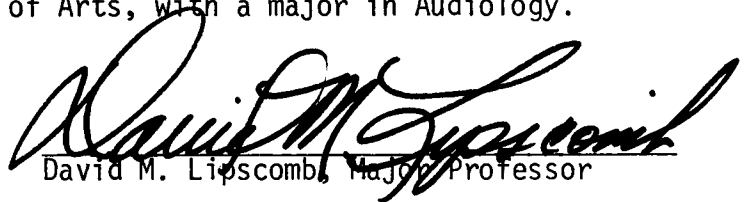


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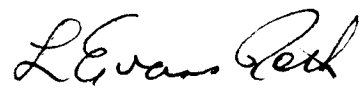

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MACULAR RESPONSE TO AUDITORY STIMULATION IN CHINCHILLA

A Thesis

Presented for the

Master of Arts

Degree

The University of Tennessee, Knoxville

Ellen C. Levi

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ABSTRACT

The purpose of this study was to investigate possible macular response to low frequency sound. While in the presence of a pure tone, the electrical response measured at the vestibule was compared to the electrical response measured at the round window in five chinchilla. The electrical activity at each recording site was noted for 100, 250, 500 and 3000 Hz in increasing 10 dB increments. Input-output functions (IOF's) were constructed for the purpose of comparing response curves from the vestibule electrode to response curves from the round window electrode. Vestibular IOF's generally paralleled the cochlear IOF's for 100, 250, 500 and 3000 Hz. All vestibular readings were lower in output voltage indicating a predominately far-field cochlear response. The cochlear IOF's average voltage for the points of nonlinearity was slightly higher for 3000 Hz than for 100 Hz. However, the average voltage for the points of nonlinearity for 100 Hz vestibular IOF's was almost twice as high as the average voltage for the points of nonlinearity for 3000 Hz vestibular IOF's. Similarly, the mean maximum IOF voltage for 3000 Hz cochlear IOF's was higher than the mean maximum IOF voltage for 100 Hz cochlear IOF's, and vestibular IOF's mean maximum voltage was almost twice as much for 100 Hz than for 3000 Hz. This suggests that the macular areas, when stimulated by low frequency sound may be contributing to the total electrical response obtained at the vestibular electrode. It was concluded the mean results tend to support the theory that low frequency

sound does activate the maculae such that small electrophysiological output can be detected. Additionally, these results offer important implications for including vestibular considerations in aural habilitation/rehabilitation.

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CHAPTER I

INTRODUCTION

The auditory mechanism gradually evolved from the vestibular system. Therefore, it has been postulated that acoustic stimulation can be mediated through the vestibular receptor organ in the event of auditory deficit. In order for vestibular function to participate in audition, an acoustic stimulus must elicit neural activity from the vestibular receptor. Such neural activity sets up an electrical field which can be detected.

If acoustic stimulation activates a measurable vestibular electrical potential, it could set a precedence for investigating vestibular (peripheral, and possible brainstem, central or cortical) electrical potentials, evoked by auditory stimulation. It could also have future implications in supporting (1) vestibular assessment as a part of the routine audiometric test battery, and (2) utilization of the vestibular system in aural rehabilitation as a concurrent modality with audition to perceive speech.

Most auditory habilitation/rehabilitation approaches utilize auditory stimuli and/or visual/manual communication. One method, the Verbo Tonal Method, postulates that the human vestibular receptor responds to acoustic stimuli between 1/2 and 1000 Hz. Additionally, acoustic stimuli between 16 and 20,000 Hz activates the human auditory receptor. Therefore, vestibular and auditory reception overlap for sound between 16 and 1000 Hz (Guberina and Asp, 1981). This method

operates under the theory that the frequency region important in developing rhythm and intonation of speech is below 300 Hz. Thus, low frequencies are amplified (down to 1/2 Hz) in initial stages of aural habilitation (Asp, 1971), in order to activate other sensory systems with auditory stimuli. If electrical activity is shown to radiate from the otolith organs in response to sound, this would offer support to the Verbo Tonal Theory.

Purpose

The purpose of this study was to electrophysiologically investigate whether there is macular response to auditory stimulation by using a methodology unlike any other found in the research literature. Specifically, the experimental question was: Does the input-output function (IOF) obtained from an electrode placed at the vestibule parallel, maintain lower output voltage, or show a summing affect to the IOF obtained from an electrode placed at the round window when sinusoidal acoustic stimulation is directed into normal chinchilla ears?

Anatomical Evidence

Based on the anatomical features of the inner ear, it is reasonable to hypothesize that auditory stimuli can activate the vestibular receptors. The inner ear consists of both the end organ for hearing and the end organ for balance which are housed in the same bony labyrinth within the petrous portion of the temporal bone (Zemlin, 1968; Gerber, 1974; Newby, 1979).

The portion of the membranous labyrinth which contains the end organ for balance communicates with the membranous labyrinth containing the end organ for hearing via the canal reuniens [Hensen's duct (Vinnikov and Titova, 1964; Zemlin, 1968)]. Kraut (1910) reported the canal reuniens is obliterated in the human adult, whereas, Siebenmann and Ono (1918) suggested the canal reuniens remains patent throughout life allowing endolymphatic fluid to flow from the cochlea (hearing portion of the membranous labyrinth) into the vestibule (balance portion of the membranous labyrinth). The narrowness of the canal reuniens, however, impedes the passage of high frequency disturbances of endolymph from the cochlea to the vestibule.

Not only is endolymphatic fluid continuous between the various compartments of the membranous labyrinth, but each component is suspended in the continuous fluid filled perilymphatic space. Additionally, vestibular sensory receptor organs (especially the maculae) are located close to the oval window, the point at which air conducted stimuli enters the cochlea.

Pertinent Vestibular Anatomy and Function

Within the human vestibular (balance) membranous system, there are five sense organs. Three are located in the semicircular canals (cristae). The remaining two are located in the vestibule (maculae or otolith organs).

The vestibule contains a membranous system with two sacs, the utricle and saccule. Maculae, which lie in different planes, are

located within the vestibular membraneous sacs. Experimental work to date offers only a sketchy picture regarding their auditory mode of function, if any. These otolith organs are possibly dual or multi-purpose sensors whose function range from (1) collecting continuous information about body position in relation to the center of earth's gravity to (2) monitoring the velocity and degree of rotational changes of head position (Lowenstein, 1971; Vinnikov and Titova, 1964; Guberina and Asp, 1981), as well as the macula within the saccule (3) perceiving vibration (Vinnikov and Titova, 1964) and acoustic stimuli (Vinnikov and Titova, 1964; Guberina and Asp, 1981).

Definitions of Terms

The following terms were defined to assist the reader with the terminology used in the present study:

Input-output function. An input-output function (IOF) is a graphic representation of a system's output when the input of the system is varied. In the present investigation, the output, measured in designated areas of the middle ear (represented on the vertical axis in microvolts), was electrical activity radiating from the inner ear. The input, presented to the ear canal (represented on the horizontal axis in decibels), was sinusoidal acoustic signals that varied in intensity and frequency.

Macular response. Macular response is increased electrical activity radiating from the otolith organs in the presence of sensory stimuli. In this study, sensory stimuli were sinusoidal acoustic signals.

Parallel input-output functions. For the purpose of this study, the linear portions of the input-output functions, if extended indefinitely, would be equidistant at all points.

Point of nonlinearity. The point of nonlinearity occurs in an input-output function where the linear relation between the output of the system and its input stops, and a "nonlinear relation between the response of the system and the forces acting upon it" starts (Wever and Lawrence, 1954, pg. 131).

CHAPTER II

REVIEW OF THE LITERATURE

The following areas are discussed in the review of the literature: (1) evolution of the mammalian inner ear, (2) evidence supporting maculae stimulation during audition, and (3) the cochlear potential measurement method used in this study. Each topic is treated separately in this chapter.

Phylogenetic Development of the Mammalian Inner Ear

Controversy over theories of the ear's origin is evident throughout the literature. The acustico-lateralis theory considers the inner ear to be a derivative of the lateral line sensory system (Wever, 1974), based on knowledge that (1) in early embryologic growth, the inner ear and lateral line develop from the same ectodermal anlage (Mitrophanow, 1889; Wilson, 1891), and (2) at peripheral and brain stem levels, similarities (hair cells, covering structures of organs, and neural innervation) exist between the lateral line and inner ear structures (Mitrophanow, 1889; van Bergeijk, 1967). Furthermore, this theory views the inner ear and lateral line to have had one function, that of hearing (Ayers, 1892).

A second theory developed by van Bergeijk (1966, 1967) suggests the lateral line gave rise to the vestibular labyrinth, based on the following arguments: (1) that although the lateral line and inner ear arise from common ectodermal tissue in embryologic growth, the original

cells split, and each mass of cells produce organs of its own type (Wilson and Mattocks, 1897), indicating the inner ear does not come from the same cells that give rise to the lateral line; (2) ciliated and structural similarities among the lateral line and inner ear hair cells are not exclusive to those organs, but merely reflect their common ectodermal origin (Wever, 1974); and (3) although both systems are innervated in a similar fashion, by intermingled fibers from the cochlear nuclei (Herrick, 1897, 1899, 1901), this does not indicate these fibers are functionally identical or that one cluster has evolved from another.

Van Bergeijk (1966, 1967) contends that the maculae and cristae developed out of the lateral line system as a superior mode of sensing linear and angular accelerations. With the emergence of the swimbladder, the maculae and cristae were capable of detecting sounds. Pressure waves in the water cause the swimbladder to expand and contract (i.e., vibrate) at the frequency of the pressure changes. Since the swimbladder is indirectly connected to the labyrinth by the Weberian ossicles, some labyrinthine hair cells respond when the swimbladder vibrates.

In view of the above facts, this author finds van Bergeijk's treatment of this subject more credible than the acustico-lateralis theory. Van Bergeijk (1966, 1967) not only suggested the lateral line gave rise to the vestibular labyrinth, but the cochlear labyrinth evolved from this labyrinth. The following overview on the evolution of the mammalian inner ear assumes van Bergeijk's theories.

The vestibular and auditory sense evolved and became increasingly refined through structural amendments and changes in the receptor organs. It is important to remember the inner ear is a motion sensing apparatus. An organism initially (i.e., at the beginning of animal life), only needed to sense its own body movements by using its existing statocyst (Guggenheim, 1948).

Lateral line organ. As evolution progressed and animals moved about, the very simple statocyst was no longer adequate. Therefore, numerous surface receptors called lateral line organs emerged (Guggenheim, 1948) which detected movement in the organism's surroundings (Parker and Van Huesen, 1917; Jielof et al., 1952; Dijkgraaf, 1963). For example, as a fish is in motion, the lateral line organs detect water currents along the fish's surface.

Harris and van Bergeijk (1962) showed lateral line organs of killfish respond to water displacements propagated by a near field sound source (vertically vibrating sphere), for tone stimuli between 50 and 333 Hz. Van Bergeijk (1967) points out, however, the single lateral line organ of a fish is inadequate to localize a source of motion, but is a receptor of hydrodynamic motions. The lateral line system, on the other hand, which consists of many lateral line organs spread over an animal's body, is capable of near-field hearing (or localization), providing an appropriate nervous system is present.

These primitive motion detecting organs could be arranged in a more efficient manner beneath the skin. Thus, a closed system of fluids and sense organs developed, the labyrinth.

Labyrinth. When the labyrinth developed, it appears to have functioned purely as an inertial navigation system. The labyrinth receptor organs, deeply embedded beneath the skin surface, were insensitive to environmental events. The receptors, therefore, selectively responded to accelerations of the animal rather than movements in the environment. The labyrinth's sensitivity to angular acceleration was increased by making a ring-shaped system, whereas, sensitivity to linear acceleration was optimized by increasing the inertial mass. This was accomplished by adding calcium carbonate granules (otoconia) and modestly expanding the receptor organ (van Bergeijk, 1967). Thus, the otolith macula came into being.

One of the more primitive vertebrate, of present day, is the sea lamprey, *Myxine*. This fish has a labyrinth composed of a single otolith macula and one semicircular canal containing two cristae (van Bergeijk, 1967; Baird, 1974). A later species, the fresh-water lamprey, *Petromyzon*, has three otolith maculae, two semicircular canals, and a small sensory spot called papilla neglecta (de Burlet, 1934). Fish which evolved after the sea and fresh-water lamprey have the most advanced fish vestibular labyrinth form, consisting of three semicircular canals, utricle, saccule and lagena. The labyrinth has shown small changes throughout the subsequent evolution of vertebrates, except for the gradual emergence of a special hearing organ (Wersäll and Flock, 1965; van Bergeijk, 1967; Smith and Takasaka, 1971; Baird, 1974).

Swimbladder. Incidental to its primary function, the swimbladder expands and contracts when placed in an alternating pressure field (e.g., pressure waves). The movements of the swimbladder wall are transmitted across the Weberian ossicles, which are four pairs of bones that connect the anterior part of the swimbladder with fluid chambers adjacent to the sacculus. The ossicles displace the lymphatic fluids in these chambers, which in turn displace the endolymphatic fluids in the sacculus. This sets up vibratory motion in the portion of the macula which rests on an unyielding tissue base. Its otoconial layer (which connects to the tips of the hair cell cilia), however, having greater density than the surrounding endolymphatic fluid, will lag in phase when responding to fluid displacements. Hence, the cilia bend and the hair cells are stimulated (van Bergeijk, 1967; Wever, 1974). In summary, the enclosed labyrinth is capable of responding to environmental sounds in the presence of a primary sound receptor such as the swimbladder.

Amphibia. As animal life emerged from water, they possessed the necessary adaptations to survive on land. The ear was no exception.

The amphibian inner ear contains two maculae specialized for auditory reception, the amphibian papillae and basilar papillae. The former is present in all Amphibia; the latter is absent in some species (van Bergeijk and Witschi, 1957; Geisler et al., 1964; van Bergeijk, 1967; Wever, 1974). The papillae have tectorial membranes instead of otoliths, are connected to the perilymphatic duct in the form of very thin membranes, and are innervated by nerve fibers with a size distribution similar to the mammalian cochlear nerve (Geisler et al., 1964). The remaining receptor structures in the labyrinth, present no highly unusual changes.

The bony portion of the amphibia labyrinth is more ossified than that of the fish, but cartilage is found within the walls. A vestibular (oval) window is found on the lateral wall of the labyrinth (Baird, 1974). Fluids and soft tissue line the labyrinth base from this window to the medial base. These structures permit alternating pressures in the labyrinth fluids to pass through the labyrinth (Wever, 1974) and stimulate the two papillae.

Cochlear potentials, recorded from the labyrinth in response to sound stimuli, revealed 400 Hz and 1500 Hz to be regions of best auditory sensitivity in bullfrogs (Frishkopf and Goldstein, 1963; Frishkopf and Geisler, 1966) and treefrogs (Weiss and Strother, 1965). It is believed that the lower region reflected activity of the amphibian papilla and the upper region represents activity of the basilar papilla.

Reptile. In general, the reptile labyrinth is well ossified showing definition of semicircular canals, a vestibule and the cochlea is characterized by structural variations (Wever, 1965; Baird, 1974). The reunient (sacculo-cochlear) duct connects a distinct cochlear duct to the posterior region of the saccule (Baird, 1974). The auditory papilla is located in the cochlear duct, adjacent to the otolith macula of the lagena. Unlike the vestibular receptors, this papilla is situated on a suspended movable membrane (basilar membrane) and is covered with a tectorial membrane (Smith and Takasaka, 1971). The literature contains very little information on the vestibular structures. The utricle, an arched elongated tube, communicates with the semicircular canals as in higher vertebrates. A short utriculo-saccular duct joins the utricle to the large saccule (Baird, 1974).

When the columella footplate (of the middle ear) moves in and out of the oval window, the cochlear fluid mobilizes by means of the round window. This membrane-covered window is free to bulge in and out under the alternating pressures. A round window does not exist in certain reptiles, however, these reptiles possess an alternate system for fluid mobilization (Wever, 1974) which is not relevant to this text.

Birds. Generally, the labyrinth is structurally uniform across all orders of birds. The cochlear duct, a slightly curved tube, varies in length from less than 3 mm in humming birds to 10 mm owls (Schwartzkopff, 1968). It connects to the sacculus by a ductus reuniens whose outside diameter is only slightly smaller than the cochlear duct. Within much of the ductus reuniens lie blood vessels which are continuous between the cochlea and sacculus. The cochlear duct, separated into two perilymphatic spaces, abruptly ends at the distal end of the cochlea. The macula of the lagena is situated here. Along the main length of the tube lies the basilar membrane with its receptor organ lying on top (Smith and Takasaka, 1971; Wever, 1974).

The anterior semicircular canal is elongated, the posterior semicircular canal is moved laterally to a site that approaches the transverse plane, the utricle displays relative and actual shortening, and the sacculus is markedly reduced in the bird (Baird, 1974). Bird's cristae, utricular macula and papilla neglecta are similar to reptiles (Dohman, 1961). Unfortunately the saccular and lagenar maculae of birds have received little attention in the literature.

Mammals. Mammalian inner ears, in general, are highly regular in structure. Prototheria (monotremes), a rather primitive subclass of living mammals, represent the only known exception (Smith and

Takasaka, 1971; Wever, 1974). Differences noted in highly developed mammalian labyrinths, as opposed to bird labyrinths, are (1) the lagena is absent from the distal end of the cochlea duct, (2) the auditory receptor is elongated and coiled around the central core of nerve fibers, (3) concentrated within the stria vascularis are the capillary networks, and (4) the organ of Corti, a highly refined auditory receptor emerges (Smith and Takasaka, 1971).

In summary, the maculae in fish, functioning initially as gravity and motion sensors, became receptors of sound vibrations. It is reasonable to suggest the amphibian's basilar and amphibian papillae functioned as equilibrium sensors prior to their auditory receptor function, due to structural similarities between the auditory papillae and cristae (Wever, 1974). From the reptile through the mammal, maculae and cristae are not considered receptors of auditory stimuli because the auditory organ emerged as a special organ for which sound was the most effective stimulus (i.e., the easiest way to activate this special organ is with acoustical stimulus). The mammalian maculae, however, can be stimulated by a high intensity low frequency acoustical signal, which will be considered next.

Vestibular Stimulation by Sound

In reviewing the literature, a considerable body of evidence indicates the maculae can be activated by high intensity low frequency acoustical stimulation. Previous studies of acoustical vestibular stimulation tend to fall into three categories:

Visual-field effects. Tullio (1926) was the first to observe vestibular symptoms and/or signs can be produced by an acoustic stimulus. In 1929 Tullio observed, while using pigeons as subjects, that cristae of semicircular canals can be activated by an acoustic stimulus. Additionally, he showed this response (1) increases if the bony canal is fenestrated and (2) persists after the cochlea has been destroyed.

Visual-field displacements, equilibrium changes, and subjective sensations of nausea or dizziness have been noted when humans (or guinea pigs) were exposed to high intensity acoustical stimulation or pressure changes in the external auditory meatus (Wever and Bray, 1936; Dickson and Chadwick, 1951; Ades et al., 1958; Mohr et al., 1965; Parker et al., 1968b; Reschke et al., 1970; Parker et al., 1978). Wever and Bray (1936) reported some subjects felt slightly dizzy and nauseous when exposed to stimuli from 15 to 17 Hz at levels up to about 104 dB SPL. Dizziness and unsteadiness was reported by personnel working on jet engines "during the running of engines on the test bed or during the running up of aircraft jet engines on the airfield" (Dickson and Chadwick, 1951). This sense of equilibrium disturbance was observed when aircraft noise was above 140 dB SPL. No nystagmus was elicited, therefore, the authors speculated the utricle was the locus of stimulation. Mohr et al., (1965) investigated the tolerance limits of five "noise-experienced" subjects exposed to up to 154 dB SPL in the 1 to 100 Hz frequency range. The subjects were exposed for two minutes to broad-band, narrow-band and pure tone signals. Broad-band

and narrow-band noise exposure was not above 148 dB SPL, and elicited no intolerable non-auditory effects. At maximum exposure (150-154 dB SPL) to pure tones in the 43 to 73 Hz range, visual blurring was objectively and subjectively observed in all subjects. Some subjects complained of mild nausea when exposed to a 153 dB SPL, 100 Hz tone.

Ades et al., (1958) investigated non-auditory effects of deaf human subjects in the presence of high intensity sound. The intensity required to elicit small eye movements in one deaf subject was 120 to 125 dB (reference level not specified) in the 260 to 1075 Hz range. Marked nystagmus was produced from this same subject at 126 to 136 dB in the 260 to 1075 Hz range. Parker et al., (1978) reported visual displacements in 62 of 133 human subjects which were exposed to 125 dB SPL repetitive audiofrequency (100-5000 Hz) tone bursts. The subjects' vision was considered displaced if during the sound exposure, he reported motion of a black cross (7.6 x 7.6 cm) located 122 cm away at eye level. The largest amount of visual displacement reports followed stimulation in the 500 and 1000 Hz frequency range at repetition rates of about 1/sec. The authors suggested the visual displacements resulted from stimulation of the vestibular end organs.

Parker et al., (1968b) examined the hypothesis "acoustical vestibular stimulation is the result of DC displacements of the stapes footplate." Stapes displacements may be provoked by stimulating the ear canal with slow time-vary pressure. Eye movements of 18 guinea pigs were observed and recorded while being exposed to slow time-varying pressure changes in the ear canal. Periodic and static pressure was varied between 0.1 and 10 Hz at intensities of 2.5 to 10 cm Hg. Eye

movements were observed through a microscope or recorded with stainless steel electrodes located above and below or on both sides of one eye. The three general classes of eye movements observed, oscillatory eye movements, counterrolling and nystagmus, correlated with the slow time-varying pressure changes in the external auditory meatus. Since the eye movements observed are conventionally associated with vestibular activation, the authors concluded vestibular end organs may be activated by acoustic stimuli. Using guinea pigs as subjects, Reschke et al., (1970) investigated the minimum static pressure intensity in the ear canal necessary to elicit head and eye movements. Additionally, changes in response latency, amplitude and duration were observed when the stimulus intensity, duration, and onset rate were varied. Results indicated 1.5-2.0 cm Hg was the minimum stimulus intensity required to produce a response, and amplitude and duration of head movements significantly correlated to stimulus intensity and duration, respectively. The authors concluded head and eye movements were elicited because high pressure was created in the perilymph, from stapes footplate displacement, which produced a fluid flow through the vestibular membranous labyrinth. Consequently, there was direct mechanical stimulation of the semicircular canal receptors. The authors also suggested the same mechanism may stimulate the vestibular system by low frequency inaudible sound and audio-frequency high intensity sound.

Vestibular damage. Vestibular damage has been observed in animals following exposure to intense sound (McCabe and Lawrence, 1958; Albernaz et al., 1959; Parker et al., 1968a). McCabe and Lawrence (1958) stimulated 12 guinea pigs and 14 guinea pigs with acoustic

stimuli of 150 and 136 dB SPL, respectively. A random noise of 100 to 10,000 Hz was utilized, and each animal was exposed to the noise for twenty minutes. Histologic examinations of the vestibular labyrinth revealed the saccule to be the locus of damage. Most readily destroyed were the otoconiae of this structure. Fifty-eight percent of these animals presented collapsed saccules. There was not consistency in the degree of damage as a function of stimulus intensity. Other structures in the vestibule were not damaged. Based on their findings, the literature which indicates dual function of the saccule (acoustic and vestibular), and the "rectilinear character of noise-induced vertigo," the authors concluded symptoms reported by individuals exposed to intense sound are possibly mediated through the saccule.

Albernaz et al., (1959) exposed 46 guinea pigs to high intensity pure tones. Each guinea pig was stimulated by a single frequency varying from 170 to 50,000 Hz. Exposure time varied from one to four minutes, and pure tone intensities varied between 140 dB and 163 dB SPL. Histologic examinations on the non-auditory labyrinth indicated rupture of the membranous partition, which separates the inferior and superior portions of the vestibule, was the most common finding. Twenty-five percent of the specimens were found to have ruptured saccules, while 33 percent of the saccules were found to be collapsed. The utricle was ruptured in 33 percent of the specimens, but total collapse of the utricle was not found.

Parker et al., (1968a) examined structural damage in the vestibular labyrinth of 10 guinea pigs after each had been exposed to wideband noise at intensities of 140, 148 or 154 dB SPL. Gross dissection showed

no change in the vestibular labyrinth. One animal exposed to 154 dB SPL was examined histologically. Findings included partial collapse of the saccular membrane, bilaterally, a ruptured right utricle whose otoconiae had collected into groups of varying sizes with some loss, and the otoconial layer of each saccule folded over at one point.

Electrophysiologic. Electrophysiologic measures have been obtained from (a) the vestibular portion of the VIII cranial nerve or (b) the round window, brainstem and auditory cortex, following destruction of a portion or the entire cochlea. Parker and von Gierke (1971) investigated the relationship of air pressure changes in the external auditory meatus and responses from primary vestibular afferent nerve cells. Observations were made on 32 neurons of guinea pigs; eleven gave increases and decreases of action potential rate in response to pressure changes in the external auditory meatus, while the remaining 21 neurons could not be activated by either sound or pressure. They concluded their data supports the hypothesis regarding vestibular activation by intense infra- and audio-frequency sound.

Aran et al., (1979) recorded click-evoked electrical responses at the round window of guinea pigs one month after the animals had been treated with very large doses of aminoglycosides amikacin. Histological examinations found only a few outer hair cells present along the entire length of the basilar membrane, primarily in the third row of the extreme apex of the cochlea. However, the vestibular function and receptors appeared unaffected. A significant number of nerve fibers were found innervating the remnants of the organ of Corti. Averaged response

patterns resembled those of the compound action potential (clear, short-latency, highly synchronized, diphasic responses), suggesting they were of a neural nature. Thus, the authors concluded that these responses arose from either direct mechanical excitation of nerve fibers innervating the remnants of the organ of Corti or vestibular nerve fibers (indicating the vestibular sense organs were acoustically stimulated).

A follow up study by Aran et al., (1980) investigated the nature of the highly synchronized, short-latency, click-evoked responses recorded at the round window of amikacin-treated guinea pigs. The onset and evolution of these responses were studied during and after (up to one year) guinea pigs were treated with large doses of aminoglycoside amikacin. Cochlear responses were recorded by permanent electrode implantation at the round window. A few days following the start of the amikacin treatment, the normal auditory nerve compound action potential disappeared, but was replaced by the typical diphasic, short-latency (0.3 ms), small amplitude response that occurred in the previous study. This response remained constant until the termination of the study (up to almost a year). The authors proposed that in view of the rapid onset and long-term stability, this response may originate from an existing system which is not detectable under normal conditions, but is displayed when the cochlear structures are impaired by amikacin. They further suggested that this existing system would most likely lie in the vestibular receptors (i.e., the saccule) which were histologically found to be only slightly affected in this study. They did caution that

on the basis of the present data, their proposals were purely speculative.

Cazals et al., (1980) recorded auditory evoked responses at the round window, brainstem and auditory cortex of amikacin-treated guinea pigs. Permanent electrodes were implanted at the round window, vertex and contralateral cortex. Animals were sedated only during brainstem recordings. An unfiltered click and a series of third-octave filter clicks constituted the acoustic stimuli. Histologic findings and round window responses were identical to the above two studies. Brainstem responses were consistent, but different from normal guinea pig responses because of "their reduced amplitude and the absence of the normally predominant late waves," indicating auditory evoked neural activity in the brainstem is drastically reduced after the destruction of cochlear hair cells. The authors pointed out that these responses resembled evoked potentials of the vestibular nuclei reported by others. Additionally, they suggested this indicates the vestibular system may be responding to sound. The auditory cortex responses "were of the same order of magnitude and duration as those from the normal animal" except there was a reduction and delay of the first positive peak and a delay in the negative peak. The investigators suggested this result does not support the hypothesis of vestibular response to sound, but the distortion of the response wave form must be kept in mind.

A final article worth noting reports a study by Miller (1970) that deals with the audibility curve of the chinchilla. Two chinchilla were trained to respond to pure tones by the method of instrumental avoidance conditioning in a double-grilled cage. The cage was

suspended below the loudspeaker and above a blanket of fiberglass which had a high absorption coefficient for low frequency sounds. After being tested (in a sound field), both cochleas of each animal were surgically destroyed. The animals were retested to determine threshold for nonauditory responses to sound. The audibility curve obtained for the two deaf chinchilla was near 90 dB SPL in the frequency range from 0.18 to 1.0 kHz. Total destruction of both cochleas in each animal was verified by histological examination. The author did not discuss the nonauditory responses, but simply reported the results. In view of the above findings, it is evident another sensory system of the chinchilla was stimulated by high intensity low frequency sound. The vestibular system possibly was activated by the stimuli since the suspended cage minimized tactile input.

The above studies indicate the vestibular system can respond to an acoustic signal. Few studies, however, have considered electrophysiologic events of the peripheral vestibular systems while the cochlea is intact. This is probably due to the unusually high electrical potentials in the cochlear duct, which will be addressed next.

Cochlear Potential Measurement Method

Cochlear DC polarization. Smith et al., (1958) and Gannon et al., (1958) investigated the electrical polarization of the endolymph in the cochlear duct, utricle, saccule, and ampulla. The investigators were surprised to find the large DC potentials (resting potentials) were limited to the scala media. DC potentials recorded were:

+77 millivolts (mv) in the cochlear duct, +1 mv in the saccule, +4 mv in the utricle, and -1 mv in the ampulla. The DC potentials in the cochlea are much larger than the DC potentials anywhere else in the labyrinth. Therefore, when the labyrinth is acoustically stimulated (but not overstimulated), the electrical activity generated in the cochlea is much greater than any other stimulated area in the labyrinth.

The cochlear potential. Wever and Bray (1930) observed that when electrodes were placed on the medulla or auditory nerve of a decerebrate cat, they could pick up potentials which were relatively faithful reproductions of sound stimuli directed into the ear canal. The investigators suggested these responses were the action potential of the eighth nerve, but Adrian (1931) demonstrated the same phenomenon when the nerves were anesthetized or destroyed by acid. Adrian attributed the results to mechanical vibration of the cochlea and suggested the potentials were a result of some kind of microphonic action in the cochlea. Additionally, he noted the optimal recording site outside the cochlea was at the round window. This view was supported by other research, and the cochlear microphonic was accepted as the electrical response of the cochlea.

Wever and Lawrence (1954), in a series of experiments, observed distortions in the middle ear and mechanical distortions within the cochlea. In the fourth experiment, a 1000 Hz signal was directed into cat ears at a moderate level, then raised in 5 or 10 dB steps. At each step, the stimulus and response waveforms, cochlear electrical

responses (in microvolts) and sound at the round window were recorded, until the safe performance limit of the loudspeaker was reached. An intensity function for the cochlear responses was plotted for the cat's ear. The input intensity, in decibels, was placed on the abscissa (linear scale) and the cochlear response (or output), in microvolts, was placed on the ordinate (logarithmic scale). The function was linear at low and moderate input intensities, but the function gradually "bent over" with the increase of high input intensities. The input waveforms, measured at the tympanic membrane, remained sinusoidal at all intensity levels, while the cochlear response waveforms appeared sinusoidal up to a moderately high input level, then became increasingly distorted as the high input level increased. The round window sound waves remained sinusoidal well beyond the maximum point of the response curve. The authors reported these response curves (input-output functions) are "stable and easily repeatable" provided high input intensity levels (where the function bends over) are applied only momentarily. They cautioned the reader, however, not to carry the response curve too far, because serious injury and progressive impairment of the responses will occur.

Dallos (1973) reports the relationship between the cochlear output and sound input has become a familiar one. He discusses three distinct segments of the function: (1) In the linear segment, the cochlear responses increase proportionally to increases in intensity. This portion extends from the lowest measurable limit (which depends on the interaction of system noise, biological noise and instrumentation)

to where departure from linearity occurs. (2) The region that departs from linearity to the maximum of the function is characterized by increasing amounts of harmonic distortion in the cochlear potential. The cochlear potential curve ceases to rise linearly as intensity increases, thus, this is the "simple saturation" or "overloading" region. (3) In the final declining stage of the curve, the electrical output in the cochlea decreases as very high intensities increase. "This phenomenon indicates that a process in excess of a simple saturating type of nonlinearity is in effect at high intensity levels." This process remains perplexing to investigators looking for evidence to support explanations of this phenomenon.

CHAPTER III

METHODS AND PROCEDURES

To investigate the possible existence of macular response to acoustical stimulation, anesthetized chinchilla were presented various pure tones. For each test frequency, the subject's electrical activity generated at the round window was compared to the electrical activity generated at the vestibule.

Subjects

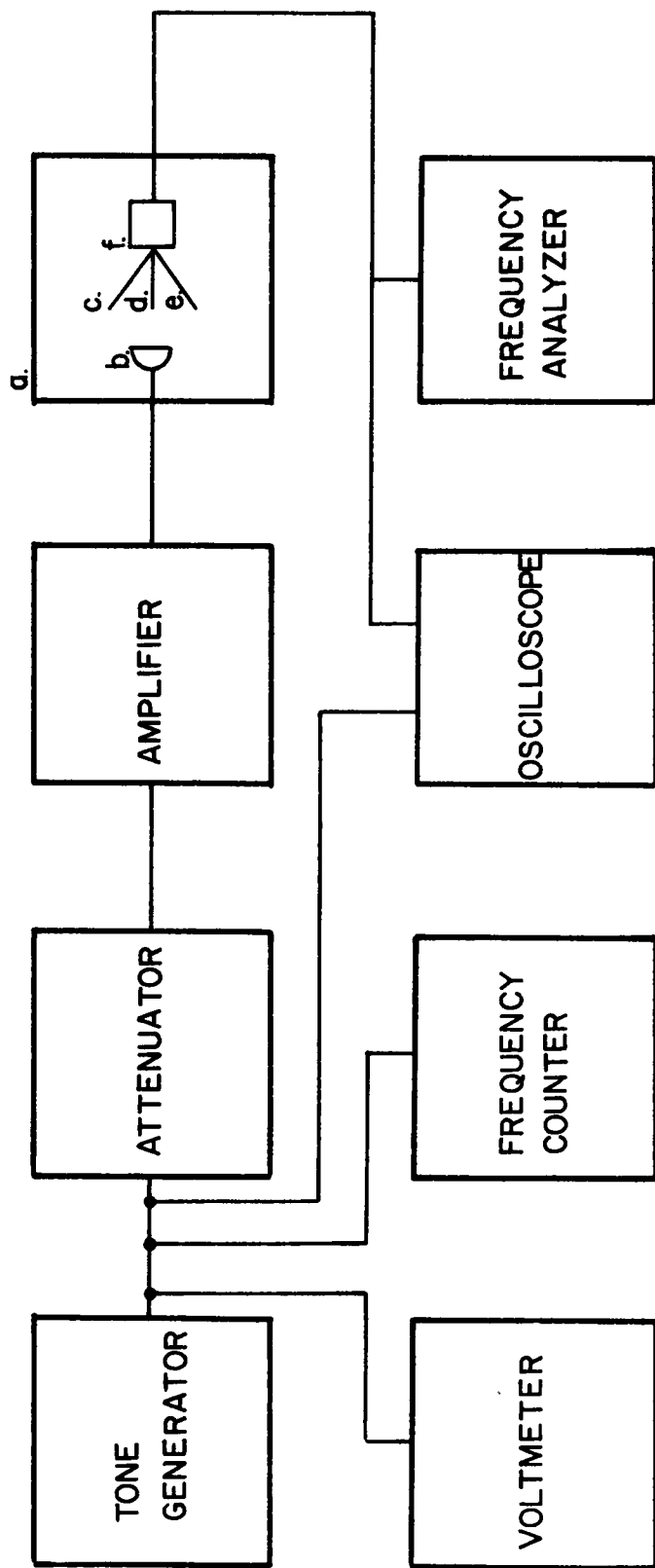
Six standard gray chinchilla that appeared to be in good health with demonstrated normal cochlear function were selected for this study. To qualify, a normal cochlear potential input-output function (IOF) was required. This criterion is manifest as a linear increase in output voltage with a linear increase of the sinusoidal stimulus input (in dB SPL). At high input intensity levels, of course, the function no longer increases in a linear fashion, resulting in a "bend-over function." The linear portion of the curve was required to occur over at least a 40 dB range.

Five of the six chinchilla were experimental subjects. The sixth chinchilla served as a control subject to assess reliability of electrode placement.

Instrumentation

A diagram of the instrumentation used to measure cochlear potentials is shown in Figure 1. The tone generator, a Brüel and Kjaer, model 1022, Beat Frequency Oscillator was monitored by a Hewlett Packard, model 400 H, Vacuum Tube Voltmeter and a General Radio, model 1192, Frequency Counter, for stable output voltage and accurate frequency setting. A ± 3 Hz criterion was used. Pure tone stimulus attenuation was provided by a Hewlett Packard, model 3500, Attenuator Set. Signal amplification was provided by a custom built five watt power amplifier, prior to being transduced by a Hal Hen, model 2104, hearing aid receiver. Initial measurements were contaminated by an electrical field created around the hearing aid receiver and cord at high input intensity levels. To eliminate this problem, the hearing aid receiver and cord were encased in a shielded enclosure.

The signal was directed to the left ear by attaching a snap ring adapter onto the transducer and placing a 5 centimeter (cm) length of tubing (0.085 cm- internal diameter; 0.125 cm- external diameter) onto the adapter. The free end of the plastic tubing was inserted into a 30 cm strip of rubber surgical tubing with an approximate internal diameter of 0.2 cm. The loose end of the surgical tubing was filed down to an external diameter of 0.7 cm to enable a tight fit when the tube was placed into the animal's external auditory meatus. Surgical tape was used to hold the surgical tubing in the animal's ear. While being tested, the animal was located in an IAC, model 401, sound-treated booth.



- a. SOUND-TREATED BOOTH
- b. TRANSDUCER - HEARING AID RECEIVER
- c. 1ST ACTIVE ELECTRODE
- d. 2ND ACTIVE ELECTRODE
- e. GROUND ELECTRODE
- f. PREAMPLIFIER

Figure 1. Block diagram of evoked response audiometry for measuring cochlear potentials.

Cochlear potentials received by implanted silver-ball electrodes were amplified 1000 times by a Grass, model P-511, AC Preamplifier whose power was supplied by the Grass, model RPS 106B, Regulated Power Supply. The preamplifier low frequency cut-off was set for 30 Hz during all measurements, while the high frequency cut-off was set for 1000 Hz during measurements involving 100 Hz sinusoidal stimuli, for 3000 Hz during measurements involving sinusoidal stimuli of 250 and 500 Hz, and for 10,000 Hz during measurements involving sinusoidal stimuli of 3000 Hz. By filtering the preamplifier input, extraneous physiological and environmental noise was eliminated, leaving the desired cochlear potential for study.

The amplified output was monitored on one channel of a Tektronix, model RM 502 A, Oscilloscope, while the sinusoidal stimulus was monitored on the second channel. The amplified cochlear potential was measured by a Brüel and Kjaer, model 2107, Frequency Analyzer, which was tuned to the stimulus frequency. Roll-off of the analyzer section was greater than 40 dB/octave.

Equipment Calibration and Checks

Linearity of the Hewlett Packard Attenuator was checked using a 300 Hz stimulus and connecting a Hewlett Packard, model 400 H, Vacuum Tube Voltmeter to the output terminal of the attenuator. The signal was attenuated in 10 dB steps and voltage output was read from the voltmeter, then converted into decibels (see Appendix A). The output was within ± 0.2 dB of each 10 dB designation on the attenuator,

indicating satisfactory linear output.

Calibration of the acoustical stimulus was achieved by placing the free end of the surgical tubing into a Zwislocki coupler, directing the acoustical signal into the adjacent Brüel and Kjaer, model 2619, 1/2-inch microphone. The external diameter of the surgical tubing was such that an airtight seal was easily obtainable when inserted into the coupler. Microphone output was directed to a Brüel and Kjaer, model 2107, Frequency Analyzer whose filter was tuned to the frequency being analyzed. Absolute output was recorded from the indicating meter of the frequency analyzer in dB sound pressure level (SPL), RMS slow, for 100, 250, 500 and 3000 Hz. Amplifier gain was permanently adjusted so that when a one volt (V), 500 Hz tone was generated and the attenuator was set for 0 dB attenuation, the indicating meter of the frequency analyzer read 130 dB SPL. This level served as the reference voltage for decibel readings recorded at each frequency, in successive attenuation steps of 10 dB, until the noise floor or lowest decibel reading on the indicating meter of the frequency analyzer was reached. The system was calibrated at the beginning and midway of data collection. The system's output was checked immediately after measurements were obtained from the last subject (see Appendix B). System output was linear from the highest attenuator setting that decibel readings were obtainable, to 10 dB (inclusive) attenuation for 250, 500 and 3000 Hz. Linearity existed from 90 dB attenuation to 20 dB (inclusive) attenuation for 100 Hz. The linear portion of the system was characterized by output within -2.3 dB of each 10 dB designation on the attenuator when the lowest linear attenuator setting for each frequency served as the reference output.

The system's non-linearity at high intensity levels was not great enough to affect the overall configuration of the IOF's. The range of error between the two calibration and one system check was 3.2 dB or less, which was sufficient for the purpose of this study.

Surgical Technique

Ss were anesthetized with chloropent (240 mg/kg) administered into the intraperitoneal space. Fur between the midline of the skull and left pinna was removed to expose skin for incision. The exposed area was cleaned using 70 percent ethyl alcohol. Two incisions were made in this area parallel to midline. One incision extended from the anterior to the posterior portion of the superior bulla. The second incision extended from the superior to the inferior portion of the posterior bulla. Small cotton balls were used to control bleeding. Blunt dissection provided a means to separate the tissue from the bone with minimal loss of blood, a factor which kept blood from entering the bulla. A small spreader was placed into the incision, exposing the bone.

Two teflon-coated silver electrodes with uninsulated ball tips approximately 0.1 cm in diameter were implanted in the following areas of each animal's left middle ear:

- (1) A round-window electrode was directed thru a hole approximately 0.25 cm^2 in the central portion of the inferior posterior bulla to the vicinity of the round window.

(2) A vestibular electrode was inserted thru a hole approximately 0.25 cm^2 in the mid-section of the superior bulla and oriented towards the vestibule.

Each electrode was anchored to the bulla and held securely in place by dropping dental acrylic over the wire. Dental acrylic was also used to cover the hole in the bulla to insure that the post-surgical impedance characteristics of the animal's middle ear was relatively unchanged. The distance between the two ball electrodes in the middle ear space was approximately 4 millimeters.

A third teflon-coated silver electrode was fashioned into a hook electrode and inserted into the skin that covers the superior portion of the posterior bulla. This electrode was located midway between the ball electrodes and served as the second active electrode for recording electrical activity at the round window and at the vestibule.

The ground electrode was a stainless steel needle electrode. This electrode was placed into one of the pads of the animal's left foot.

Measurement Procedures

Experimental subjects. Two cochlear IOF's were measured for each test frequency (100, 250, 500 and 3000 Hz). Obtaining measurements at 3000 Hz served as a control, thus a comparison of macular response to low and high frequency acoustical stimulation could be considered in the data analysis. Frequencies below 100 Hz were not used due to transducer output limitations and low frequency acoustic noise providing an untenable noise floor. The measurement protocol for each subject was as follows:

(1) Cochlear IOF's were recorded while the round window electrode served as the first active electrode at 500, 250, 100, then 3000 Hz.

(2) Vestibular IOF's were then recorded when the vestibular electrode was the first active electrode at 3000, 500, 250, then 100 Hz. Ten to fifteen minutes elapsed between cochlear electrode measurements and vestibular electrode measurements to control for temporary threshold shift.

Baseline for each IOF was a cochlear potential of 1 microvolt [μ V (1 millivolt was read on the indicating meter of the frequency analyzer)]. The input signal was increased in 10 dB steps and the voltage output was recorded. Each input-output function was plotted on semi-logarithmic paper with the attenuation level in dB SPL on the abscissa and the recorded electrical response in μ V's on the ordinate.

Control subject. The measurement procedure implemented with this subject was identical to the experimental subjects. With this chinchilla, however, the cochlear and vestibular electrodes were each implanted on five separate occasions. Measurements were obtained after each placement. Care was taken to never stimulate the animal's ear over 100 dB SPL during all measurements, therefore, reducing the possibility of permanent cochlear damage due to constant overstimulation of the ear. Measurement variability due to electrode placement could be considered with the data obtained from this subject.

CHAPTER IV

RESULTS AND DISCUSSION

The findings of this study are discussed in two sections. Reliability of procedures will be discussed in the initial section. The second section will discuss results of the experimental data on an individual and group basis.

Reliability of Procedures

Reliability of the measurement procedures used in this study and repeatability of the cochlear potentials as a function of electrode placement were evaluated.

Test-retest. Reliability of the voltage output (electrical potentials) measured at the round window and vestibule was established by selecting two animals and obtaining repeat input-output functions (IOF's) without altering electrode placement and while the animal was still anesthetized. The second voltage readings were compared to the initial voltage outputs obtained for each frequency tested. High input intensity levels (above 100 dB SPL) were excluded from this procedure to avoid sound overstimulation. See Table 1 for a summary of the results.

Table 1. Test-retest differences of repeated input-output functions (IOF's) subtracted from initial IOF's in decibels. Hz-hertz.

Subject	Cochlear IOF's				Vestibular IOF's			
	100 Hz	250 Hz	500 Hz	3000 Hz	100 Hz	250 Hz	500 Hz	3000 Hz
C-5	-3	-1	+1	0	-2	-1	-1	-1
C-7	-1	-2	+1	-1	+1	+2	+1	+3

Samples from both extremes of the results are shown in Figure 2. Differences in the initial and repeated IOF's (i.e., the linear portion of the functions) were 3 dB or less. This indicates acceptable repeatability of the voltage output measurements considering that ± 5 dB is the allowable tolerance in behavioral testing. Of the sixteen pairs of IOF's (each pair consisted of the initial and repeated IOF's), the difference between two pairs of IOF's was 3 dB; three pairs of IOF's differed by 2 dB, ten pairs of IOF's varied no more than 1 dB, and one pair of IOF's were identical. Six of the initial IOF's required more intensity than their repeated IOF counterpart, whereas, nine of the repeated IOF's required more intensity than their initial IOF counterpart (note signs in Table 1). There is no relationship between reliability of voltage output measurements and recording site. That is, variability of voltage output measurements recorded at the round window was not more or less than the variability of voltage output measurements recorded at the vestibule.

Electrode placement. The control subject (C-6) served to establish reliability of the cochlear potentials as a function of electrode placement. Electrodes were repeatedly placed at the round window and vestibule five times. Following each electrode placement cochlear and vestibular IOF's were obtained. An attempt was made to control for permanent or temporary threshold shift by avoiding input intensities over 100 dB SPL.

The five cochlear IOF's recorded for each test frequency were compared by calculating the maximum input variability (in decibels) of the five IOF's at one output level. Using a conservative approach, the output level chosen for each frequency was dependent upon the widest

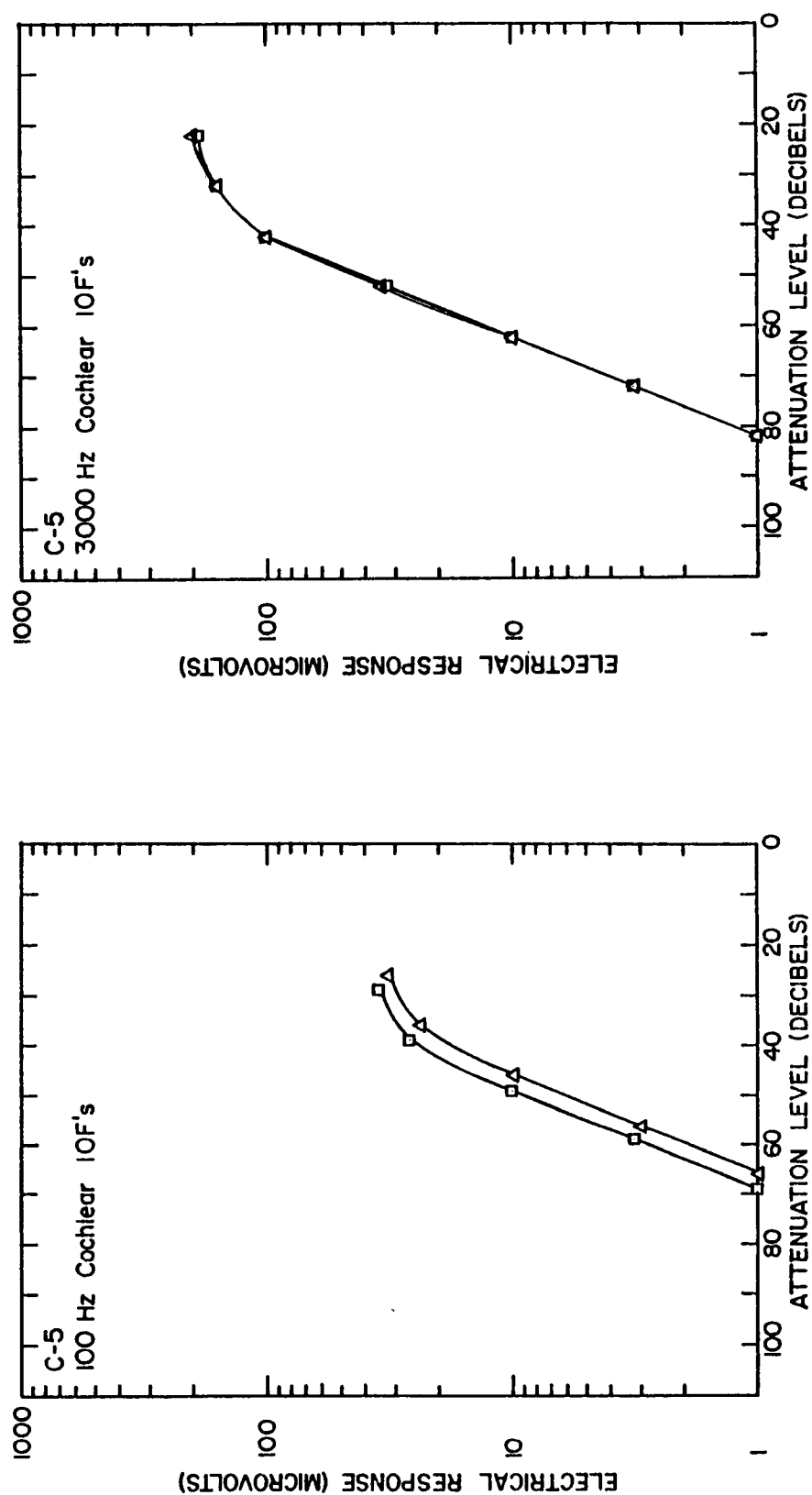


Figure 2. Examples of input-output functions (IOF's) obtained from repeated voltage output measurements. $\square$ - initial voltage output recorded; $\triangle$ - repeated voltage output recorded; Hz-hertz.

variability of the linear portions of the five IOF's. The five vestibular IOF's recorded for each test frequency were compared in the same manner as the cochlear IOF's discussed above. A summary of the results are listed in Table 2.

Table 2. Maximum variability of input-output functions (IOF's) as a function of five repeated electrode placements on one animal (C-6). dB-decibels; Hz-hertz.

Test Frequency (Hz)	Cochlear IOF's				Vestibular IOF's			
	100	250	500	3000	100	250	500	3000
Maximum Variability (dB)	10	8	10	13	12	8	7	10

Results of electrode placement control study are shown in Figure 3. Differences in the five IOF's at any recording site frequency were no greater than 13 dB. For the round window recording site, differences between the five IOF's were 8 dB or less for 250 Hz, 10 dB or less for 100 and 500 Hz and 13 dB or less for 3000 Hz. For the vestibule recording site, differences between the five IOF's were 7 dB or less for 500 Hz, 8 dB or less for 250 Hz, 10 dB or less for 3000 Hz and 12 dB or less for 100 Hz.

For the 3000 Hz round window recording site, increasing amounts of intensity were required to obtain each subsequent IOF, suggesting some degree of temporary or permanent threshold shift which contributed to the 13 dB variability in the IOF's at that frequency. For the remaining round window recording site (i.e., 100, 250 and 500 Hz), IOF's recorded third, fourth and fifth required 5 to 7 dB more intensity than IOF's recorded first and second. This could have been due to temporary or permanent threshold shift occurring after cochlear potentials were

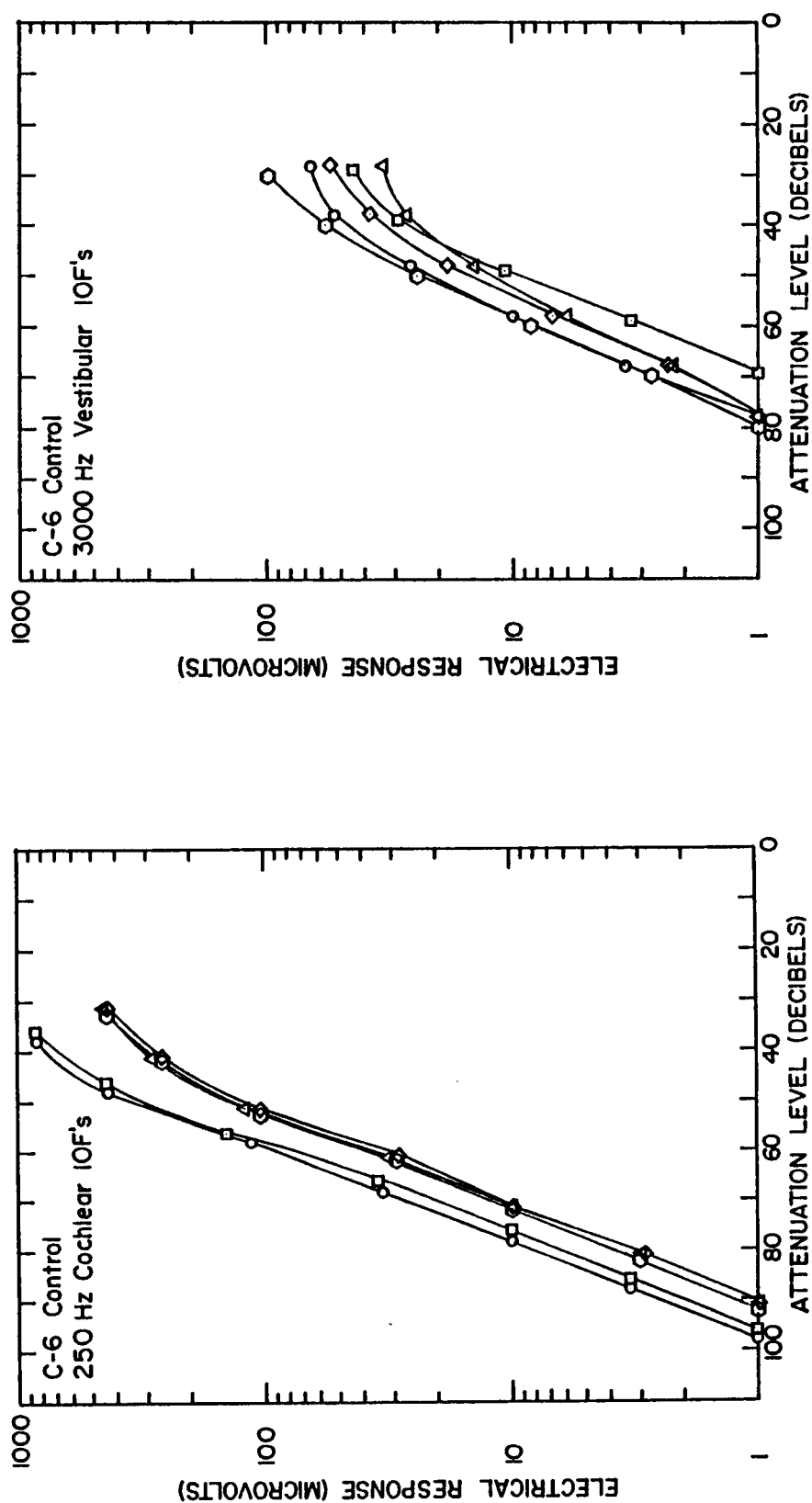


Figure 3. Examples of input-output functions (IOF's) obtained from repeated electrode placement. □ - IOF obtained after first electrode placement; ○ - IOF obtained after second electrode placement; △ - IOF obtained after third electrode placement; ◇ - IOF obtained after fourth electrode placement; ○ - IOF obtained after fifth electrode placement; Hz-hertz.

recorded a second time.

Although overall variability of the vestibular IOF's appear less, these IOF's seem to vary more as a function of electrode placement than threshold shift. This is suggested by the fact that intensity required in recording the IOF's did not consistently increase with repeated measurements (Figure 3). Variability of the cochlear potentials as a function of electrode placement is expected at the vestibule because it is a far-field recording of the cochlear potentials (i.e., a more distant far-field recording than the round window). Reliability of the cochlear potentials as a function of electrode placement was considered acceptable because this study evaluated growth function and not measurements of absolute output.

Analysis of Experimental Data

In this section, comparisons between cochlear IOF's and vestibular IOF's for each test frequency will be discussed. Additionally, the points of nonlinearity and maximum points of cochlear and vestibular IOF's for 100 Hz will be compared to the points of nonlinearity and maximum points of cochlear and vestibular IOF's for 3000 Hz. These findings will be discussed on a group and individual basis.

Recording site comparisons. For each experimental subject, output voltage for all test frequencies from both electrodes were plotted on semi-logarithmic paper (Figure 4 and Appendix C). One animal (C-3) was not included in the data analysis due to grossly spurious responses (see Appendix D). Electrical activity of C-3, recorded from the vestibular electrode, was considerably less than the other experimental animals. This may have been due to a poor electrode placement (i.e.,

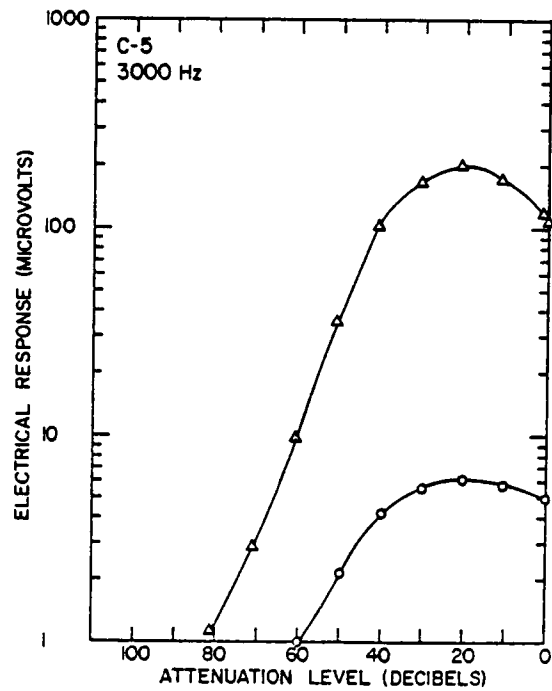
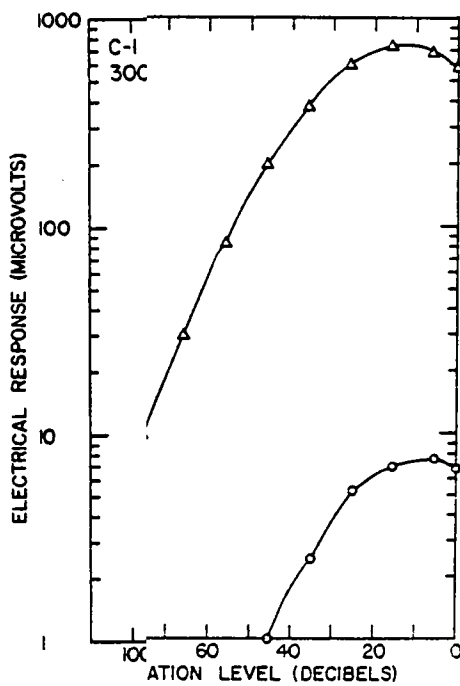
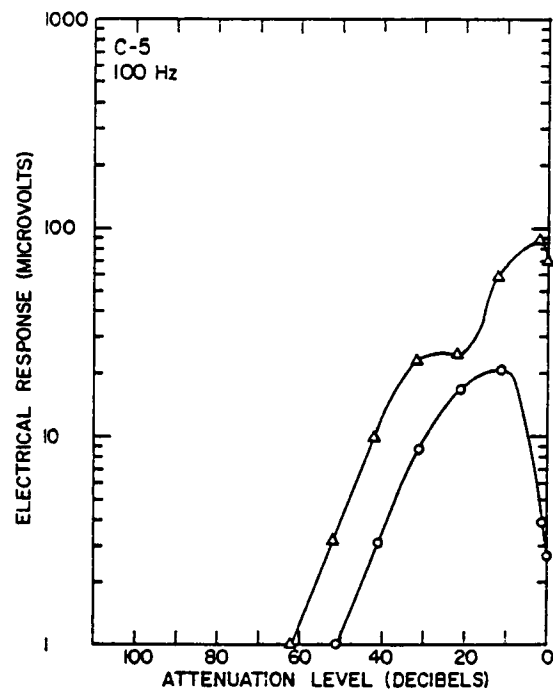
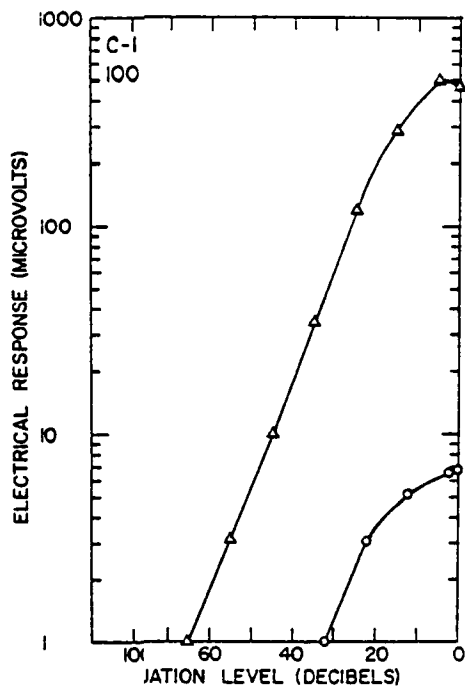


Figure 4. ○—○ -vestibular IOF.

*E:

either touching bone or moved before the dental acrylic dried). Additionally, a greater amount of biological noise was observed when obtaining vestibular IOF's from C-3 than the other experimental animals, making it impossible to record the electrical potentials with any degree of accuracy.

Cochlear and vestibular IOF's for each frequency were compared between subjects to consider if the vestibular IOF parallels, maintains lower output voltage or shows a summing affect to the cochlear IOF. Of the sixteen pairs of IOF's compared (each pair consisted of the cochlear and vestibular IOF for one frequency), twelve vestibular IOF's paralleled their cochlear IOF counterpart, although, they produced a consistently lower output voltage. The linear portion of the twelve pairs of IOF's paralleled one another and their cochlear IOF point of nonlinearity (CPN) occurred within at least 5 dB of their vestibular IOF point of nonlinearity [VPN (see Table 3)]. (The point of nonlinearity for each function was established by drawing a straight line that extends through and beyond the linear portion of the function. The point of nonlinearity was identified as the point where the function began to curve away from the straight line. Two people independently established the points of nonlinearity for all the IOF's as a check.)

Linear portions of the remaining four of the sixteen pairs of IOF's compared, (C-1 for 100 Hz, C-4 for 3000 Hz and C-5 for 250 and 3000 Hz,) are parallel, with the vestibular IOF always exhibiting lower output voltage. However, the CPN of C-1 for 100 Hz, C-4 for 3000 Hz and C-5 for 250 and 3000 Hz occurs at an intensity level which is 13 dB higher, 16 dB lower, 8 dB higher and 12 dB higher, respectively,

Table 3. Points of nonlinearity (in decibels of attenuation) of the cochlear and vestibular input-output functions (IOF's).* CPN-cochlear IOF point of nonlinearity, VPN-vestibular IOF point of nonlinearity; Diff-difference; Hz-hertz.

Subject	Frequency											
	100 Hz				250 Hz				500 Hz			
	CPN	VPN	Diff		CPN	VPN	Diff		CPN	VPN	Diff	
C ₁	19	32	13		27	32	5		31	35	4	
C ₂	29	31	2		39	35	4		53	50	3	
C ₄	23	24	1		35	38	3		49	49	0	
C ₅	40	36	4		44	52	8		52	52	0	

*C-3 was excluded due to grossly spurious results.

than their VPN counterpart. In all four pairs, the VPN occurs at a lower output voltage than the CPN. The range of variability due to electrode placement (see Table 2, page 36), however, would qualify these four pairs of IOF's to be considered parallel to one another. For example, C-1 for 100 Hz CPN is 19 dB of attenuation and its VPN is 32 dB of attenuation. Maximum variability for cochlear IOF's and vestibular IOF's is 10 dB and 12 dB, respectively. If the CPN varied +5 dB of attenuation and the VPN varied -6 dB of attenuation the two points of nonlinearity would be within 2 dB.

Frequency comparisons. Since the vestibular IOF's parallel the cochlear IOF's, any electrical activity being generated by the maculae in response to low frequency auditory stimulation was too small to significantly influence the far-field cochlear IOF configuration. However, more detail analysis of the relative points of nonlinearity provided indication that macular output was measured.

The point of nonlinearity will be discussed in microvolts because the amplitude of the cochlear potentials are considered in this section as opposed to the intensity level (in dB of attenuation) of the input that was considered in the preceeding section. The average voltage for the points of nonlinearity were calculated for all frequencies of each electrode placement (see Table 4). Comparisons of the voltage averages were made using responses to 100 and 3000 Hz stimuli. For these comparison frequencies, the mean voltage for cochlear IOF's were 98.12 and 105.0 μ V, respectively, and the mean voltage for vestibular IOF's were 8.12 and 4.78 μ V, respectively.

The average electrical response for 3000 Hz point of nonlinearity at the cochlea was higher than the average electrical

Table 4. Points of nonlinearity (in microvolts) of the input-output functions recorded at the round window and vestibule.* Hz-hertz.

Subject	Round Window Electrode Placement				Vestibule Electrode Placement			
	100 Hz	250 Hz	500 Hz	3000 Hz	100 Hz	250 Hz	500 Hz	3000 Hz
C ₁	150	200	230	70	20	39	31	10
C ₂	80	200	240	170	4	4.5	5	6
C ₄	150	270	250	75	2.5	3	3	1.5
C ₅	12.5	32.5	33	105	6	5	10	1.6
$\bar{x}$	= 98.12	175.6	188.25	105.0	8.12	12.86	12.25	4.78
Range	12.5-150	32.5-270	33-250	70-170	2.5-20	3-39	3-31	1.5-10

*C-3 was excluded due to grossly different results.

response for 100 Hz point of nonlinearity. This relationship between 100 and 3000 Hz would be expected to hold up when the recording site was farther away, unless a secondary electrophysiological influence contributes to the overall electrical activity being picked up by the far-field electrode. The rationale for the preceding statement can best be explained by an example. A 10 volt 100 Hz pure tone and a 10 volt 3000 Hz pure tone are transduced through a loudspeaker in a free-field. Intensity measurements are taken in front of the loudspeaker at three and six feet for 100 and 3000 Hz. If the intensity measured for 3000 Hz is twice as much as the intensity measured for 100 Hz at three feet, then the intensity measured at six feet will be proportionally greater for 3000 Hz than for 100 Hz. However, this relationship between 100 and 3000 Hz would be modified if a 100 Hz near-field signal is picked up when measurements of the original sound source are taken at six feet. In this case, the intensity measured for 100 Hz may possibly be greater than the intensity measured for 3000 Hz.

The reversal of the relationship between these comparison frequencies was apparent when an electrode was placed at the vestibule. The average electrical response for 100 Hz point of nonlinearity was higher than the average electrical response for 3000 Hz point of nonlinearity at the vestibule. The macular areas, when stimulated by low frequency sound may, therefore, be contributing to the total electrical response. The difference between the average voltage for 100 Hz and 3000 Hz VPN is not overly large, but in view of the low DC polarization of the saccule (+1 mv) and utricle [+4 mv (Smith et al., 1958; Gannon et al., 1958)], this difference would not be expected to be very large. This is particularly true since the average voltage

for 3000 Hz CPN is larger than the average voltage for 100 Hz CPN.

Another interpretation of this reversal is frequency effect on far-field recordings. The possibility of this interpretation is reduced due to the small distance involved between the cochlear and vestibular electrodes (4 mm) and the relative placement of the electrodes. That is, the cochlear electrode is "X" distance from the cochlear area that is activated by a 3000 Hz pure tone and "Y" distance from the cochlear area that is activated by a 100 Hz pure tone. The vestibular electrode is "X + Z" distance from the 3000 Hz generator area of the cochlea and "Y + Z" distance from the 100 Hz generator area of the cochlea. Therefore, the same relative distance between electrode and cochlear generators is maintained by electrode placement.

The mean maximum IOF voltage was calculated for each response (see Table 5). Comparisons made between 100 and 3000 Hz found mean voltages for the cochlear IOF's were 292.0 and 370.75 μ V, respectively, and mean voltages for vestibular IOF's were 30.45 and 16.88 μ V. The pattern of electrical responses for the mean maximum IOF voltage was like the electrical response pattern of average voltage for the points of nonlinearity. The average maximum IOF voltage was higher for 3000 Hz than for 100 Hz at the round window. However at the vestibule, the average maximum IOF voltage was higher for 100 Hz than for 3000 Hz. Once again, we would expect to see the same voltage relationship between the comparison frequencies at the cochlea to exist in a far-field recording, unless other electrical activity generated adds to the overall electrical response. This reversal observed for the mean maximum IOF voltage adds support to the notion that the vestibular

Table 5. Maximum points (in microvolts) of the input-output functions recorded at the round window and vestibule.* Hz-hertz.

Subject	Round Window Electrode Placement				Vestibule Electrode Placement			
	100 Hz	250 Hz	500 Hz	3000 Hz	100 Hz	250 Hz	500 Hz	3000 Hz
C ₁	340	420	460	220	75	86	69	38
C ₂	240	520	900	320	19	23	24.5	16
C ₄	500	890	970	740	6.8	11.5	12	7.4
C ₅	88	120	150	203	21	19.3	21	6.1
$\bar{X}$	292.0	487.5	620.0	370.75	30.45	34.95	31.62	16.88
Range	88-500	120-890	150-970	203-740	6.8-75	11.5-86	12-69	6.1-38

*C-3 was excluded due to grossly different results.

electrode was receiving an electrical response from the macula when low frequency sound was directed into the ear canal.

Since the results support the hypothesis that acoustic stimulation activates a measurable vestibular electrical potential, the data from this study offer important implications for including vestibular considerations in aural habilitation/rehabilitation. The vestibular system can be a concurrent modality for hearing impaired people to develop, in order to better perceive speech. Aural habilitation/rehabilitation approaches, such as the Verbo Tonal Method, allow the vestibular system to participate in the reception of auditory stimuli by utilizing low frequencies.

Individual results. When viewing the results from each subject, there is variability in comparing the output voltages. C-1 displays larger electrical responses for 100 Hz than for 3000 Hz at points of nonlinearity of cochlear and vestibular IOF's and maximum points of cochlear and vestibular IOF's (see Table 4 and 5, page 43). C-2 displays larger electrical responses for 3000 Hz than for 100 Hz at points of nonlinearity of cochlear and vestibular IOF's and maximum points of cochlear IOF's, but indicated a larger electrical response for 100 Hz than for 3000 Hz at maximum points of vestibular IOF's. C-4 for 100 Hz indicates larger electrical responses than for 3000 Hz at points of nonlinearity of cochlear and vestibular IOF's, and displays larger electrical responses for 300 Hz than for 100 Hz at maximum points of cochlear and vestibular IOF's. C-5 indicates larger electrical responses for 100 Hz than for 3000 Hz at points of nonlinearity and maximum points of vestibular IOF's, and displays a larger electrical

response for 3000 Hz than for 100 Hz at points of nonlinearity and maximum points for cochlear IOF's.

No explicit reason can be cited by the author to account for the considerable amount of variability that exists among the subjects. Problems encountered by the vestibular electrode placement may be a possible reason. When this electrode varies in distance from the vestibule, the total output picked up by the electrode is influenced. It is sufficient to say, however, that the findings must be viewed cautiously in light of subject variability.

Summary

It was found that IOF's recorded at the vestibule generally paralleled IOF's recorded at the cochlea at a lower output voltage for each test frequency. This suggests any electrical activity generated by vestibular maculae in response to low frequency auditory stimulation, was too small to be detected with such a gross measurement and analysis method.

Further data analysis showed the mean output voltage for the points of nonlinearity of cochlear IOF's for 3000 Hz is slightly higher than for 100 Hz, and the reversal is seen for vestibular IOF's. That is, the mean output voltage for 100 Hz is almost twice as much as for 3000 Hz at the points of nonlinearity of vestibular IOF's. The same relationship appeared when the mean maximum IOF voltage for 100 Hz was compared with 3000 Hz. The mean maximum voltage of cochlear IOF's for 3000 Hz was somewhat higher than for 100 Hz, but the mean maximum voltage of vestibular IOF's for 100 Hz was almost twice as much as for 3000 Hz. These reversals that occurred suggest the

chinchilla maculae may be generating enough electrical activity, when stimulated by low frequency sound, to contribute to the overall electrical response picked up by an electrode placed at the vestibule.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purpose of this study was to investigate possible macular response to low frequency sound. While in the presence of a pure tone, the electrical response measured at the vestibule was compared to the electrical response measured at the round window.

Six standard gray chinchilla selected for this study demonstrated good health and normal cochlear potential input-output functions. Two silver ball electrodes were implanted in each animal's left ear, one in the vicinity of the round window, the other was oriented towards the vestibule. The electrical activity at each recording site was noted for 100, 250, 500 and 3000 Hz in increasing 10 dB increments, using 1 microvolt as a sensitivity criterion. Pure tone input did not exceed 133 dB SPL. One animal was disqualified. Two animals were randomly selected for test-retest measures and one animal, C-6, served as a control to establish measurement reliability as a function of electrode placement. The control study involved repeating electrode implantation and measurement procedures five times. Pure tone input did not surpass 100 dB SPL for both test-retest measurements and the control study, in an attempt to control for threshold shift. Input-output functions (IOF's) were constructed for the purpose of comparing response curves from the vestibule electrode to response curves from the round window electrode.

Test-retest measurements were within ± 5 dB and for the control animal, differences in the five IOF's did not exceed 13 dB at any recording site frequency. Reliability of the procedures was considered acceptable for purposes of this study. IOF's constructed from potentials obtained at the vestibule generally paralleled the IOF's constructed from potentials obtained at the round window for 100, 250, 500 and 3000 Hz. All vestibular readings were lower in output voltage because this was predominately a remote (far-field) cochlear response. The average voltage for the points of nonlinearity for 3000 Hz cochlear IOF's was slightly higher than the average voltage for the points of nonlinearity for 100 Hz cochlear IOF's. However, the average voltage for the points of nonlinearity for 100 Hz vestibular IOF's was almost twice as high as the average voltage for the points of nonlinearity for 3000 Hz vestibular IOF's. Another similar finding was the mean maximum IOF voltage for 3000 Hz cochlear IOF's was higher than the mean maximum IOF voltage for 100 Hz cochlear IOF's. The vestibular IOF's mean maximum voltage was almost twice as much for 100 Hz than for 3000 Hz. These findings suggest chinchilla maculae may be generating enough electrical activity, when stimulated by low frequency sound, to contribute to the overall electrical response obtained at the vestibular electrode.

Conclusions

The mean results of this study tend to support the theory that low frequency sound does stimulate the peripheral vestibular organs (i.e., the maculae), such that small electrophysiological output can be detected. Implications of the findings for aural habilitation/

rehabilitation are the vestibular response should not be disregarded. Methods, such as the Verbo Tonal Method, which utilize low frequencies should be expected to yield satisfactory results partly on the basis of the contribution of the vestibular mechanism response to an auditory signal.

Limitations of the Study

The following factors are limitations cited by the author:

- (1) These measurements were gross measurements as opposed to single unit measures of cochlear and vestibular neural response.
- (2) Difficulties encountered by electrode placement (especially the vestibular electrode), influenced variability in the measurements.
- (3) It would have been useful to have been able to test frequencies below 100 Hz when measuring the cochlear and vestibular potentials. Equipment limitations and noise background precluded doing so.

Implications for Further Study

Suggestions for future research warranted by this study include:

- (1) A study investigating cochlear potentials following destruction of the auditory end organ and/or the vestibular end organ.
- (2) Replicating this study using microelectrodes placed in the sensory and/or neural portions of the maculae and organ of Corti.
- (3) Replicating this study, however using stimulus frequencies below 100 Hz.

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APPENDIXES

APPENDIX A

Table 6. Results of the linearity check of the attenuator used in the system. dB- decibel.

Attenuator Setting	Voltage Output (millivolts)	Decibel Level re: 0dB Attenuation
0	9900	0
10	3100	-10.1
20	990	-20.0
30	320	-29.8
40	98	-40.1
50	31	-50.1
60	9.7	-60.2
70	3.1	-70.1
80	0.98	-80.1
90	0.31	-90.1
100	0.091	-100.1

APPENDIX B

Table 7. Results of acoustic calibration and linearity check of the system. Hz-hertz; $\leq$ less than.

Decibels of Attenuation	Acoustic Output in Decibels											
	Calibration before Subject 1				Calibration before Subject 4				System check after Subject 6			
	100 Hz	250 Hz	500 Hz	3000 Hz	100 Hz	250 Hz	500 Hz	3000 Hz	100 Hz	250 Hz	500 Hz	3000 Hz
0	133.1	132.1	130	117.7	132.9	133.3	130	114.5	132.1	133.0	129.4	114.8
10	121.8	120.7	119.3	108.3	118.8	122.2	119.3	105.0	119.2	121.8	118.5	105.3
20	108.8	109.5	108.5	98.2	106.8	110.9	108.6	95.1	107.2	110.5	107.8	95.3
30	98.0	98.9	98.3	88.6	96.0	100.6	98.4	85.5	96.3	100.1	97.4	85.6
40	87.7	88.8	88.3	78.5	85.7	90.2	88.3	75.4	85.9	89.8	87.4	75.5
50	77.4	78.6	78.0	68.6	75.4	80.2	78.1	65.5	75.7	79.6	77.2	65.7
60	67.3	68.6	68.1	58.4	65.3	70.0	68.1	55.3	65.6	69.5	67.2	55.4
70	57.2	58.6	58.1	48.7	55.3	60.1	58.1	45.6	55.6	59.5	57.2	45.7
80	47.3	48.8	48.3	38.7	45.4	50.1	48.2	35.5	45.6	49.7	47.3	35.6
90	36.5*	38.5*	38.2	<30.0	35.1*	40.6*	38.3	<30.0	35.4*	40.2*	37.3	<30.0
100	----	----	<30.0		----	----	<30.0		----		<30.0	

*Noise floor.

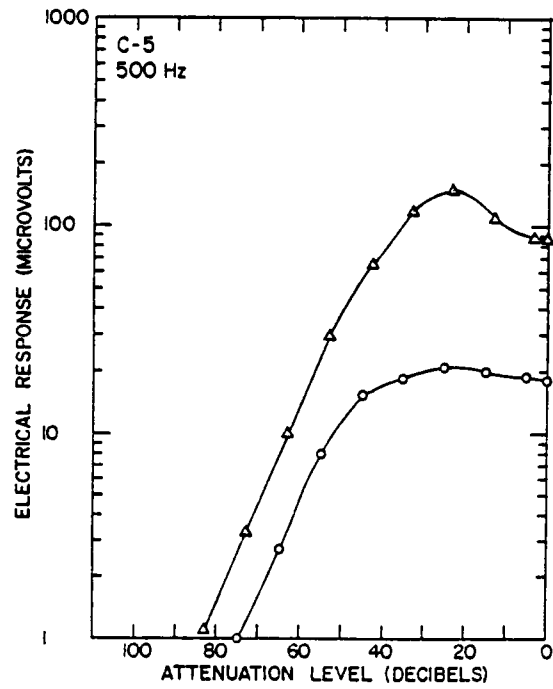
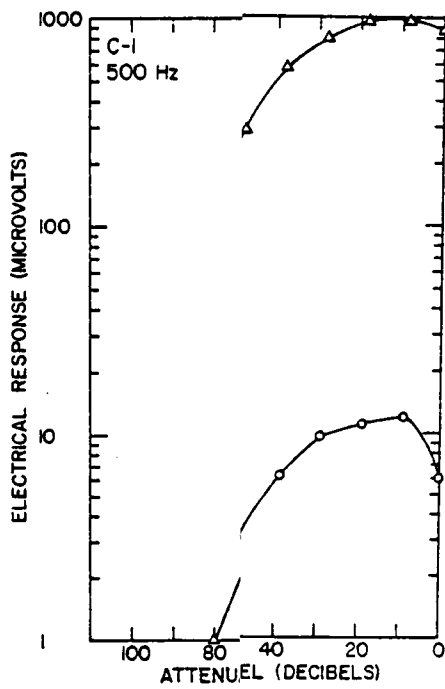
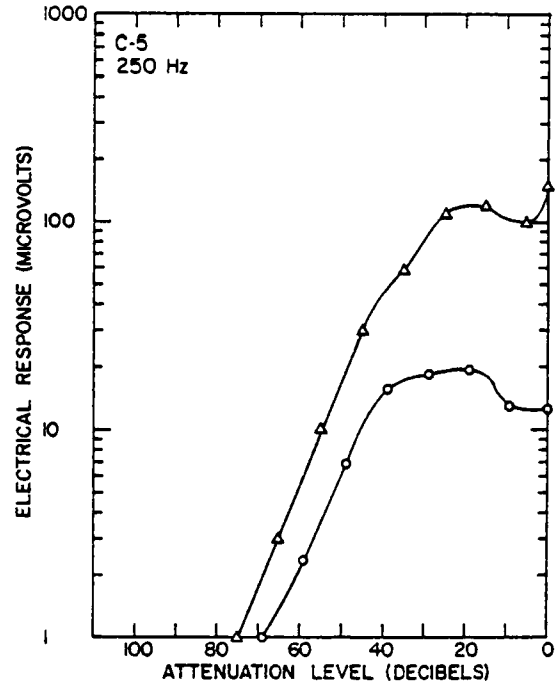
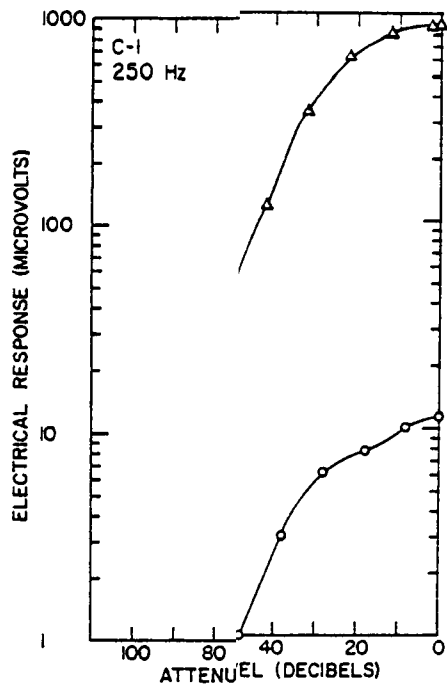


Figure 5. ○—○ vestibular IOF.

*Exc

APPENDIX D

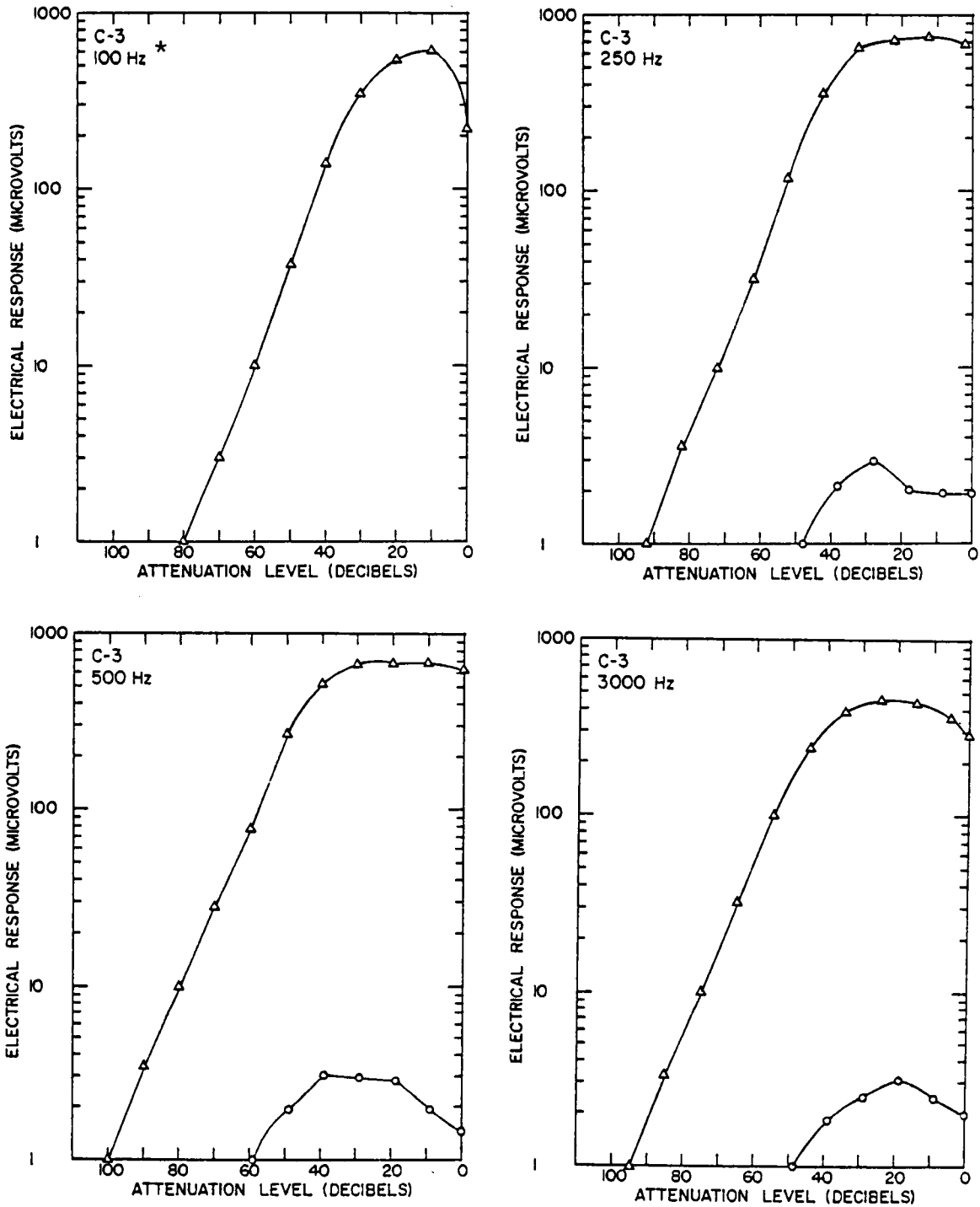


Figure 6. Input-output functions (IOF's) plotted for C-3. $\triangle-\triangle$ - cochlear IOF; $\circ-\circ$ - vestibular IOF; Hz-hertz.

*Measurements from vestibular electrode were not obtainable due to biological noise.

VITA

Ellen Levi was born in Portsmouth, Ohio on June 22, 1956. She attended elementary and secondary schools in Portsmouth, Ohio and was graduated from Portsmouth High School in June 1974. The following August she entered Indiana University, Bloomington, Indiana, and in August 1978 she received a Bachelor of Science degree in Communication Disorders from The University of Texas, Austin. From September 1978 through June 1979 she worked for the Texas School for the Deaf, Austin, as an audiologist's assistant. She entered the Graduate School of The University of Tennessee, Knoxville, in September 1979. The author received a Master of Arts degree with a major in Audiology in August 1981.