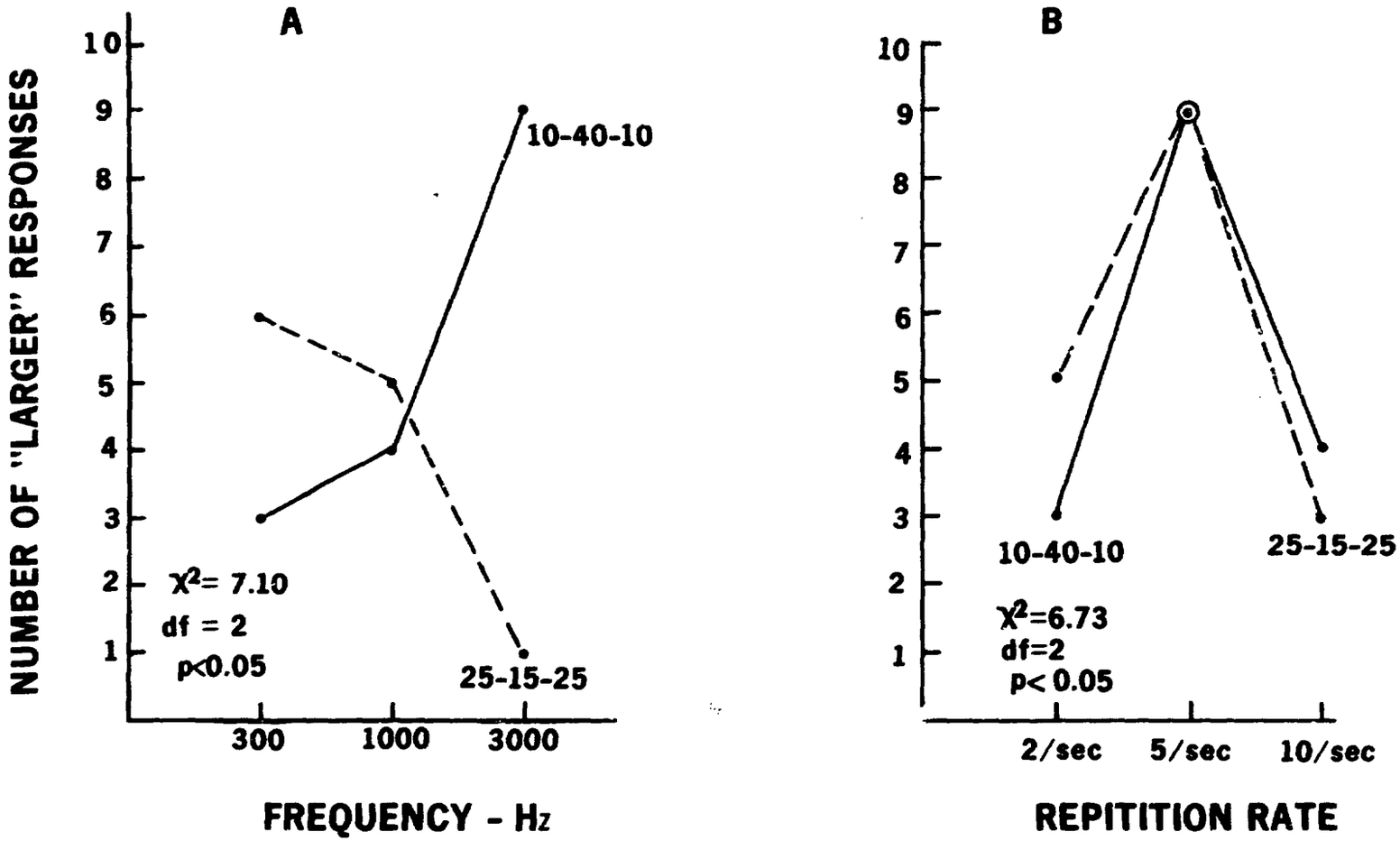
Response differences as a function of the intermittent sound stimulus characteristics were observed in 10 ears from 6 monkeys. The following characteristics of the tone bursts were varied: frequency (300- to 3000-Hz), intensity (120- to 172-dB),

duration (50- to 200-msec), repetition rate (1/sec to 10/sec), and onset/offset time (5- to 50-msec).

Effects of varying stimulus duration were observed in two ears. The results indicate that variation of the stimulus duration between 50- and 120-msec did not produce notable differences in eye movement amplitude. For longer stimulus durations, some decrement in response amplitude was observed.

Paired comparisons observations were performed varying stimulus onset/offset time and repetition rate. Complete paired comparisons observations of onset/offset time were obtained from two ears. Overall (collapsed across frequency and repetition rate) none of the onset times produced a larger response than the other two onset times at a statistically significant level. However, in one subset of data a clear interaction between stimulus frequency and onset/offset time was revealed. As illustrated in Fig. 21-A, the number of observations for which a particular onset'offset time produced a "larger" response varied as a function of frequency (collapsed across repetition rates). At the high frequency the short onset time tended tc produce a larger response, whereas at the low frequency the longer onset time seemed to be more potent. Differences between the two onset/offset curves as a function of stimulus frequency are significant beyond the 0.05 level ($\underline{X}^2 = 7.10$, $\underline{p} < 0.05$ with 2 $\underline{df}$).

Complete paired comparisons data on the effects of variation in repetition rate were obtained for two ears. One of these ears yielded the data illustrated in Fig. 21-B. The two curves represent the number of "larger" responses elicited by different repetition rates for two stimulus onset/offset times. The data were collapsed across frequency (300-, 1000-, and 2000-Hz) to yield these curves. $\underline{X}^2$ analysis indicates that the 5/sec repetition rate elicited a "larger" response more frequently than repetition rates of 2/sec and 10/sec (collapsed across


A
B
NUMBER OF "LARGER" RESPONSES
10
9
8
7
6
5
4
3
2
1
10-40-10
25-15-25
χ²= 7.10
df = 2
p<0.05
300
1000
3000
FREQUENCY - Hz
χ²=6.73
df=2
p< 0.05
2/sec
5/sec
10/sec
REPITITION RATE

frequency and onset/offset time; $\underline{X}^2 = 6.73$, $\underline{p} < 0.05$ with 2 $\underline{df}$). The interactions of repetition rate by frequency and repetition rate by onset/offset times did not approach statistical significance. Data from the second ear that yielded a complete paired comparisons study of repetition rate did not show a statistically significant trend in favor of the 5/sec repetition rate.

Observations with Human Beings

The effects of intermittent and continuous 1000-Hz tones on human equilibrium was examined by Harris (ref 18). Harris demonstrated that sound monaurally presented at intensities as low as 95-dB produced statistically significant decrements in the ability of a subject to maintain equilibrium in a rail test. Harris' results suggested that intermittent sound might provide a more effective stimulus for the vestibular system than continuous sound.

Reschke, Homick, Landreth, and Parker (ref 31) recently reported the results of an experiment on transient visual field shifts evoked by acoustical stimulation in man. Among the findings reported by Reschke et al, are the following: (1) Rapid onset tone bursts (less than 50-msec rise time) evoke transient lateral shifts of the visual field. (2) Slow onset tone bursts (greater than 50-msec rise time) evoke tilting or rotation of the visual field which subjectively appears to have a greater latency than the lateral visual field shifts. (3) Maximum response sensitivity was observed in the 800- to 900-Hz frequency range. (4) The appearance of visual field shifts in response to sound was correlated with the middle ear muscle reflex.

Recently we undertook a second series of studies concerning the apparent visual field shift evoked by repetitive acoustical transients in human beings. These studies employed the

psychophysical techniques of magnitude estimation and paired comparisons: the observer's task was to indicate the apparent magnitude of displacement of an object in the visual field following exposure to train of identical acoustical transients (magnitude estimation) or to indicate which of two trains of transients, which were similar with the exception of one dimension, evoked greater apparent movement (paired comparisons).

These apparent visual field shift studies are incomplete. However, the trends of the initial observations are as follows. First, sound stimulation at the 120- to 125-dB level produces apparent displacement of the visual field in about 50% of the individuals examined. Characteristics of the apparent motion vary across observers and within observers across time. Second, slow repetition rates tend to produce greater apparent motion than rapid repetition rates. There is a slight suggestion of a resonance at repetition rates of 1/sec to 1.3/sec; however, the apparent motion produced by stimuli in the 1/sec repetition rate range is greater than the apparent motion produced by stimuli in the 3/sec to 5/sec repetition rate range. Third, the stimulus frequencies that elicit the largest apparent displacement responses vary across individuals. In general, stimuli of 500- and 800-Hz evoke a greater response than do stimuli of 100-, 300-, and 1000-Hz. Fourth, the observations for stimulus durations of 50- to 500-msec yield no clear trend.

INTERACTION BETWEEN ACOUSTICAL VESTIBULAR STIMULATION AND OTHER TYPES OF VESTIBULAR STIMULATION

Observations have been performed concerning the interaction between sound and three other forms of vestibular stimulation (angular acceleration, caloric stimulation, and alcohol injection) employing guinea pigs and monkeys.

Acoustical Vestibular Stimulation and Angular Acceleration

The effects of angular acceleration on the latency of eye

movements evoked by pressure transients were investigated employing three guinea pigs. Angular displacement was around the animal's longitudinal body axis (Z-axis) with the animal in the prone position and had a magnitude of 90 degrees. The angular displacement approximated a ramp function; the major stimulus parameter varied was rotation duration (5- to 10-sec). Acoustical stimulation (a pressure square wave slightly greater than the minimum necessary to elicit nystagmus) was presented at the termination of the angular displacement or during angular displacement.

The latency of the eye movements evoked by the static pressure stimulus was determined by direct observation through an operating microscope and with the aid of an oscillograph. Latencies were determined across a series of stimulations when the pressure stimuli were combined with angular acceleration (experimental condition) and when the animal had been stationary for at least 1-min (control condition). The sequence of conditions was counterbalanced and the results were analyzed with a paired "t" test.

As has been described previously (ref 28), static pressure evokes a complex eye movement from the guinea pig. This eye movement consists of a counterrolling component and a nystagmus component. For one animal angular displacement of the head toward the pressure stimulated ear produced a significant decrease in the latency of the nystagmus response to the static pressure ($t = 4.994$, $df = 29$, $p < 0.001$). Similar results were obtained in a second experiment with another animal. Because the position of the statolith organs with respect to gravity changes during horizontal axis rotation, the results obtained in these experiments cannot be attributed to semicircular canal action with confidence. This difficulty was overcome by subjecting the animal to rotation around the Z-axis with the Z-axis oriented vertically. These observations have not been completed.

Acoustical Vestibular Stimulation and Caloric Irrigation

The effects of caloric stimulation on the latency of eye movements evoked by pressure transients was investigated employing 10 guinea pigs. Water caloric stimuli were presented through a tube which terminated near the tympanic membrane. Hot calorics were 48-deg C; cold calorics were 25-deg C. The apparatus was set to a flow rate of 0.2 cc per sec.

The guinea pigs appeared to be quite insensitive to caloric stimulation. Only rarely were eye movements evoked during the caloric stimulation; even in those instances we cannot be sure whether the responses were the result of the caloric character of the stimulus or some other characteristic such as the pressure produced by the water flow. Further, no evidence of response to caloric stimulation was seen when the animal was prone; only when the animal's Y-axis was in the vertical plane and the nose was elevated 30- to 45-deg was evidence of caloric stimulation of the vestibular system obtained.

Two types of experiments were performed. In the first type, hot or cold stimulation was presented to the top ear for 10- to 30-sec followed immediately by static pressure stimulation of the contralateral ear (successive stimulation). In the second type of experiment, caloric and static pressure stimulation were presented simultaneously. At least 1-min elapsed between presentation of the caloric stimuli. The static pressure was set to a level that was slightly greater than the threshold for eliciting eye movements. Latencies of counterrolling and nystagmus were recorded as in the experiment on interaction between angular acceleration and acoustical vestibular stimulation.

The pattern of eye movements evoked by static pressure following cold caloric irrigation differed from the pattern of eye movements following hot caloric irrigation. After

contralateral caloric stimulation, the ventral component of the pressure-evoked counterrolling was more pronounced when cold water was used than when hot water was used. Differences in latency of counterrolling following hot and cold caloric stimulation were small and not statistically significant. On the other hand, nystagmus differences were pronounced. For one animal, the nystagmus latency following cold caloric stimulation was larger than the latency following hot caloric irrigation ($\underline{t} = 1.73$, $\underline{df} = 19$, $\underline{p} < 0.05$). Essentially the same result was seen in two other animals.

The interaction between caloric stimulation and sound is currently being examined in monkeys. The results of the observations are incomplete.

Acoustical Vestibular Stimulation and Alcohol Injection

The effects of alcohol on eye movements evoked by sound were examined in 3 monkeys and 4 guinea pigs. The general procedure followed was to determine the animal's threshold and then to repeat threshold determinations following intravenous injection of normal saline solution (control condition) or ethanol (experimental condition). Alcohol doses ranged from 0.5- to 4-cc of 100% ethanol. Gas chromatograph analyses of blood samples indicated blood alcohol levels ranging from undetectable to 6.6%.

The influence of alcohol on the response evoked by acoustical vestibular stimulation differed for the guinea pigs and the monkeys. In the case of the guinea pigs, the latency of nystagmus evoked by a particular intensity of static pressure in the external auditory meatus was not affected by alcohol injection up to the point of death. On the other hand, the rotatory eye movements evoked by transient sound bursts were strongly affected by alcohol injection in the monkeys. Essentially, the monkeys appeared to "pass out." Initially,

sound evoked eye movements could be detected at approximately the original levels if strenuous efforts were made to arouse the monkey. However, with the passage of time (ranging from 5- to 30-min apparently depending on amount of alcohol injected) it became impossible to arouse the monkeys, and no eye movements related to the acoustical stimulation could be detected. The loss of sound evoked eye movements for one monkey is illustrated in Fig. 22.

The studies reviewed in this section support the view that sound activates the vestibular system by stimulating semicircular canal receptors. Further, it can be suggested that the combination of acoustical stimulation and acceleration should produce greater disturbance of human performance that requires accurate vestibular information than when either acceleration or sound are presented alone. This prediction should be examined employing human observers.

The results of the alcohol studies were somewhat surprising. On the basis of Schroeder's studies (refs 33 and 34) we had anticipated that alcohol injection would potentiate the response produced by acoustical stimulation. The reason for the failure to observe potentiation, particularly in the monkey, is unclear. The experiment probably should be repeated employing human observers before we embark on extensive speculation.

MISCELLANEOUS ADDITIONAL EXPERIMENTS

Before performing the observations reported in the preceding sections, we undertook a series of preliminary experiments that were concerned with the effects of pressure transients in the guinea pig. We wished to ascertain that the head and eye movement responses evoked by pressure transients were a result of vestibular endorgan stimulation.

Five preliminary experiments were performed. First, we

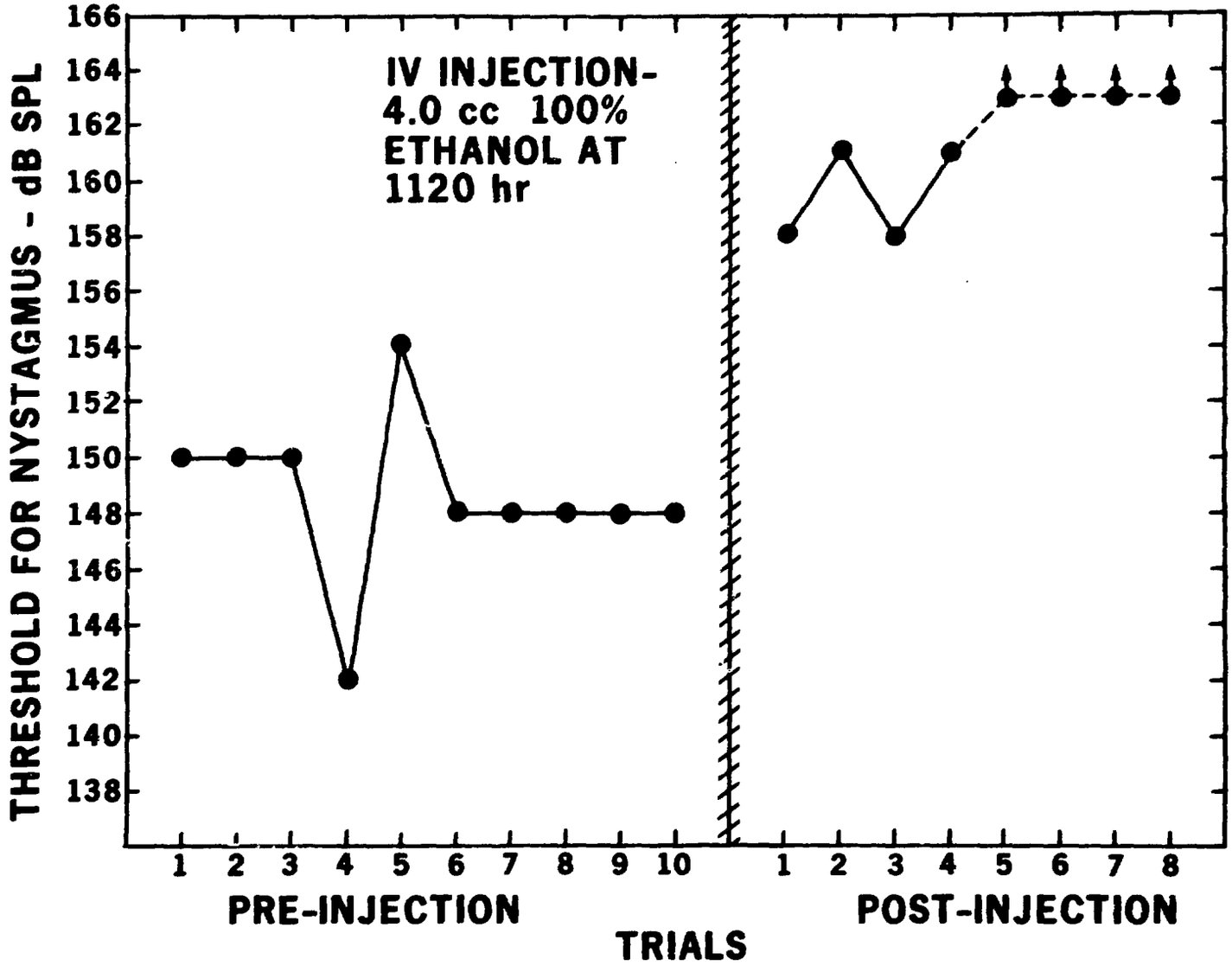


Figure 22. Effects of alcohol injection on the thresholds for sound-evoked nystagmus in the monkey.

sectioned the eighth cranial nerve unilaterally in six guinea pigs. No physiological vestibular responses could be obtained from the ears on the side of the lesion. These results indicate that the transient pressure stimulus affects receptors served by the eighth nerve. Second we subjected guinea pigs to streptomycin intoxication, which produces destruction of vestibular and cochlear sensory hair cells (ref 37). Little or no physiological vestibular response to pressure transients could be obtained from the streptomycin intoxicated animals. The implication of these results is that physiological vestibular responses to pressure transients are mediated by membranous labyrinth sensory hair cells.

The third preliminary experiment attempted to determine whether the cochlear or vestibular hair cells are responsible for the eye movement responses to pressure transients. Stimulation deafness was produced by high intensity, long duration noise exposure. This procedure destroys the cochlear sensory hair cells (ref 38). Nystagmus could be elicited from noise-deafened animals by pressure transient stimulation at approximately the same intensities as prior to noise exposure, indicating that the cochlear hair cells are not responsible for this response.

The fourth and fifth preliminary experiments sought to determine the vestibular receptor that mediates the eye movement responses to pressure transients. We removed the statolith mass from the statolith organs by centrifugation (see ref 25). Nystagmus was elicited at the usual levels of pressure transient stimulation; a subsequent experiment indicated that this procedure reduced the amplitude of head movement responses to pressure transients. Finally, we surgically blocked the semicircular canals (see ref 8). Following blockage of all three canals, eye movement responses to pressure transients were eliminated. Incomplete responses were observed in those instances where only one or two of the three canals was blocked. The results of this

experiment are difficult to interpret because of the high incidence of postoperative middle ear infection. The observations are consistent, however, with the hypothesis that pressure transients stimulate the semicircular canal receptors.

SECTION III

DISCUSSION

The results of the experiments described in the preceding section do not provide us with complete answers to our questions concerning the biomechanical and physiological mechanisms of acoustical vestibular stimulation. A major difficulty is the failure of the monkey to exhibit physiological vestibular responses to pressure transients (at the intensities that we employed), whereas monkeys demonstrate these responses to audiofrequency sound at approximately the same intensities as the guinea pig or human beings.

In the first part of this discussion we consider differences between guinea pig and monkey ears that may help us to understand the differences in responses that we have observed. The second part of the discussion focuses on possible mechanisms of acoustical vestibular stimulation and attempts to assess our current position.

ANATOMICAL DIFFERENCES BETWEEN GUINEA PIG AND MONKEY EARS

The ears of monkeys and guinea pigs are quite similar; however, there are a few anatomical differences between these species that may help to explain the response differences that we have observed. Three possibly important anatomical differences between the middle ears of these two species have been noted. First, the malleus and incus are fused in the adult guinea pig, whereas these two middle ear bones remain separate in the adult monkey. Second, the anterior process of the malleus is well developed in the guinea pig and severely limits medial displacement of the malleus manubrium. Our observations suggest that the guinea pig's malleus anterior process may provide a fulcrum for malleus rotation when the tympanic membrane is

strongly displaced; this may account for the bidirectional stapes displacement that we have noted when the guinea pig is exposed to increased pressure transients. The anterior process of the monkey's malleus does not appear to limit medial malleus displacement. Third, the angle between the manubrium of the malleus and the long process of the incus is approximately 15 degrees in the monkey and about 45 degrees in the guinea pig.

Information concerning differences in the labyrinths of guinea pigs and monkeys is not readily available. For example, we do not know the relative ease of fluid flow through the perilymphatic and endolymphatic ducts in these species; we do not know if there are differences in the relative stiffness of the various labyrinth membranes. Clearly, information concerning these points is required before we can confidently account for the response differences that we have observed.

MECHANISMS OF ACOUSTICAL VESTIBULAR STIMULATION

Development of a biomechanical/physiological model for vestibular stimulation by sound energy is one of the goals that has been pursued in our laboratory. Before proceeding to consideration of particular hypothetical mechanisms, we note three assumptions concerning the general nature of the system.

Assumptions

The following assumptions underlie our acoustical vestibular stimulation hypotheses. First, we assume that sound energy elicits vestibular responses as a result of its action upon vestibular endorgans. In other words, we do <u>not</u> believe that sound energy somehow bypasses the vestibular receptors and directly affects central nervous system nuclei. Visual, olfactory, and gustatory responses would be expected if sound directly affected the central nervous system, and this is not the case (with the possible exception of focused ultrasound). This assumption is supported by the preliminary experiments

that are summarized in Section II, p. 57. Second, we assume that sound energy elicits vestibular responses by displacing a component of the vestibular endorgans. This assumption is based on well-established observations of vestibular physiology which indicate that vestibular endorgans are activated by the shearing force produced when accessory structures are displaced with respect to the sensory hair cells (see Section I, p. 5). This assumption is also supported by the observation that vestibular responses evoked by particular sounds have the same form as those responses elicited by "adequate" vestibular stimulation (acceleration) and that essentially the same response can be observed across several stimulus replications. Third, we assume that vestibular endorgan components are displaced as a consequence of labyrinth fluid displacement. This assumption is based on the observation that the middle ear transduces sound energy into labyrinth fluid displacement, as noted in Section I, p. 5.

Alternative Hypotheses

As noted in the preceding section, we assume that sound activates vestibular receptors as a result of labyrinth fluid displacement. Alternative hypothetical mechanisms of acoustical vestibular stimulation reflect the possible types of fluid displacement in the labyrinth.

We distinguish between three main classes of sound-induced labyrinth fluid displacement: (1) ac volume displacement, (2) eddy currents, and (3) dc volume displacement. Sound stimulation at ordinary intensity levels results in stapes oscillation; the stapes oscillation produces oscillation of the endolymph and perilymph (ac volume displacement) which is compensated by ac displacement of the elastic round window membrane (see Section I, p. 5). Localized rotatory fluid motion--eddy currents--appear during high velocity fluid displacement. Deetjen (ref 9) and von Békésy (ref 5) have

described the appearance of eddy currents in the labyrinth during acoustical stimulation. Nonlinear stapes displacement during high intensity sound stimulation may result in dc volume displacement of labyrinth fluid.

High intensity sound can produce a dc labyrinth fluid volume displacement in the following manner. At appropriate intensities and frequencies of acoustical input, the stapes moves farther laterally during the rarefaction phase of the sound wave than it moves medially during the condensation phase (refs 23 and 14; Section II, p. 31). Consequently, the average position of the stapes during stimulation differs from its resting position, and fluid must flow through the labyrinth in order to fill the volume created by this shift in average stapes position. The elastic release points discussed in Section I, p. 5, are potential sources for the required fluid. One possible dc volume displacement pathway is from the round window around the cochlear heliocotrema to the oval window; fluid displacement along this pathway would result in inward deflection of the round window membrane until the membrane reached its elastic limit. Fluid might also be displaced from the cranial cavity through the endolymphatic and perilymphatic ducts to the oval window. Finally, an increased volume of blood might flow through the labyrinth capillaries in order to compensate for a change in the average stapes position.

Two mechanisms can be proposed to account for the acoustical vestibular stimulation observations that have been described in the preceding sections. First, vestibular receptors may be activated by the dc labyrinth fluid volume displacement associated with nonlinear stapes displacement. For this mechanism to be effective, fluid would have to be displaced along the endolymphatic duct and/or blood capillary pathways. It seems reasonable to suggest that fluid flow along these pathways would be opposed by a relatively high resistance; accordingly, potential vestibular stimulation as a result of

this fluid flow should have a relatively long time constant (see Fig. 9). Second, the receptors of the vestibular apparatus could be stimulated by a combination of the dc volume displacement and eddy currents in the labyrinth fluids. This second mechanism can be visualized in the following manner. Eddy currents are produced in the labyrinth fluids as a result of high velocity fluid oscillation during audiofrequency sound exposure. Normally these eddy currents remain localized in the cochlear region of the labyrinth. Increasing sound intensity has two effects. First, the strength of the eddy current may be slightly increased. Second, stapes nonlinearity produces a dc flow of fluid through the labyrinth that displaces the eddy current from its usual location toward one of the vestibular endorgans. The manner in which this might work may be clarified if you consider the situation when a canoe paddle is passed through the water of a moving river. Passage of the paddle through the water creates small swirls or eddy currents that are carried downstream by the current of the river until they dissipate. The relatively long response time constant that was suggested for the first mechanism would also be postulated with this second mechanism.

Observations with guinea pigs and human beings support a dc fluid displacement mechanism of acoustical vestibular stimulation. Guinea pigs exhibit clear physiological vestibular responses to pressure transients. It is difficult to conceive of eddy currents being generated by pressure transient ramp functions such as those illustrated in Figs. 6 and 7; nevertheless, ramp function stimulation does elicit eye and head movement responses from guinea pigs. Consequently, the dc labyrinth fluid flow produced by static displacement of the stapes is apparently sufficient to stimulate guinea pig vestibular receptors. The experiments described in Section II, p. 57, suggest that the semicircular canal crista organs are activated by this fluid flow. In the case of the observations with human beings apparently a particular level

of volume displacement must be reached before the vestibular receptors are activated; however, the observations are consistent with a dc fluid displacement mechanism.

When we examine the monkey's response to acoustical stimulation, the picture becomes confused. Part of our problem is attributable to the fact that we have been unable to obtain direct dc fluid volume displacement measurements from the labyrinths of either guinea pigs or monkeys up to the present time. In the absence of direct fluid volume displacement observations, we can suggest that perilymph pressure changes are correlated with dc volume displacements. Examination of Figs. 6, 7, and 15, keeping this assumption in mind, is instructive. Rotatory nystagmus has been observed in the monkey following stimulation with an 800-Hz tone at 149-dB SPL. Figure 15 indicates that an audiofrequency stimulus of this magnitude can result in an 0.03-mm Hg perilymph pressure drop in the monkey's semicircular canal. Fig. 7 demonstrates that perilymph pressure drops of approximately 0.08-mm Hg can be elicited by pressure transients at the tympanic membrane in the monkey. If a perilymph pressure drop of 0.03-mm Hg is associated with physiological vestibular responses to audiofrequency sound, why do perilymph pressure drops of more than double this value fail to produce similar vestibular responses when pressure transients comprise the stimulus?

At least three answers can be given to the preceding question. First, our assumption regarding the correlation between perilymph pressure change and volume displacement may be incorrect; for a given perilymph pressure value, the magnitude of labyrinth fluid flow may be less in the monkey than in the guinea pig. Second, dc volume displacement alone may not be an effective vestibular stimulus for the monkey. It is quite conceivable that the various elastic release points in the monkey present a different pattern of opposition to fluid flow in the monkey from that which obtains in the guinea

pig. If this is the case, the pattern of dc fluid displacement resulting from stapes nonlinearity in the monkey could completely bypass the vestibular receptors. Consequently, the dc displacement-eddy current mechanism of acoustical vestibular stimulation may be required to explain the results with monkeys. Third, the middle ear nonlinearity may result in larger labyrinth fluid pressure changes at tone onset than during continuous stimulation.

We offer no explanation for the apparent discrepancy between the observations with monkeys and those with human beings, at the present time. Perhaps the inner ears of monkeys and human beings differ in some critical, yet currently unknown manner. Before proceeding with a theoretical analysis, the monkeys should be studied employing the techniques of Ingelstedt et al (ref 21) and human beings should be examined with external auditory meatus pressure transients.

Further support for the dc displacement-eddy current hypothesis is found in the observations with repetitive audiofrequency sound. In human beings, acoustic transients evoke motion sensations at levels well below those at which sustained sound results in vestibular response. The stapes nonlinearity should result in a movement of the eddy current produced by the audiofrequency component of the stimulus. Kobrak's observations (ref 23) suggest that the onset of this nonlinearity in human beings should be in the 110- to 120-dB range, which corresponds quite well with the observed onset of vestibular responses. In this regard the apparent onset of stapes nonlinearity in cats (ref 14) and guinea pigs (Section II, p. 31) occurs at levels 10- to 20-dB higher than in human beings. This conclusion, while it fits with our observations, should be viewed with caution because of the differences in techniques employed by Kobrak, by Guinan and Peake, and in our laboratory.

Elsewhere (ref 27) we have suggested that repetitive audiofrequency stimulation should activate the vestibular system as a result of the demodulation properties of the nonlinear middle ear transmission. Audiofrequency sound modulated with infrasound or interrupted must result in a rectified component at the output of the middle ear that would manifest itself as infrasound or changing static pressure at the input to the inner ear. It might therefore be more effective with respect to vestibular stimulation than primary infrasound or static pressure stimuli at the tympanic membrane, which would be considerably attenuated by the middle ear. Further experimental data to clarify these mechanisms are required.

The acoustical vestibular stimulation mechanisms suggested by our research differ from those proposed by previous investigators. Deetjen (ref 9) observed the formation of eddy currents in labyrinth fluids during intense acoustical stimulation. He hypothesized that the eddy currents stimulate the semicircular canal crista organs because they produce endolymph displacement. We reject the hypothesis that eddy currents alone are sufficient to elicit vestibular-induced eye and head movements for the following reasons. First, several lines of evidence suggest that the mechanisms which transduce sound pressure into ac labyrinth fluid displacement saturate in the 120- to 140-dB SPL range (refs 6 and 38). If eddy currents alone account for the appearance of physiological vestibular responses, we would expect to observe these responses at stimulus intensities below 135-dB SPL. Second, Figs. 13 and 14 suggest that change in the average position of the stapes first appears for stimulation in the 134- to 144-dB SPL intensity range. The correlation between the appearance of this form of stapes nonlinearity and physiological vestibular responses is consistent with the suggestion of a combination eddy current-dc fluid displacement hypothesis of acoustical vestibular stimulation (in the monkey).

In 1935, von Békésy (ref 5) proposed that the statolith organs are stimulated by high intensity sound exposure. He suggested that eddy currents produce displacement of the statolith organ sensory epithelium. The hair cells are stimulated because the motion of the statolith mass lags behind the motion of the sensory epithelium. Our observations suggest that the semicir:ular canal crista organs rather than the statolith organs are stimulated by intense sound. This conclusion is valid, however, only for the types of responses that we recorded. Other types of vestibular responses to acoustical stimulation may derive from statolith organ displacement (see Section II, p. 57).

SECTION IV

CONCLUSIONS

The experiments that we have described are concerned with determining the mechanisms of acoustical vestibular stimulation. Two possible stimulation mechanisms are proposed: (1) a dc fluid displacement hypothesis, and (2) a combination dc fluid displacement-eddy current hypothesis. Biomechanical and physiological responses to acoustical stimulation have been examined in guinea pigs, monkeys, and human beings. The acoustical stimuli included (1) pressure transients (step and ramp functions of pressure change at the tympanic membrane), (2) infrasound, (3) intense audiofrequency sound, and (4) repetitive audiofrequency transients. Stapes displacement and perilymph pressure change were the biomechanical responses examined. Physiological responses included vestibular nerve recording, eye movements (slow rolling and nystagmus), head movements, perceived displacement of the visual field, and postural equilibrium.

The results of experiments with acoustical pressure transients are as follows.

- Longitudinal-axis stapes displacement was produced by step and ramp functions of pressure in guinea pigs. Increased pressure at the tympanic membrane elicited a bidirectional stapes displacement; tympanic membrane pressure decreases resulted in unidirectionally increasing lateral stapes displacement. A transfer characteristic relating tympanic membrane pressure change to stapes displacement for the guinea pig is given in Fig. 4. For human cadavers, the stapes displacements evoked by pressure transients were monotonic; however, a nonlinear response was produced by static pressure increases (Fig. 5).

• **Perilymph pressure recordings yielded results which were** essentially equivalent to the stapes displacement observations for the guinea pig. For the monkey, perilymph pressure changes were a monotonic function of tympanic membrane pressure changes and were of smaller magnitude than those observed in the guinea pig. Transfer characteristics relating perilymph pressure changes to pressure transient stimulus intensity are given in Figs. 6 and 7 for the guinea pig and monkey, respectively.

• Changes in rate of vestibular neuron response were elicited by pressure transients at the tympanic membrane of the guinea pig. Tympanic membrane pressure increases resulted in a decrement in neuron action potential rate and vice versa.

• Head and eye movements were evoked from unanesthetized guinea pigs by pressure transients. Minimum stimulus intensities required to elicit these responses were in the range of 1.5- to 2.0-cm Hg.

• No evidence of vestibular-induced eye movements could be detected in monkeys exposed to pressure transients up to 40-cm Hg.

• Nystagmus was evoked from about 6% of the normal human observers who were exposed to whole-body pressure increases. These observers all exhibited unusually high forcing pressures for opening the Eustachian tube on one side.

Stimulation with infrasound yielded the following observations:

• Perilymph pressure changes replicated the infrasound stimulus waveform at frequencies in the low infrasonic (0.5- to 2-Hz) and low audiofrequency (40- to 50-Hz) ranges. Stimulation between these frequency ranges resulted in complex perilymph pressure changes that were composed of at least two response

components. Peak to peak perilymph pressure evoked by particular stimulus intensities were lower for the monkey than for the guinea pig. The frequency response of the monkey's ear differed from the frequency response of the guinea pig's ear, when examined with infrasound.

• Consistent vestibular-induced eye movements could not be detected in guinea pigs, monkeys, or human beings exposed to infrasound at intensities up to 172-dB SPL.

Sustained audiofrequency sound stimulation results were as follows:

• The average position of the guinea pig stapes during intense audiofrequency sound stimulation differed from the resting position. The magnitude of this stapes nonlinearity is a logarithmic function of stimulus intensity. The minimum stimulus intensity required to produce stapes nonlinearity in the guinea pig was about 134-dB SPL.

• Intense audiofrequency stimulation produced dc perilymph pressure changes which can be related to stimulus intensity by a power function for both the guinea pig and the monkey. The magnitude of perilymph pressure response for a given stimulus intensity was greater in the guinea pig than in the monkey.

• Guinea pigs, monkeys, and human beings exhibited nystagmus in response to audiofrequency stimulation. Minimum stimulus intensities necessary to produce nystagmus are similar for all species: 135- to 145-dB SPL.

Repetitive audiofrequency transients produced the following results:

• Transient eye movements were evoked from guinea pigs and monkeys in response to repetitive audiofrequency transients. The

stimulus characteristics required to evoke the eye movements were similar in the two species.

- Eye movements were not obtained from human observers at the stimulus levels that we employed; however, the observers did report visual field displacements correlated with stimulus presentations.

- None of the three species examined in these experiments yielded clear evidence of a resonance response; i.e., no repetition rate evoked consistently stronger responses than the other repetition rates employed.

- Postural equilibrium was disturbed by repetitive audiofrequency transients at significantly lower intensities than with sustained audiofrequency sound.

The guinea pig observations support a dc volume displacement mechanism of acoustical vestibular stimulation. However, the monkey data and the results with human beings are consistent with a dc volume displacement-eddy current hypothesis.

REFERENCES

1. Ades, H. W., "Orientation in Space," Benox Report: An Exploratory Study of the Biological Effects of Noise, ONR Project NR 144079, The University of Chicago, 1953.

2. Ades, H. W., Graybiel, A., Morrill, S. N., Tolhurst, G. C., and Niven, J. I., Nystagmus Elicited by High Intensity Sound, Research Project NM 13 01 99, Subtask 2, Report No. 6, Naval School of Aviation Medicine, Pensacola, Florida, 1957.

3. Ades, H. W., Graybiel, A., Morrill, S. N., Tolhurst, G. C., and Niven, J. I., Nonauditory Effects of High Intensity Sound on Deaf Human Subjects, Research Project NM 001 102 503, Report No. 5, Naval School of Aviation Medicine, Pensacola, Florida, 1958.

4. Alford, B. R., Jerger, J. F., Coats, A. C., Billingham, J., French, B. O., and McBrayer, R. O., "Human Tolerance to Low Frequency Sound," American Academy of Ophthalamology and Otolaryngology Transactions 70, 40-47, 1966.

5. Békésy, G., von, "Uber akustische Reizung des Vestibular-apparatus," Pflug. Arch. ges. Physiol. 236, 59, 1935.

6. Békésy, G., von, Experiments in Hearing, McGraw Hill Book Co., New York, 1960.

7. Camis, M., The Physiology of the Vestibular Apparatus, Clarendon Press, Oxford, 1930.

8. Correia, M. J., and Money, K. E., "The Effects of Blockage of All Six Semicircular Canal Ducts on Nystagmus Produced by Dynamic Linear Acceleration in the Cat," Acta Oto-laryng 69, 7, 1970.

9. Deetjen, H., "Akustische Stromungen der Peilymphe," Zeits. Bio. 39, 159, 1899.

10. Evans, M. J., "Infrasonic Effects on the Human Organs of Equilibrium," Proceedings of Fall Meeting of the British Acoustical Society, 71-104, 1971.

11. Evans, M. J., and Tempest, W., "Some Effects of Infrasonic Noise in Transportation," J. Sound and Vibration 22, 19-24, 1972.

12. Fex, J., "Efferent Inhibition in the Cochlea Related to Hair Cell Activity: Study of Postsynaptic Activity of the Crossed Olivocochlear Fibers in the Cat," J. Acoust. Soc. Amer. 41, 666, 1967.

13. Graybiel, A., and Fregley, A. R., A New Quantitative Ataxia Test Battery, Report No. 107, Naval School of Aviation Medicine, Pensacola, Florida, 1963.

14. Guinan, J. J., and Peake, W. T., "Middle-ear Characteristics of Anesthetized Cats," J. Acoust. Soc. Amer. 41, 1237, 1967.

15. Gulick, W. L., Hearing: Physiology and Psychophysics, Oxford University Press, New York, 1971.

16. Hardy, M., "Observations on the Innervation of the Macula Sacculi in Man," Anat. Rec. 59, 403, 1934.

17. Harris, C. S., Effects of Acoustical Stimuli on the Vestibular System, Technical Report 71-58, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1971.

18. Harris, C. S., Effects of Increasing Intensity Levels of Intermittent and Continuous 1000 Hz Tones on Human Equilibrium Technical Report 72-11, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1972.

19. Harris, C. S., and Sommer, H. C., Human Equilibrium During Acoustical Stimulation by Discrete Frequencies, Technical Report 68-7, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1968.

20. Howard, I. P., and Templeton, W. B., Human Spatial Orientation, John Wiley and Sons, London, 1966.

21. Ingelstedt, S., Ivarsson, A., and Tjernström, Ö., "Vertigo Due to Relative Overpressure in the Middle Ear," Acta Oto-laryng. 78, 1-14, 1974.

22. Kennedy, R. S., A Bibliography of the Role of the Vestibular Apparatus Under Water and Pressure: Content Oriented and Annotated, Report No. 1, Naval Medical Research Institute, Pensacola, Florida, 1972.

23. Kobrak, H. G., "Construction Material of the Sound Conduction System of the Human Ear," J. Acoust. Soc. Amer. 20, 125-130, 1948.

24. Parker, D. E., "Interaction Between Electrical and Mechanical Vestibular Stimulation: Observations on Rabbits and Men," J. Exper. Psychol. 84, 96, 1970.

25. Parker, D. E., Covell, W. P., and von Gierke, H. E., "Exploration of Vestibular Damage in Guinea Pigs Following Mechanical Stimulation," Acta Oto-laryng. Suppl. 239, 1968.

26. Parker, D. E., and Reschke, M. F., "Mechanisms of Acoustical Vestibular Stimulation I. Middle Ear Nonlinearity," Minerva Otorinolaringologica 22, 240-249, 1972.

27. Parker, D. E., and von Gierke, H. E., "Vestibular Nerve Response to Pressure Changes in the External Auditory Meatus of the Guinea Pig," Acta Oto-laryng. 71, 456, 1971.

28. Parker, D. E., von Gierke, H. E., and Reschke, M. F., "Studies of Acoustical Stimulation of the Vestibular System," Aerospace Med. 39, 1321, 1968.

29. Rasmussen, G. L., "Efferent Fibers of the Cochlear Nerve and Cochlear Nucleus," In Neural Mechanisms of the Auditory and Vestibular Systems, G. L. Rasmussen and W. F. Windle (Eds.), Charles C. Thomas, Springfield, Illinois, 1960.

30. Reschke, M. F., High-intensity, Audiofrequency Vestibular Stimulation in the Guinea Pig, Unpublished Doctoral Dissertation, Department of Psychology, Miami University, Oxford, Ohio, 1971.

31. Reschke, M. F., Homick, J., Landreth, J., and Parker, D. E., "Acoustical Vestibular Stimulation in Man," Minerva Otorinolaringologica 25, 1975.

32. Reschke, M. F., Parker, D. E., and von Gierke, H. E., "Stimulation of the Vestibular Apparatus in the Guinea Pig by Static Pressure Changes: Head and Eye Movements," J. Acoust. Soc. Amer. 48, 913, 1970.

33. Schroeder, D. J., "Influence of Alcohol on Vestibular Responses to Angular Acceleration," Aerospace Me 42, 959-970, 1971.

34. Schroeder, D. J., Alcohol and Disorientation-related Responses I. Nystagmus and "Vertigo" During Caloric and Optokinetic Stimulation. FAA Office of Aviation Medicine Tech. Rep. No. 71-6, Civil Aeromedical Institute, Federal Aviation Administration, Oklahoma City, 1971.

35. Smith, C. A., and Rasmussen, G. L., "Nerve Endings in the Maculae and Cristae of the Chinchilla Vestibule, With Special Reference to the Efferents," In Third Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-152, National Aeronautics and Space Administration, Washington, D. C., 1967.

36. Weiss, H. S., Mundie, J. R., Cashin, J. L., and Shinabarger, E. W., "The Normal Human Intra-aural Muscle Reflex in Response to Sound," Acta Oto-laryng. 55, 505, 1962.

37. Wersall, J., and Hawkins, J. E., Jr., "The Vestibular Sensory Eplithelia in the Cat Labyrinth and Their Reaction to Streptomycin Intoxication," Acta Oto-laryng. 54, 1, 1962.

38. Wever, E. G., and Lawrence, M., Physiological Acoustics, Princeton University Press, Princeton, 1954.

39. Wiederhold, M. L., and Kiang, N. Y. S., "Effects of Stimulation of the Crossed Olivocochlear Bundle on Single Auditory Nerve Fibers in the Cat," J. Acoust. Soc. Amer. 40, 1427, 1970.

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