ACTION POTENTIALS RECORDED FROM THE PROMONTORY AND EAR CANAL SIMULTANEOUSLY, WITH INDUCED MIDDLE-EAR LIQUIDS

by

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A Thesis Submitted to the Faculty of the DEPARTMENT OF SPEECH AND HEARING SCIENCES
In Partial Fulfillment of the Requirements For the Degree of MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1979
STATEMENT BY AUTHOR

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ACKNOWLEDGMENTS

I would like to thank Dr. Theodore J. Glattke for making this investigation possible. He was a brilliant source of information and inspiration, and offered the direction, confidence, and friendship which enabled me to do this thesis.

I would also like to thank Dr. T. J. Hixon and Dr. W. R. Hodgson for their editorial criticisms.

I am especially grateful to all those friends who showed me encouragement, understanding, and a sense of humor from the beginning to the end.
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ABSTRACT

This experiment was conducted to determine the characteristics of the compound action potential response under conditions simulating conductive hearing loss in the guinea pig. Responses were obtained from both the promontory and the external ear canal in order to compare two commonly used recordings.

The results were: that response amplitude is decreased in both the ear canal and promontory sites when liquid conditions were induced, response latency increased at both sites under the liquid conditions, and threshold values increased for both recording sites when the liquid conditions were present as compared to the baseline recording thresholds.

A major finding of this study was that $N_2$ was dominant in ear canal recordings and increased in comparison to $N_1$ as the frequency and intensity decreased. Although $N_2$ was present in the promontory responses, it was not affected by stimulus parameters to the degree observed for the ear canal recordings. $N_2$ became even more dominant over $N_1$ with the introduction of liquids into the system.

It was speculated that the electrically conductive properties of the different liquids influenced their response. These findings suggest that some caution may be
required when surface recording sites are used for obtaining responses from patients.
INTRODUCTION

Electrocochleography (ECoG) involves the measurement of electrophysiologic potentials resulting from the presentation of various acoustic stimuli to an ear. It is possible to estimate the integrity of the peripheral auditory system using ECoG because the characteristics of the potentials used for analysis are associated with various structures of the cochlea or the auditory nerve.

This study is concerned with the measurement of changing characteristics of an electrophysiologic manifestation of VIIIth cranial nerve activity, known as the compound action potential (AP). AP's are considered the principal component in ECoG. Major landmarks of the recording of this potential were established by Wever and Bray (1930) and Derbyshire and Davis (1935). Since that time, with the help of averaging computers and other technological developments, recording techniques have been refined. Reliable AP responses can now be recorded from indwelling electrode sites (Deatherage and Davis, 1959; Yoshi, Ohashi, and Suzuki, 1967; Portmann and Aran, 1971; Eggermont and Odenthal, 1974; Naunton and Zerlin, 1976), or surface electrodes (Sohmer and Feinmesser, 1967; Yoshiè et al., 1967; Jewett, 1970; Moore, 1971; Montandon, Megill, et al., 1975).
Many reports have dealt with the question of how a sensori-neural loss will affect waveform, threshold, amplitude, and latency of an AP (Davis et al., 1958; Yoshie and Ohashi, 1969; Eggermont and Odenthal, 1974; and others). Experiments which studied the effects of a conductive problem on ECoG response characteristics have not enjoyed such an extensive history. Expected results with a conductive hearing loss are consistent with the effect of a reduction in stimulus magnitude. AP's associated with conductive loss are not significantly different from those expected in normal-hearing subjects. However, some discrepancies have been indicated in the literature on this topic. Large variations and changes in amplitude as well as unique waveforms have been noted (Eggermont and Odenthal, 1974; Montandon, Shepard, et al., 1975). The variability of results from previous studies regarding conductive hearing losses has prompted the present investigation.
REVIEW

Characteristics of the Compound AP

Wever and Bray (1930) first recorded electrical potentials from the auditory nerve of a cat. The activity was thought to represent only neural responses but was later recognized as being composed of whole-nerve compound AP's and Cochlear Microphonics (CM) (Derbyshire and Davis, 1935).

An AP for an abrupt auditory stimulus is illustrated in Figure 1. The AP is byphasic in nature, each component consisting of a negative and then subsequent positive phase. This compound response is considered by contemporary authors to be formed by the summed activity of hundreds of nerve fibers, firing essentially in synchrony (Eggermont and Odenthal, 1974). The waveform, amplitude, latency, and stimulus threshold of a visible N₁ response are characteristic measures of AP's obtained for analysis in ECoG. A brief discussion of these measurements follows.

Waveform

The shape of a normal compound AP depends on the frequency of the stimulus. Derbyshire and Davis (1935) and later Teas, Eldredge, and Davis (1962) showed that at low frequencies the AP follows each cycle of the sine wave. However, above 2000 Hz the AP is apparent at the beginning
Figure 1. The Compound Action Potential and Typical Input-Output Function for Latency and Magnitude
and end of a signal only, demonstrating an "on-effect" and an "off-effect" (Goldstein and Kiang, 1958; Eggermont and Odenthal, 1974).

Latency

The latency of an AP can be defined as the time between the arrival of a stimulus at the eardrum and the peak of the \( N_1 \) component of the AP. Latencies have been found to increase with decreasing frequencies (Zerlin and Naunton, 1975), and decrease with an increase in stimulus intensity (Deatherage and Davis, 1959).

Amplitude

Amplitude of an AP is determined by measuring the magnitude from a prestimulus baseline tracing to the peak of the \( N_1 \) response of an action potential. This property of the response is thought to increase with the number of activated nerve fibers (de Boer, 1977), which makes it frequency-dependent as well as intensity-dependent (Naunton and Zerlin, 1976). Other factors, such as the conductivity of the system from which a potential is recorded and noise levels within the recording equipment, can influence the relationships among stimulus properties and response amplitude, as well as waveform (Durrant and Ronis, 1975).
Growth

Tasaki (1954) was the first to obtain comparisons between the timing of single unit discharges and the AP. He noted a parallelism between the size of $N_1$ and the probability of obtaining double discharges from single primary neurons. Some recent researchers who support this contention are Teas et al. (1962), Eggermont and Spoor (1973), and Eggermont and Odenthal (1974). These researchers as well as others strongly suggest that due to the shape of the input-output functions obtained from subjects in research experiments (an increase in amplitude followed by a plateau with a subsequent increase), two neural populations might contribute to the response. The first population represents a group of sensitive neurons that respond at low intensities and thus determine AP threshold. Once this group ceases to contribute to the VIII nerve response at higher stimulus levels, a second less sensitive group begins to contribute to the total response. These two threshold populations were thought to originate at the outer and inner hair cells, respectively (Davis, 1961; Dallos and Bredberg, 1973).

In other experiments, no evidence was found to support the contention that the two hair cell populations have different thresholds. Özdamar and Dallos (1976) have reported that there are no clear electrophysiological signs of two distinct populations responding with different thresholds. The slow growing, low level segment of the
input-output function was identified with the sharp tip region of the tuning curves of responding units. The higher level, rapidly-growing segment, was associated with recruitment of higher frequency units that respond on the tail portion of their tuning curves. Thus the low and high parts of the input-output curves were interpreted in terms of the excitation of the narrow and wide segments of the cochlear receptor.

Threshold

The threshold of AP responses for various click and total stimuli is estimated to be within approximately 10-20db of behavioral thresholds (Salomon and Elberling, 1971; Odenthal and Eggermont, 1974; Zerlin and Naunton, 1975). Shifts in threshold have been seen for flat conductive hearing losses as well as for some frequency-specific losses. Those shifts will be discussed later in this manuscript.

Origin of the Compound AP

It is widely assumed that the AP reflects the simultaneous firing of nerve fibers that innervate the basalmost portion of the cochlea. This reasoning is based on the assumption that in order to build up a sizeable AP, time synchrony among the individual sources is required (Dallos, 1973). Fibers originating from more apical regions are activated after an appropriate traveling wave delay.
Deatherage and Davis (1959) stated that the latency of an AP response reflects the modal value of the latencies of many neurons that have been synchronously stimulated. This suggestion supports a conclusion that an intact basal hair cell segment is required to achieve normal AP sensitivity.

While the AP is considered to be a response of the auditory nerve, the question of its specific site of origin has recurred frequently in the literature. In 1950, Davis, Fernandez, and McAuliffe wrote that the origin of the AP was in the spiral ganglion. Some other reports speculating about the origin of the AP have been those of Davis, Tasaki, and Goldstein (1952); Tasaki (1954); Pestalozza and Davis (1956); and Teas et al. (1962). Some of these earlier investigators believed that the whole nerve activity was registered as an AP as the neural depolarization passed through the internal auditory meatus. Teas et al. (1962) later refined this opinion by specifying that what is signified as the AP is the emergence of the electrical changes from the internal auditory meatus. It is now more apparent that the axons contribute to the AP response, while the cell body is primarily responsible for metabolic functions (Dallos, 1973).

$N_2$

$N_{1\,II}$ (denoted by $N_2$ by Coats and Dickey, 1970 and Coats, 1971) can often be seen as an additional negative
component after the characteristic $N_1$ response. The $N_2$ deflections have essentially the same waveform as $N_1$ (negative then positive), but are smaller in magnitude. $N_2$ is always present in guinea pig recordings and may have a different origin than in humans, for whom it arises only at higher stimulus levels (Spoor, Eggermont, and Odenthal, 1976). Two of the more frequently discussed hypotheses regarding $N_2$ will be briefly reviewed here.

Mitchell and Fowler (1976) found that $N_2$ changes in peak latency and waveform considerably with a change in the location of the electrode recording sites. These authors believe that this evidence supports the hypothesis that $N_2$ is composed of the repetitive firing of cochlear afferents and neurons in the cochlear nucleus or brainstem. Similarly, Durrant and Ronis (1975) found that $N_2$ changed in amplitude along with a change in the recording site.

The second major hypothesis concerning the origin of $N_2$ suggests that the firing of cochlear receptor cells at the apex of the cochlea contributes to the production of $N_2$. Pugh et al. (1972) provide major support of this contention. Their conclusion is supported by the following findings:

1. Changes in position of recording electrodes produce different changes in the amplitude of $N_1$ and $N_2$.
2. Paired click stimuli permit electrical summation of $N_2$. 
3. High frequency noise attenuates $N_1$ to a greater degree than $N_2$.

4. Certain degrees of low frequency masking attenuate $N_2$ to a greater degree than $N_1$.

5. Selective cooling of the apex of the guinea pig cochlea results in a relatively greater reduction in $N_2$ than in $N_1$.

The fact that $N_2$ changes with a change in the recording site, as reported by Mitchell and Fowler (1976) and Pugh et al. (1972), could also be interpreted as support of the evidence supplied by Pugh et al. for apical firing of the cochlear afferents being the origin of $N_2$.

The origin of $N_2$ is still a highly disputed question. Whether it is due to threshold differences in the hair cells, apical firing of the cochlear receptor cells, or some other phenomenon is yet to be determined.

**Conductive Experiments**

A review of studies directed toward or including the measurement of a conductive hearing loss by ECoG over the past ten years suggests that a conductive loss will result in a shift of an input-output function to the right on the intensity axis (Yoshie, 1968; Ruben, 1967; Eggermont and Odenthal, 1974; Montandon, Shepard, et al., 1975; de Boer, 1977, Weiderhold, Martinez, Scott, and de Fries,
Some of the individual characteristics of the AP will be discussed below.

Latency

This characteristic has been cited as a fairly stable component of the AP. Aside from the shift to the right of the intensity axis stated above, a truncation of the input-output curve also exists when a conductive loss has occurred (Montandon, Shepard, et al., 1975; Weiderhold, Martinez, Scott, and de Fries, 1978). This truncation is apparent with respect to latency and growth characteristics of the AP.

Amplitude

It is this aspect of the compound AP in which the most variations have been reported. For example, Montandon, Megill, et al. (1975) found that maximum amplitude values of the AP's from an ear with a conductive loss were larger than those obtained from a subject with normal hearing. They hypothesized that these enlarged AP values were due to a change in the electrical conductivity of the middle-ear membrane perforations and middle-ear fluid. Similarly, de Boer (1977) obtained higher maximum amplitudes AP's from his conductive subjects. De Boer also agreed that these results were due to a change in conduction. Finally, Weiderhold, Martinez, Scott, and de Fries (1978) found that in using tubal ligation with cats to cause a middle-ear
effusion, AP amplitudes increased due to the probable im-
provement of the electrical conductive pathway.

In contrast to these findings, Eggermont and
Odenthal (1974) found that no high amplitude values existed
when recording from subjects with a conductive loss. They
also noted that the normal input-output function was not
applicable to the input-output function obtained from
responses of a subject with a conductive loss.

Studies showing great variability of the AP response
associated with conductive hearing loss have used ear canal
recording sites (Yoshie, 1968; Yoshie and Ohashi, 1969;
Montandon, Shepard, et al., 1975; Elberling, 1976;
Weiderhold, Martinez, Scott, and de Fries; and others). The
more stable data have come from studies using promontory or
round window recording sites (Ruben, 1967; Yoshie and Ohashi,
1969; Eggermont and Odenthal, 1974; and others). Hence, it
seems possible that recording site selection may influence
the response characteristics of a compound AP.

**Goals**

This study was prompted by the variability of
findings reported for conductive hearing loss. The pre-
dominant questions were:

1. Will the ear canal responses mimic the promontory
responses in the normal ear, for either baseline or
simulated conductive-loss conditions?
2. If the two sites do not have the same response characteristics, how do they differ?
PROCEDURE

Subjects

Electrocochloegraphic recordings were obtained for twelve albino guinea pigs. Data from five subjects comprise the present findings. Data from seven of the guinea pigs were not used due to surgical complications or because of a change in instrumentation. The subjects' weight ranged from 228 grams to 475 grams. Approximately eight hours were allowed per subject for preparation and recordings.

Preparations

Animals were transported from The University of Arizona Animal Resource Center where they were maintained. Upon arrival their weight was determined and they were anesthetized with interperitoneal sodium pentobarbital (Nembutal) at a rate of 30 mg/kg. Supplemental doses of 15 mg/kg were administered as needed. Depth of anesthesia was estimated by testing for loss of withdrawal and corneal reflexes. Xylocaine was administered around the lateral and ventral areas of the soft tissue adjacent to the mandible. Body temperature was maintained by draping the subjects and placing them on a heating pad (G. Rupp).

A tracheotomy was then performed. The trachea was exposed by midline incision. A tracheal stoma was then
formed by a small incision between two of the cartilaginous rings. A small ventilating tube which connected to an artificial respirator (Narco Bio Systems, Inc., Model VSKG) was secured in the stoma.

All subjects in this study received a small vertical incision at the base of the pinna to enable insertion of the ear bar. This facilitated straightening of the external canal for proper placement of the ear bars. The subject was mounted in a stereotaxic frame (D. Kopf Instr. Co.) to stabilize the head in preparation for surgery.

The right bulla was then exposed by making an incision ventral to the right mandible. Soft tissue was elevated with dull dissection. The external carotid artery was ligated when it interfered with the surgical field.

Recordings were obtained using an open bulla system. Dallos (1973) has commented that the principal effect of an open bulla system is a shift in resonance to a lower-than-normal frequency. The anticipated shift was considered not to be critical in the present study.

**Electrodes**

The promontory electrode was an 18 gage hypodermic needle, insulated with Isonel 31 (Schenectady Varnish Co.) with the exception of the tip. The ear canal electrode was an insulated (Formvar) stainless steel 7 mil wire, lacking insulation approximately one cm from the tip. The wire
electrode was inserted in the floor of the canal with a hypodermic needle. The communally shared reference electrode was also 7 mil wire stripped in a manner similar to the active ear canal electrode. It was placed in soft tissue of the subject's neck, contralateral to the test ear (see Figure 2). The stereotaxic frame served as the ground.

**Stimuli and Instrumentation**

Tone bursts of 500, 1000, 2000, and 4000 Hz, as well as rarefaction clicks were presented through a small insert earphone (Audiovox 9C). The transducer was inserted at the end of a hollow ear bar which was held firmly in place by the stereotaxic unit. The hollow ear bar was inserted into the ear canal up to the tympanic membrane.

Tone bursts were generated by a function generator (Interstate F46) and shaped by an electronic switch (Grason-Stadler 829-D) with a rise-decay time of .5 msec.

Electrical waveforms were routed through a step attenuator (HP 350D) and an impedance-matching transformer (UTC LS-33). Stimulus SPL was determined by calibration of the transducer/ear bar combination with a Bruel and Kjaer (2202) sound level meter and associated coupler.

A plateau of 10 msec was established for the tone duration. The interstimulus time interval was 90 msec. The transient stimuli were rectangular pulses of 100 µsec duration.
Figure 2. Placement of Recording Electrodes
All stimuli were externally triggered at a rate of 10 per second under control of the averaging computer (Data General, Nova 3). This repetition rate was used because of evidence that there is reduction in response magnitude and increased threshold with higher repetition rates (Eggermont and Odenthal, 1974; Zerlin and Naunton, 1975).

The tonal stimuli were presented in random phase in order to abolish the CM component of the elicited response. The AP could then be recorded free from any intermingled CM as well as electrical artifacts that may have been present (Eggermont and Odenthal, 1974). A dual-channel oscilloscope (Tektronix RM 504) was used to monitor signal parameters.

The electrical signals derived from the promontory and ear canal of the subjects in response to the auditory stimulus were so small that they could hardly be distinguished in the normal background noise. By using an average response computer and repeating the stimulus at a rate of 10 per second with a 100 sample average, the signal-to-noise ratio was improved (Spoor, 1974). The computer was programmed to record responses from both the ear canal and promontory simultaneously.

The signals detected by the electrodes were amplified by differential amplifiers (Tektronix RM 122) placed in the recording chamber, a sound attenuated room. All other recording apparatus was located outside the chamber. The gain of the preamplifiers was 1000, with a
passband (3 db down) from 300 Hz to 3000 Hz. The output of both preamplifiers was led through the wall of the room to the main buffer amplifiers (custom built), to provide a total gain of 400,000 for ear canal recordings and 20,000 for promontory recordings (see Figure 3 for schematic).

**Experimental Conditions**

An initial baseline condition was established to obtain the animals' AP responses prior to modifying the middle-ear system. These baseline data served as a reference for changes occurring when the middle ear system was modified, as well as to insure the experimenter that subsequent baseline measures had returned to an unmodified state. Additional baseline sets were obtained after removal of the two liquids used in this study.

Following the first baseline recording, the bulla of the animal was partially filled with distilled water, by irrigation with a syringe and a 22 gage hypodermic needle. The bulla was filled to a level just below where the needle electrode met the promontory, so that the electrode was not immersed in the liquid medium (see Figure 2). Recordings were then obtained for the various stimuli for all intensity levels which visibly elicited a response. A second baseline recording was obtained following the removal of distilled water. Liquid was removed by gentle suction, once again using a 22 gage hypodermic needle and syringe, as well as by
Figure 3. Schematic of Instrumentation
swabbing the open bulla using a cotton wick. Saline was introduced into the bulla after the second baseline was obtained. Recordings were then obtained from the promontory and ear canal with the presence of this medium. A final baseline recording was obtained following the removal of the saline.

Each of the tone bursts and the transient stimuli were presented at stimulus SPL's ranging from response threshold to maximum limits of the apparatus, in 10 dB steps, for every experimental condition.

**Analysis**

The amplitude of a response was determined by taking the difference between a baseline value occurring directly before $N_1$ and the maximum negative deflection (or "peak") of $N_1$ itself (see Figure 1). Individual amplitude values were obtained from the computer by use of a cursor. Once the cursor was placed on the data point of interest, a numerical value corresponding to the baseline value of the data point was displayed on the operator's terminal. The difference between the baseline and negative peak was then divided by the total amplification of the system to determine the magnitude of the original, unamplified response.

The latency of a response was determined by using the cursor to measure the time period from the beginning of the stimulus to the maximum negative peak of a response.
Once again, the values for each site were displayed by the computer. The bin number which was occupied by the point of maximum negative deflection in a response was multiplied by 96 μsec to account for the time value assigned to each bin.
RESULTS

The typical AP obtained from all subjects was a series of one or two electrically negative deflections (or "peaks") recorded from the ear canal as well as the promontory (see Figure 1). Response magnitudes and latencies were averaged over the subjects in order to represent group trends.

Thresholds

500 Hz

All three of the baseline condition threshold measurements for the promontory were at approximately 40 dB SPL. The addition of a liquid medium into the bulla created a 10 dB threshold shift, so that thresholds for the liquid conditions were at 50 dB SPL.

The three ear canal baseline thresholds were at 50 dB SPL. Introduction of either of the two liquid media shifted the response threshold to 60 dB SPL.

1000 Hz

The average baseline response for promontory recordings at this frequency was 35 dB SPL. Introduction of liquid decreased threshold sensitivity to 10 dB. This
caused threshold values for both saline and distilled water conditions to be at approximately 45 dB SPL.

Ear canal recordings indicated a baseline threshold of 55 dB SPL. Introduction of liquid media into the system caused a decrease in threshold to 65 dB SPL.

2000 Hz

Baseline responses for promontory recordings at this frequency were at 30 dB SPL. When liquids were introduced thresholds decreased by 10 dB, indicating a shift to 40 dB SPL before a response could no longer be seen.

Ear canal recordings resulted in a baseline threshold which corresponded to approximately 40 dB SPL. The introduction of liquids once again increased threshold values so that the final response occurred at 50 dB SPL.

4000 Hz

Baseline recordings reached threshold at 20 dB SPL. Saline and distilled water conditions increased the threshold response by 10 dB to 30 dB SPL.

Baseline thresholds were established at 30 dB SPL in the ear canal, with a 10 dB shift up for threshold values under the liquid conditions.

Clicks

Results from using clicks were similar to those obtained with a 4000 Hz tone burst. Thresholds decreased
by 10 dB with the influence of the liquid media. Ear canal thresholds were higher than promontory thresholds by 10 dB for the baseline values.

Figure 4 illustrates threshold shifts due to the introduction of liquid into the bulla, in the format similar to a conventional audiogram.

**Amplitude and Growth of Responses from the Promontory**

Amplitude values for all conditions varied directly with an increase in stimulus frequency of SPL.

**Initial Baseline**

Maximum amplitudes for the control condition were higher than any of the subsequent baseline conditions. For a 4000 Hz signal, the initial baseline maximum amplitude was 119 μV. A 66 μV maximum amplitude was obtained for the second baseline and 56 μV for the third baseline.

**Baseline #2**

Following the removal of distilled water, amplitude values recorded from this baseline were generally lower than the initial baseline values. An example of maximum amplitude values for the maximum intensity of a stimulus (80 dB SPL) was given above. Similarly, at 60 dB (re: threshold), the amplitude value for a 4000 Hz signal was 28 μV as compared to 66 μV for the initial baseline. This trend continued for other intensity values as well.
Figure 4. Threshold Shifts in the Promontory and Ear Canal with the Introduction of Liquids
Baseline #3

Following the removal of saline, the condition had higher amplitude values than in the second baseline for the lower frequencies and lower amplitude values for the higher frequencies. At 500 Hz the amplitude of the response for a maximum intensity (80 dB SPL) stimulus was 26 µv. Baseline #2 had an amplitude value, from a response resulting from similar parameters, of 18 µv. However, at 4000 Hz the amplitude value from a response from this condition was only 56 µv as opposed to a 65 µv value at the second baseline.

Liquids

In general, amplitude values obtained from liquid conditions were smaller than baseline amplitude values. Such a difference can be seen when comparing the responses for maximum stimulus levels. Seventy dB (re: threshold) will be considered "maximum" stimulus intensity due to the 10 dB increase in threshold for liquid conditions. At 500 Hz the maximum amplitude values for saline and distilled water were 4.5 µv and 11.5 µv, respectively. The three baseline conditions had a range of 14 µv to 21 µv at 70 dB (re: threshold). Similarly for a click stimulus presented at maximum intensity, the amplitude values for saline and distilled water were 26 µv and 49 µv. The baseline response amplitudes ranged from 29 µv to 63 µv for the same relative stimulus intensity (70 dB re: threshold).
Maximum amplitude values elicited for saline conditions were generally smaller than the maximum amplitude values elicited from distilled water conditions. For example, at 500 Hz the maximum amplitude value for the saline condition was 4.5 μv as compared to an 11.5 μv value for distilled water. Similarly, for clicks the maximum amplitude value for the saline condition was 26 μv, as compared to a 48 μv maximum amplitude value for the distilled water condition.

There was a general trend for the amplitude values to steadily decrease as the stimulus intensity neared threshold for that subject. For instance, at 4000 Hz Baseline #1 had an amplitude value of 119 μv for a maximum intensity (80 dB SPL) stimulus. Just before threshold was reached the amplitude value decreased to 5.6 μv.

Due to the range of absolute amplitudes, all data were converted to a percentage of the maximum amplitude for a specific condition so that input-output functions could be plotted on the same coordinates (see Figures 5 through 9). A single data point could sometimes be seen at the "threshold" SPL, representing only one subject from the group. Those single points were disregarded in computing mean thresholds.

In comparing the AP general growth function for the baseline conditions, a more rapid rate of growth was noted with an increase in SPL for the third baseline (the baseline
Figure 5. Mean Amplitude Growth at the Promontory and Ear Canal for All Conditions for 500 Hz Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 6. Mean Amplitude Growth at the Promontory and Ear Canal for All Conditions for 1000 Hz Stimuli. ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 7. Mean Amplitude Growth at the Promontory and Ear Canal for All Conditions for 2000 Hz Stimuli — ▲ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 8. Mean Amplitude Growth at the Promontory and Ear Canal for All Conditions for 4000 Hz Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, ◊ = Saline, ◇ = Distilled Water.
Figure 9. Mean Amplitude Growth at the Promontory and Ear Canal for All Conditions for Click Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
following the removal of saline) as compared to the other two baseline slope functions. The rate of amplitude growth was also much greater for saline than for distilled water conditions, or any of the other baseline conditions. Distilled water had a rate of growth for lower frequencies that was similar to the baseline conditions. However, a faster rate was obtained for distilled water in the higher frequencies (4000 Hz and click stimuli). Figures 5 through 9 illustrate the growth curves for all experimental conditions.

Amplitude and Growth of Responses from the Ear Canal

Response amplitudes were extremely variable for all experimental conditions from ear canal recordings, although a general trend was seen for intensity and frequency parameters as well as a change in liquid condition.

Initial Baseline

Maximum amplitudes for the same intensity (re: threshold) were smaller at this baseline than those amplitude values obtained from other baseline conditions. For example, at 4000 Hz the maximum amplitude was 1.87 μv for this condition, whereas the maximum amplitude value for baselines #2 and #3 were 2.79 μv and 3.14 μv, respectively. Amplitudes also varied directly with stimulus frequency. At 500 Hz the maximum amplitude for this baseline was 1.14 μv,
as compared to a 1.87 μv value for a 4000 Hz stimulus at maximum intensity (80 dB SPL).

Baseline #2

Following the removal of distilled water, amplitudes recorded from this condition were larger than the initial baseline maximum amplitudes. This can be illustrated by looking at a 4000 Hz stimulus at maximum intensity (80 dB SPL). The maximum amplitude value for this condition was 2.79 μv as compared to a 1.87 μv maximum amplitude value for the initial baseline. Once again, amplitude values of responses within this condition grew with an increase in stimulus frequency. At 500 Hz for a response obtained from a maximum intensity stimulus, the maximum amplitude was 1.67 μv as compared to a 2.79 μv value for a 4000 Hz stimulus at maximum intensity.

Baseline #3

Following the removal of saline, the condition corresponded to a generally higher maximum amplitude value than any of the other baseline conditions. For example, the maximum amplitude for a 4000 Hz stimulus at maximum intensity (80 dB SPL) was 3.14 μv, as compared to a 1.87 μv value for the initial baseline and a 2.79 μv maximum amplitude value for baseline #2.
Liquids

In general, amplitude values obtained from liquid conditions were smaller than those values obtained from the baseline conditions. This is in comparison to the same SPL values (re: threshold). Saline generated a greater maximum amplitude value than the distilled water condition. For example, at 4000 Hz for a maximum intensity stimulus, the saline condition had a maximum amplitude value of 2.93 µv as compared to distilled water which only had a maximum amplitude value of 2.33 µv.

Amplitude values from the ear canal were also converted to percentage values from the maximum amplitude for a condition, so that the input-output functions could be plotted on the same coordinates for comparison (see Figures 5 through 9). A systematic rate of growth was seen for amplitude values within a given stimulus condition.

In general, it appeared that the rate of growth for amplitudes increased with an increase in stimulus frequency for the baseline condition, and decreased with an increase in frequency for the liquid conditions. There was a greater rate of change in amplitudes in the liquid conditions for the lower frequency stimuli, than in the baseline conditions.
Latency Values from the Promontory

Only slight variations in latency were noted between subjects as well as between conditions. In general, baseline conditions paralleled each other, and the introduction of liquid resulted in latencies that were slightly greater than observed for the baseline conditions.

Latency was dependent on both frequency and intensity for all conditions, decreasing as stimulus frequency increased and increasing as stimulus intensity decreased (see Figures 10-through 14). Sixty dB (re: threshold) will be used as a reference for all examples of latency values, since all conditions and signal parameters had a response at this intensity level.

Initial Baseline

This baseline condition resulted in the shortest latency values for any of the conditions. For example, the range of latencies was from 2.8 msec at 4000 Hz for a 60 dB stimulus intensity (re: threshold) to 3.1 msec at 500 Hz for the same stimulus intensity.

Baseline #2

Following the removal of distilled water, this baseline condition provided latency values that were similar to the original baseline; however, they were slightly greater at the higher frequencies. The latency value for a 4000 Hz stimulus at 60 dB (re: threshold) was 2.9 msec as
Figure 10. Mean Latency Values at the Promontory and Ear Canal for All Conditions for 500 Hz Stimuli -- ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 11. Mean Latency Values at the Promontory and Ear Canal for All Conditions for 1000 Hz Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 12. Mean Latency Values at the Promontory and Ear Canal for All Conditions for 2000 Hz Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 13. Mean Latency Values at the Promontory and Ear Canal for All Conditions for 4000 Hz Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
Figure 14. Mean Latency Values at the Promontory and Ear Canal for All Conditions for Click Stimuli — ♦ = Baseline, ▲ = Baseline #2, ▼ = Baseline #3, □ = Saline, ○ = Distilled Water.
compared to the 2.8 msec value for the original baseline. A 500 Hz stimulus resulted in a 3.2 msec latency value as compared to a 3.1 msec latency for the initial baseline.

Baseline #3

Following the removal of saline, similar latency values were obtained from this baseline condition as for Baseline #2. The range was from 3.2 msec at 500 Hz to 2.9 at 4000 Hz (and clicks) for a 60 dB intensity stimulus (re: threshold).

Liquids

Under liquid conditions, the latency of the AP response at 60 dB (re: threshold) was longer than a 60 dB (re: threshold) response under the baseline conditions. Infiltration of the bulla with distilled water resulted in these longer latency values. This difference can be illustrated by looking at latency values for a couple of frequencies at a 65 dB (re: threshold) intensity. At 1000 Hz the latency value for this condition was 3.1 msec as compared to a 3 msec value for Baseline #1. However, at 4000 Hz distilled water resulted in a latency value of 2.85 msec for a 60 dB intensity stimulus (re: threshold), as compared to a 2.8 msec value for Baseline #1. Saline produced latency characteristics that were similar to the distilled water condition. The range of latencies was from 3.1 msec at 500 Hz for a 60 dB (re: threshold) intensity to
2.8 msec for a 4000 Hz stimulus. In comparison, the baseline resulted in a mean latency value of 3.1 msec at 500 Hz for a 60 dB (re: threshold) intensity stimulus, and a 2.8 msec latency for a 4000 Hz signal.

Rate of growth for liquid conditions was similar to that of the baseline conditions, resulting in parallel configurations of growth increments for all conditions (see Figures 10 to 14).

**Latency Values from the Ear Canal**

In general latencies for the liquid conditions were similar to the promontory data, with only slight variations between subjects. The baseline conditions generally paralleled each other with a definite shift along the intensity axis for liquid conditions (see Figures 10 to 14). All latency values were dependent on both frequency and intensity of the stimulus with the latency values decreasing as stimulus frequency increased and increasing as stimulus intensity decreased.

**Initial Baseline**

The shortest latencies were observed for this condition. The range was from 2.9 mse at 500 Hz for a 60 dB (re: threshold) stimulus intensity to 2.7 msec for a 4000 Hz stimulus frequency at the same intensity. Comparatively, the values for these same parameters for the other two baselines were 3 msec for 500 Hz and 2.8 for 4000 Hz.
Baseline #2

Following the removal of distilled water, the range of latencies was slightly longer than the original baseline latency values. At 500 Hz for a 60 dB (re: threshold) stimulus intensity the latency value was 3 msec, and at 4000 Hz the latency value was 2.8 msec.

Baseline #3

Following the removal of saline, latency values for this condition were similar to those of Baselines #1 and #2. The range was from 3.1 msec at 1000 Hz to 1.8 msec for click stimuli. Latency values tended to be longer in this condition for a 500 Hz stimulus however, with a value of 3.5 msec at 60 dB (re: threshold), as compared to 3.1 msec at 500 Hz for Baseline #2 and 2.9 msec for the initial baseline.

Saline

Longer latency values were seen for saline conditions in comparison to baseline values, when comparing the responses from the same SPL re: threshold. This difference existed for all stimulus frequencies, however the difference between the conditions decreased as stimulus frequency increased. For example, at 500 Hz for a 60 dB (re: threshold) intensity stimulus the latency value for this condition was 3.55 msec. The latency value for the three baseline conditions were 2.9 msec, 3 msec, and 2.9 msec, respectively. However, for a 4000 Hz signal at 60 dB (re:
threshold), the latency was 2.8 msec for the saline condition as compared to a lesser value of 2.7 for the initial baseline and 2.75 for baselines #2 and #3. The latency values for those fluid conditions were generally longer than for distilled water conditions. At 500 Hz for a 60 dB (re: threshold) intensity stimulus the latency for distilled water was only 3.45 msec and at 4000 Hz the latency value for distilled water was only 2.75 msec.

Distilled Water

Similar latency response values existed for this liquid condition as did for the saline conditions for the same SPL values re: threshold. However, as stated above for saline, the latencies were slightly longer for the saline liquid condition than for the distilled water condition.

Differences Between the Promontory and Ear Canal Recordings

Many differences in response characteristics can be seen when the two recording sites are compared. Because it is one of the goals of this thesis to explore possible difference between the two sites, the author will review the basic components of a response which were influenced due to a change in the recording site.

Amplitude

Amplitude values recorded from the external canal were much smaller than promontory recordings. This
difference can be illustrated by comparing the two different frequencies at 60 dB (re: threshold) intensity values. At 500 Hz the amplitude for a baseline promontory recording was 13 µv as compared to a .8 µv value from the ear canal baseline. Similarly for click stimuli the promontory elicited an 88 µv amplitude value where the ear canal only had a 3.6 µv amplitude. Amplitude values for both sites did change as a function of frequency and intensity however, as was stated in the individual sections. There was also a wider range per stimulus condition of promontory latency when compared with the range for ear canal recordings. The ear canal latencies ranged from 1.14 µv at 500 Hz to 10.76 µv for click stimuli, as compared to 28.26 µv to 185 µv for promontory recordings.

Another difference which can be seen between the two recording sites is that the third baseline obtained the highest maximum amplitude values in the ear canal, whereas the initial baseline obtained the highest maximum amplitudes for promontory data. For instance, the highest amplitude value in the third baseline for ear canal recordings was 3.14 µv for a maximum intensity stimulus, as compared to 1.87 µv and 2.79 µv for the other two baselines at 4000 Hz. However, the pattern is reversed when looking at promontory recordings, with the highest maximum amplitude deriving from the initial baseline (119 µv). The maximum amplitude value for the third baseline was 56.28 µv at 4000 Hz.
Latency

Ear canal recordings had a slightly greater latency than promontory recordings. This can be seen when comparing baseline means at 500 Hz and click stimuli for a 60 dB (re: threshold) intensity. For ear canal recordings the mean was 3.1 msec, where the promontory mean was 2.8 msec. For click stimuli the mean for ear canal recordings was 3.6 msec, as compared to a 1.5 msec latency value from the promontory.

Threshold

In general, there was an equal threshold shift for the promontory and ear canal recordings with the introduction of liquids. An approximately 10 dB shift was caused for all frequency and click stimuli (see Figure 4). Ear canal thresholds did not reach as low a threshold value as promontory recordings, lagging behind by approximately 10 dB.

Waveform

Response waveforms (N_1) were narrower for the promontory and the ear canal recordings for the higher frequencies. The response waveform had a tendency to spread out and become wider as the stimulus frequency decreased. For example, the N_1 width was approximately .4 ms (measured half way between the maximum negative peak and baseline) for a click stimulus at maximum intensity levels, where the response width grew to .8 ms for a 500 Hz stimulus (see Figure 15). Similarly, N_1 width for promontory recordings
Figure 15. Width Increase of $N_1$ with a Decrease in Stimulus Frequency
at maximum intensity levels was .4 msec for click stimuli, and .8 msec for 500 Hz stimuli.

Another difference between the two recording sites was the dominance of \( N_2 \) over \( N_1 \) for almost all intensity levels in the ear canal recordings. While \( N_1 \) was dominant for all intensity levels at the promontory, it was not dominant for stimuli in the ear canal. For example, at 65 dB (re: threshold) in the ear canal, \( N_1 \) had an amplitude of 1.6 \( \mu \text{V} \) and \( N_2 \) had an amplitude of 1.8 \( \mu \text{V} \) for a 1000 Hz stimulus. However, at 45 dB (re: threshold) \( N_1 \) only had an amplitude of .24 \( \mu \text{V} \) where \( N_2 \) had an amplitude of .3 \( \mu \text{V} \) (see Figures 16 and 17).
Figure 16. Comparison of $N_1/N_2$ Dominance at the Promontory and Ear Canal for 500 Hz Stimulus -- ♦ = Baseline, □ = Saline, ○ = Distilled Water.
Figure 17. Comparison of $N_1/N_2$ Dominance at the Promontory and Ear Canal for 4000 Hz Stimulus — ♦ = Baseline, □ = Saline, ○ = Distilled Water.
DISCUSSION AND CONCLUSION

Prior to a discussion of the results a brief discussion is necessary about the relationship of response findings from humans and guinea pigs. The AP response obtained for guinea pigs is similar to that found in humans. Information obtained from each group has been used in order to gain greater knowledge of origin and influences of AP response characteristics so that clinically reliable norms may be established for use with ECoG.

Comparison of Responses from Man and the Guinea Pig

Amplitude variations are similar for both species. There is a semi-dependency of growth on the intensity and frequency of the stimuli (Dallos, 1973). Variations between these general parameters are great, however (Weiderhold, Martinez, Paull, et al., 1978). Action potentials are also smaller in man than the guinea pig due to a less pronounced on-effect (Eggermont and Odenthal, 1974). This may be due to a less pronounced decay rate of a single nerve fiber in man after the start of a short tone burst, as in cochlear damping. Two populations of neural elements have been found to exist in both humans and guinea pigs (Davis, 1961, Eggermont and Odenthal, 1974). Input-output curves for
these elements are approximately the same in both species (Eggermont and Odenthal, 1974).

Discrepancies in latency are present for AP's obtained in both humans and guinea pigs (Ruben, Fisch, and Hudson, 1962; Yoshie, 1968). N1 latencies are slightly longer in man than in the guinea pig and may originate from the differences in spatial and temporal integration times of the much longer unmyelinated portions of the spiral nerve fibers in man (Eggermont and Odenthal, 1974). Dallos (1973) feels that this difference may be due to the length of the basilar membrane in man. An increase in length would increase latency due to a longer time necessary for cochlear traveling waves. Another possible reason for a difference in latency between the two species may be due to greater sensitivity for higher frequencies in the guinea pig. Because the response area for a compound AP is primarily in the basalmost portion of the cochlea, more nerve fibers may be stimulated in response to the higher tonal or click stimuli in the guinea pig than in man (Naunton and Zerlin, 1976).

The AP waveform may be modified by the number of stimulated cells, as well as the type of stimulus and recording conditions (Strong, 1973). Results found in this study will be discussed in terms of these influences, with a comparison of recording sites.
Baseline Data

The normal "growth" pattern of AP responses was an increase in amplitude along with an increase in frequency. Similar results were found by Zerlin and Naunton (1975) as well as by Eggermont and Odenthal (1974) and Brama and Sohmer (1977). When studying the frequency specificity of AP responses, these authors found that the absolute response amplitude is less at the lower frequencies than it is at the higher frequencies. It follows therefore that the click stimuli in this study elicited the largest response amplitudes, due to the stimulation of the basal area of the cochlea (Dallos, 1973; de Boer, 1977).

Growth patterns were similar for ear canal and promontory recordings. However, much smaller amplitudes were obtained at the ear canal. Both Montandon, Shepard, et al. (1975) and Weiderhold, Martinez, Scott, and de Fries (1978) noted this reduction of amplitude when recording from the ear canal. Similarly, Durrant and Ronis (1975) found a reduction in the sensitivity of recordings from the tympanic membrane as compared to intracochlear recordings. Eggermont and Odenthal (1974) summarized five experiments which entailed ear canal recordings. An approximate 10:1 amplitude ratio was indicated between promontory and ear canal recording sites, respectively.

Sound pressure level was another factor influencing AP response magnitude (see Figure 18). Similar results were
Figure 18. Examples of Responses from the Promontory and Ear Canal Sites
found by Elberling (1976) when discussing his findings in terms of stimulus parameters. He found that AP amplitude increases at both the promontory and the ear canal recording sites with an increase in intensity.

The presence of a shallow and steeper segment of the amplitude-growth function has been reported by Yoshie (1968) for click stimuli and by Eggermont and Odenthal (1974) for tonal stimuli. This growth function is not predominant in the lower frequencies of this study, however it does become more visible as the frequency is increased (see Figures 5 through 9). This may be related to the fact that the lower frequencies thresholds are normally elevated and the range of suprathreshold SPL is limited.

A systematic increase in latency with decreasing frequency was characteristic of response latencies from both the ear canal and the promontory (see Figure 19). Naunton and Zerlin found similar results, attributing this function to the temporal properties of the traveling wave. Higher frequency elements are nearer the base and are stimulated prior to low frequency elements. De Boer (1977) and Eggermont and Odenthal (1974) found similar results in regard to frequency specificity of latency characteristics.

The fact that the ear canal latencies are slightly longer than promontory latencies may be due to the filtering effects of the tissue between the generator and recording sites (Dallos, 1973). The soft tissue through which the
Figure 19. Examples of Responses to Various Stimulus Frequencies
current must travel is analogous to a system with both capacitance and resistance. The combination of these two properties may function as a complex filter and fluid may alter the volume conduction properties of the middle ear cavity.

Reduction in $N_1$ latency with an increasing intensity level is apparent at every frequency for both the ear canal and promontory sites (see Figure 18). This result is consistent with other authors' assumptions that when the stimulus intensity is increased the pattern of activity extends itself over an increasing part of the cochlea (Naunton and Zerlin, 1976; Özdamar and Dallos, 1976; de Boer, 1977).

Double peaked AP's were characteristic of responses elicited from both the promontory and the ear canal. Eggermont and Odenthal (1974) found that this was true for normal cochleas, however Dallos (1973) found that his double waveform was more often present in guinea pig responses than in responses from humans. This may be due to the fact that guinea pigs do not have their entire middle ear system encapsulated in bone as do primates, which would alter the volume conduction characteristics between species (Durrant and Ronis, 1975). Temporal bone differences may be among factors contributing to the size of the response.

There was also an apparent broadening of $N_1$ as the stimulus frequency decreased (see Figure 19). Naunton and
Zerlin (1976) found similar changes in waveforms and attributed this change to the cochlear mechanics of a traveling wave. At low frequencies, less fibers are synchronously stimulated at a greater distance from the recording site, therefore broadening the time period over which fibers discharge.

\( N_2 \) was consistently more prominent in ear canal recordings than in promontory recordings (see Figures 16 and 17). Durrant and Ronis (1975) also found that \( N_2 \) was proportionally larger for the tympanic membrane recordings than for any of their intracochlear recordings. Earlier experimenters indicated that increasing the distance between the active electrode and the cochlea decreased the amplitude ratio (\( N_1 \) was decreased and \( N_2 \) increased) between \( N_1 \) and \( N_2 \) (Rosenblith and Rosenzweig, 1951). Portmann (1968) noted only small \( N_2 \)'s when recording from the promontory.

Eggermont and Odenthal (1974) found that decreasing the stimulus intensity alters the compound wave by increasing the relative size of \( N_2 \), whereas increasing the stimulus intensity increases the size of \( N_1 \). This was found to be true for ear canal recordings from the present data, where an increase in \( N_2 \) over \( N_1 \) was found (see Figures 16 and 17).

Thresholds improved with an increase in frequency at both the promontory and the ear canal. This may have been the result of an increase in stimulation of more fibers at the basal turn, due to the temporal properties of the
traveling wave. Higher frequency elements are nearer the base and are stimulated prior to the low frequency stimuli. Since more nerve fibers are synchronously activated for the higher frequency stimuli, threshold is decreased due to stimulation of the greater length of the cochlea (Dallos, 1973).

Addition of Liquids

The influence of a change in volume conduction can significantly influence the electrical pickup of the cochlear potentials recorded at extracochlear sites beyond a simple reduction in sensitivity. It may lead to changes in the AP waveform at different sites both near and far from the potential generator (Durrant and Ronis, 1975).

Irrigations used in this study created a threshold shift for the AP responses of approximately 10 dB for all frequencies and click stimuli. The general contention that a threshold shift does occur due to the presence of liquid in the system is supported by many researchers (Yoshie, 1968; Ruben, 1967; Eggermont and Odenthal, 1974; Montandon, Shepard, et al., 1975; de Boer, 1977; Weiderhold, Martinez, Scott, and de Fries, 1978; and others). Approximately the same threshold shift occurred for both ear canal and promontory recordings (see Figure 4).

Latency values increased under liquid conditions, following the same growth patterns as the baselines (see
Figures 10-14). Researchers cited above are also in support of this finding. Ear canal latencies were longer than promontory latencies for the liquid conditions, particularly at the lower frequencies. This latency difference was also found for the baseline recordings and is probably due to the same influences of volume conduction discussed earlier.

Amplitude values decreased with the presence of liquids. Eggermont and Odenthal (1974) also found an absence of high amplitude values when recording from a subject with a conductive hearing loss. The growth function which was present under baseline conditions also persisted under liquid conditions when comparing recordings from both the ear canal and the promontory (see Figures 5-9). The amplitude values recorded from the promontory were larger than those recorded from the ear canal. Once again this difference may be due to both the distance of the recording site from the neural generators (Eggermont and Odenthal, 1974) as well as due to the liquid medium between the ear canal recording site and the stimulated area of the cochlea. The liquid would change the conductivity of the middle ear system due to its impedance values (Elberling, 1976).

The introduction of liquid did not significantly change the response waveform in the promontory, with the exception of a reduction in amplitude. However, $N_2$ became more dominant in ear canal recordings with the introduction of liquids. Many researchers notice an increase in $N_1$ from
ear canal recordings when obtained from subjects with a conductive loss (Montandon, Shepard, et al., 1975; de Boer, 1977; Weiderhold, Martinez, Scott, and de Fries, 1978). These researchers speculated that this increase in amplitude was due to a change in the electrical conductivity of the middle-ear system. If this electrical path is indeed altered with the presence of liquid, then \( N_2 \) could also increase with the change in the conductive path. Durrant and Ronis (1975) also found that \( N_2 \) dominated \( N_1 \) when recording from an extracochlear site, and speculated that this dominance was due to a change in the volume conduction of the response pathway.

It is important to note in this discussion that there is a difference in the responses elicited from the saline condition and the distilled water condition. AP thresholds are approximately the same for both conditions, although in some of the individual data saline created a greater threshold shift. The crux of this difference lies in the amplitude and latency characteristics found between the two conditions. Amplitude had a slightly higher value for saline conditions (see Figures 5-9), and the latency which corresponds with these same liquid conditions is much longer for saline than for distilled water within the liquid conditions (see Figures 5-9).

A possible reason for this difference may be due to the difference in electrical conduction between the two
liquid media. Saline has a lower electrical impedance than does uncontaminated distilled water. This is significant because it means that distilled water would not have as high a conductance as would saline. An important point to note here is that saline has more of the physical properties of the secretions which accompany an actual conductive loss in humans. Therefore, it is of interest that both amplitude and latency values obtained from the saline condition are magnified versions of the distilled water results.

The dominant N₂ response is also slightly more visible under the saline conditions, probably due to the same difference in electrical properties of the two media. This finding also supports the contention that N₂ is at least partially enhanced due to a change in the electrical conduction of the response to the recording site.

Because the amplitude values for the third baseline recording in the ear canal were even higher than in the original baseline recordings, it is possible that some of the liquid medium (saline) which was introduced prior to this recording either still remained in the bulla, or modified mucosal secretions of the bulla in order to maintain the natural chemical properties of the system. This supports the importance that alteration of the conductive pathway has on changing response characteristics.
Summary

Some important implications of this study are:

1. Amplitude increases with an increase in intensity and frequency.

2. Latency decreases as a function of frequency and intensity increase.

3. $N_2$ is always present in the guinea pig AP response waveform, and its relative contribution to the AP response increases as intensity decreases or frequency decreases, in the ear canal recordings.

4. Ear canal recordings are smaller in amplitude, have a longer latency, have higher threshold values, and are more influenced by the presence of $N_2$ than are promontory recordings. These differences between recording sites remain similar when a simulated conductive problem is introduced, with the exception of waveform.

5. The introduction of liquid influences all four parameters of the AP response: (a) amplitude decreases at both the ear canal and promontory, (b) latency increases at both the ear canal and promontory, (c) threshold increases at both the ear canal and promontory, and (d) $N_2$ becomes more dominant for ear canal recordings than it was for the baseline ear canal recordings.
6. The conductive properties of the liquid influence the response. This would imply that a change in the electrical conductivity of the response path is a primary contributor to the change in response waveform when recording from a subject with a conductive loss.

Clinical Implications

It is important to note from the previous discussion that recording from the ear canal may be influenced by several factors which may confound response characteristics. Of primary importance is the influence which volume conduction has on the response. Latency, amplitude, threshold, and especially waveform are influenced by the presence of liquid in the bulla and must be accounted for when changes occur which are deviant from the "normal" responses. Placement of electrodes will also alter the final response characteristics. More variance will be encountered when the electrodes are distant from the AP generators.

Finally, this study is in agreement with previous findings according to differences of amplitude, latency, and threshold which deviate from the norm in conductive hearing losses. ECoG can be used as an effective diagnostic tool in determining the state of the auditory nerve and conductive path of the middle-ear system.
LIST OF REFERENCES


