A Theoretical and Experimental Investigation
of the Acoustic Transmission Properties of
the External Ear

by
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In this work, a frequency domain analysis of the acoustic behaviour of the external ear is performed. In particular, the behaviour of the pinna flap, the concha, the pinna, and the ear canal is examined in the guinea pig. From the results, and from anatomical data in conjunction with electroacoustic theory, an electrical model of the external ear is formulated and terminated with an existing middle-ear analog. A similar modelling approach is applied to the human ear, and an outer-ear model is developed for man. To compare the acoustic behaviour of the guinea-pig ear to that of the human ear, a computer simulation study is performed.
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ABBREVIATIONS

SP - sound pressure
SPL - sound pressure level
P_d - sound pressure at the eardrum
P_e - sound pressure at the ear-canal entrance
P_ff - free-field sound pressure
G_p - acoustic gain of the pinna
G_c - acoustic gain of the concha
G_pf - acoustic gain of the pinna flap
G_ec - acoustic gain of the ear canal
G_oe - acoustic gain of the outer ear
$\phi_{ec}$ - phase shift contribution of the ear canal
Chapter 1

INTRODUCTION

In this study, the acoustic performance of the external ear was investigated experimentally and by using modelling techniques. In particular, we measured the input-output characteristics of the external ear and used existing anatomical data to formulate linear electrical models representing the acoustic behaviour of the outer ear.

Although the ultimate aim of this work is to gain additional insight into the function of the human outer ear in hearing, it was not practical to conduct this study on human subjects. The experimental protocol called for the surgical removal of the pinna and therefore we decided to use guinea pigs in our work. This choice was prompted by the structural similarity between the guinea pig and human outer ears. Thus, hopefully, conclusions from our experimental work can be extrapolated to the evaluation of the human outer-ear function.

In the first part of Chapter 2, we examine the functional anatomy of the human, the cat, and the guinea-pig auditory systems with emphasis on the outer ear structure. This establishes the anatomical base on which the subsequent modelling work and the interpretation of the experimental results rests. The remainder of the chapter is primarily a review of the research literature on the function of the outer ear although only the human and the cat outer ears have been investigated extensively before. This review nevertheless provides useful guidelines for experimental work on the ear of guinea pigs and for subsequent development work on the human outer-ear models.
In Chapter 3, the experimental procedure, the instrumentation, and the experimental results are discussed. The experimental protocol calls for the measurement of the acoustic gain and phase parameters in the outer ear of the guinea pig. The sound generating system, the sound recording system, and the supervisory role of the computer are also discussed. The experimental results are presented in the latter part of the chapter in two sections: (i) the acoustic gain and the phase shift contribution of the outer ear of normal guinea pigs is shown and (ii) the effect of abnormal conditions in the middle ear on the acoustic transmission characteristics of the ear canal is examined.

Modelling of the outer and middle ears of man and guinea pig is the subject of Chapter 4. In particular, models of the human and guinea-pig pinnae are formulated from anatomical considerations and experimental data. A theoretical basis for modelling the ear canal is established and then models of the human and guinea-pig ear canals are presented. To terminate the outer-ear analogs existing models of the middle ear are used.

In Chapter 5, the results of a computer simulation of the transmission characteristics of the outer ear are presented. These results are compared with the experimental data to establish the range of applicability of the models used in the simulation. Finally, from the models, several performance parameters are calculated to compare the acoustic behaviour of the outer ears of the human and the guinea pig.
Chapter 2

ANATOMY AND PHYSIOLOGY OF THE EAR

Introduction

A search of the literature before the start of our experimental work revealed that the function of the outer ear had been investigated only in man and in the cat. No data had been found on the guinea pig. Nevertheless, from the human and cat studies, useful methods were borrowed and applied to our experiments on guinea pigs.

2.1 The auditory system

The three main parts of the peripheral auditory system are the outer ear, the middle ear, and the inner ear (Fig. 2.1). The outer ear funnels the pressure fluctuations generated by a sound source to the eardrum and on to the middle ear. In the middle ear, three small bones (auditory ossicles) conduct the vibration of the eardrum to the oval window which forms the entrance of the inner ear. The inner ear (cochlea), responds to this vibratory input with a complex, time-varying displacement of the sensory cell-bearing membranes. In the sensory cells, an electromechanical conversion takes place giving rise to neural impulses (action potentials) in the primary auditory neurons. These spikes are transmitted to the brain through the eighth cranial nerve.

2.2 The anatomy of the outer ear

Structurally, the outer ear (Fig. 2.1) is the simplest part of the auditory system. It consists of two parts: (i) the pinna, which is the externally visible flap, and (ii) the external auditory meatus (ear canal),
Pinocchio Tympanic Membrane

Externa Auditory Meatus

Outer Ear Pneumatic cells

Middle Ear Tympanic cavity

Inner Ear

Fig. 2.1 The human outer and middle ear. (From Glaesscr 23)
which is the tube-like structure leading from the pinna to the tympanic membrane (eardrum).

The human pinnae are small in relation to the size of the head and they are located on the side of the skull (Fig. 2.2). Anatomically, the pinna consists of a thin plate of yellow fibro-cartilage covered with skin. Its principle parts (Fig. 2.1) are: (i) the concha (C), which is the cavity surrounding the entrance to the ear canal, (ii) the helix (H), which is the rim of the pinna and (iii) the lobule (L), or the soft lower end of the pinna.

The human ear canal measures from 2.30 cm to 2.97 cm in length and from 0.62 cm to 0.80 cm in diameter (1) in the adult male. Beginning at the pinna, approximately one third of its length is made up of cartilage whereas the remaining two thirds consists essentially of bone. The acoustic behaviour of the ear canal is predictable from its simple geometric shape.

In the cat, the pinnae are much larger in proportion to the head than in man (Fig. 2.2). Furthermore, the pinnae of the cat are located at the back of the head and are shaped differently from the human pinnae. In addition, there are no clear 'landmarks' such as the concha, the helix or the lobe within the cat pinnae. It should also be noted that the cat is capable of turning its pinnae towards the sound source in order to optimize reception. *"By doing so, the cat can increase the pressure transformation for a given source and thereby hear better, or discriminate better against other sources"* (2).

The cat ear-canal "beginning at the eardrum consists of an essentially cylindrical portion" for about three quarters of its length (1.5 cm), "thereafter, it bends sharply at an almost right angle changing its cross section from an approximately circular one to a narrow dumbbell-shaped
Fig. 2.2 The position of the pinna in the guinea pig (A), the cat (B), and the human (C).
opening which leads to the pinna" (2). Since the anatomy of the cat and human outer-ears are not similar, the sound pressure (SP) transformation by the outer ears of these two species is expected to be different.

In the guinea pig, the pinna is very large in proportion to the head (Fig. 2.2). By comparison, the guinea-pig pinna is roughly half the size of the human pinna, and yet the animal's head is roughly one fortieth of the size of the human skull. The pinnae are located on the side of the head but they are not centrally placed although they do contain the familiar landmarks found in the human ear in a somewhat different shape.

The ear canal is shaped like a tube and measures about 1 cm in length and 0.25 cm in diameter in the adult animal (section 4.2.2.).

2.3 The anatomy of the middle ear

At the inner end of the ear canal, the eardrum couples the outer ear to the middle ear (Fig. 2.1). Connected to the eardrum is a chain of ossicles consisting of three small bones, the malleus, the incus, and the stapes ("hammer, anvil, stirrup"). These bones are suspended in the middle ear where their primary function is to transmit the motions of the eardrum to the inner ear. The middle ear cavities consist of the main chamber (tympanic cavity) which is directly behind the eardrum, a smaller cavity (epitympanum) above the ossicular chain, and a series of very small cavities (pneumatic cells) lining the upper part of the middle ear. The ossicles are suspended in the tympanic cavity by ligaments and by the tensor tympani and the stapedius muscles. The tensor tympani is attached to the malleus and when contracted, it pulls this ossicle and hence the eardrum further into the middle ear. The stapedius is connected to the stapes pulling it sideways when active. It is
commonly believed that the muscles contribute to the strength and rigidity of the ossicular mechanism. In addition, since these muscles alter the transmission of sound through the middle ear, it is thought that they also serve as a protection against high intensity sounds which are potentially harmful to the inner ear.

The acoustic behaviour of the middle ear of the cat is similar in many respects to the behaviour of the human middle-ear. In particular, the cat's middle ear presents a very high terminating impedance to the ear canal and it can therefore be represented by a hard wall (2).

Although the guinea-pig middle ear (3) is structurally somewhat simpler than the human middle-ear, functionally there is little difference between them. The overall anatomical arrangement of the middle ear of these two species is the same although the shape of the ossicles is somewhat different. In addition, in the guinea pig, there are only two middle-ear cavities: the tympanum, which is situated directly behind the eardrum, and the epitympanum located above the tympanum. A narrow opening connects these two cavities causing a resonance at approximately 5 kHz and an antiresonance at about 6 kHz. The guinea-pig middle ear is considerably smaller than the human middle ear. The effective area of the human eardrum is approximately 0.55 cm$^2$ whereas the effective area of the guinea-pig eardrum is of the order of 0.25 cm$^2$. Also, the mean total volume of the middle ear cavities in man is approximately 8.5 cc compared to 0.25 cc in the guinea pig (3).

2.4 Sound transmission in the pinna

The pinna acts as a funneling device for airborne sound and it is believed (6, 7, 8) that this funneling action aids in sound localization by
creating interaural intensity differences.

To determine quantitatively the acoustic properties of the human pinna, Wiener (9) examined the diffraction of a sound wave from the human head and pinna by measuring the SP at the entrance to the ear canal \( (P_e) \) and in the free field \( (P_{ff}) \) for various orientations of the sound field with respect to the test ear. Shaw, in 1966 (10), repeated these measurements for wider frequency range \( (1 \text{ kHz} - 15 \text{ kHz}) \). His results and those of Wiener's (Fig. 2.3) are in good agreement in their common frequency range. In particular, they show that there is an increase in SP at the ear-canal entrance when the sound is on the same side as the test ear (Fig. 2.3, \( \Theta = 45^\circ \), \( 90^\circ \)) than when it is not. This increase is due mainly to the diffraction of the sound wave by the head and the pinna and is presumed to create the interaural intensity differences which aid localization.

To separate the sound diffractions caused by the head from those of the pinna, Shaw (11) used a point source located very close \( (8 \text{ cm}) \) to the pinna and measured the resulting SP at the ear-canal entrance when the canal was blocked (Fig. 2.4). He concluded that the pinna exhibits a strong angular dependance on the location of the sound source at the high frequencies. He also found that the human concha acts as a "reservoir of acoustic energy".

At normal incidence (Fig. 2.4, solid line) the result is significantly different from the one obtained with an open ear canal entrance (Fig. 2.3, \( \Theta = 90^\circ \)). In the case of open ear canal the loading impedance of the ear canal influences the measurement whereas in the case of the blocked ear canal entrance, there is no ear canal interference. To describe the acoustic gain of the pinna alone, it is more appropriate therefore to use the results shown in Fig. 2.4.

Several investigators (2, 8, 12) have attempted to measure the acoustic significance of the cat pinnae by taking measurements on an intact
ear, surgically removing the pinna and observing the resulting acoustic changes. These investigators found that the pinna of the cat transforms the oncoming sound wave only at frequencies above 1 kHz that is when the wavelength of sound is comparable to the dimensions of the pinna (Fig. 2.5). The cat's pinna also serves as a funneling device at high frequencies, diffracting sound into the ear canal and thus creating a higher SP at the eardrum.

2.5 Sound transmission in the ear canal

Wiener and Ross (4), in 1946, examined the acoustic transmission properties of the human ear-canal and hypothesized on the role of the pinna. They measured the gain of the ear canal by taking the ratio to the SP at the eardrum (P_d) to the SP at the ear-canal entrance (P_e) (Fig. 2.6). They found that the acoustic behaviour of the human ear canal is similar to that of a rigid tube open at one end and closed at the other (Fig. 2.7).

The theory describing the behaviour of tubes in a sound field is well established and can be found in most advanced textbooks on acoustics (5). The solution of the general wave equation for a rigidly terminated tube shows that the pressure ratio between the closed end and the open end exhibits a resonance peak whenever

\[ f = \frac{nc}{4l} \quad (2.1) \]

where \( n = 1, 3, 5, \ldots \)

- \( f \) is the frequency of sound
- \( l \) is the length of the tube
- \( c \) is the speed of sound (in air = 344 m/sec)

The fundamental resonance \( (n = 1) \) which occurs at about 4 kHz for a
Fig. 2.3 The average SP at the ear-canal entrance ($P_e$) versus the free-field pressure ($P_{ff}$). Solid lines represent Shaw's results for 9 subjects broken line curves represent Wiener's results for 6 subjects. (From Shaw 10)
The ratio of the SP at the blocked ear canal entrance ($P_b$) to the SP in the reflecting plane. The dot represents the position of the probe-tube microphone. (From Shaw 11)

The ratio of the SP measured at the eardrum ($P_d$) for an intact ear to the SP measured at the eardrum for a pinnaless ear (two cats). (+90° speaker pointing into the test ear, −90° speaker pointing at the non-test ear, and 0° speaker pointing at the nose). (From Wiener 2)
Fig. 2.6 The ratio of the SP measured at the eardrum (Pd) to the SP measured at the entrance to the ear canal (Pe). An average of 6 ears. (From Wiener 4)

Fig. 2.7 A comparison between the gain of the ear canal and the gain of a tube terminated with a hard wall. (From Wiener 4)
rigidly terminated tube 2.3 cm long (the average length of the human ear canal) is often referred to as the 'quarter wavelength' resonance.

In a more recent study, Wiener et al (2) examined the sound transmission characteristics in the ear canal of the cat. As in the earlier study, they determined the gain of the ear canal from the ratio of $P_d$ to $P_e$. The result (Fig. 2.8) indicates that the gain of the cat ear canal is qualitatively very similar to that observed in man (Fig. 2.6). This is surprising in view of the anatomical differences between the two ear canals. The human ear canal is a straight tube with approximately constant cross-sectional area, whereas the cat ear canal bends at right angles, is about two-thirds the length, and varies considerably in cross-sectional area between the lateral end (pinna) and the medial end (eardrum).

2.6 Sound transmission in the outer ear (pinna & ear canal)

The acoustic effects of the head and the outer ear in man cause a pressure amplification in the frequency range 1.5 kHz - 8 kHz with the gain reaching a maximum of 20 db at about 3 kHz (Fig. 2.9). This behaviour can be attributed to a combination of the 'obstacle' effects of the head and the pinna and to resonance in the ear canal. Measurements performed on human ear replicas (Fig. 2.10) and on geometric models of the ear (13) indicate that the first peak (3 kHz) is due to resonance in the ear canal whereas the second peak (6 kHz) is caused by the pinna. The obstacle effects of the head does not produce any peaks although it does provide a boost (about 5 db) at the higher frequencies ($f > 2$ kHz) (9).

In Fig. 2.11, the ratio of $P_d$ to $P_e$ is shown for five cats. As expected, the pressure ratio is different from the results obtained on man because of the anatomical dissimilarities in the external ears and in the shape of the heads in
these two species. In the response of the cat (Fig. 2.11), only one peak is observable and this peak is very similar in size and shape to the one describing the gain of the ear canal (Fig. 2.8). In the cat therefore, the gain is due mainly to the resonance in the ear canal while the obstacle effects of the pinna and the head are less pronounced.
Fig. 2.8  The ratio of the SP measured at the eardrum (P_{eardrum}) to the SP measured at the entrance to the ear canal (P_{tragus}) for three speaker positions (+90° speaker pointing into the test ear, -90° speaker pointing at the non-test ear, and 0° speaker pointing at the nose). The sharp resonance is calculated for a tube model of the cat ear-canal terminated with a hard wall. (From Wiener 2)
Fig. 2.9 The ratio of the SP measured at the eardrum \( (P_e) \) to the SP measured in the free-field \( (P_{ff}) \) at the center of the observer's head. An average of 6 ears. (From Wiener, 4)

Fig. 2.10 The acoustic response of a rubber ear replica at normal incidence (speaker pointing directly into the test ear). Dot represents the position of the probe-tube microphone. (From Shaw 11)
Fig. 2.11 The ratio of the SP measured at the eardrum ($P_d$) to the SP measured in the free field ($P_{ff}$) at the center of the animal's head for five cats. (From Wiener 2)
Chapter 3

MEASUREMENT OF THE ACOUSTIC TRANSMISSION PROPERTIES OF THE GUINEA-PIG OUTER EAR

Introduction

The human and guinea-pig auditory systems are structurally and functionally very similar. Therefore, this animal is often used in auditory experiments, particularly in studies involving the middle ear and the inner ear. Furthermore, models of the middle ear are available in the literature and can be used to facilitate our work. Relatively little effort has been spent in the past, however, on the investigation of the acoustic properties of the outer ear of the guinea pig.

In this chapter we report the results of our experimental work on the guinea-pig outer ear (37). In particular, we measured the acoustic gain and the phase shift contribution of the outer ear in the frequency range 1 kHz - 15 kHz. We have also examined the effect of an abnormal middle ear on the gain of the outer ear.

3.1 On the choice of the experimental animal

In the experimental protocol for the study of the outer ear, the surgical removal of the pinna is necessary which precludes the use of human subjects. After careful consideration of several species we decided to use guinea pigs in our work for two reasons. Firstly, there exists a strong anatomical resemblance between the guinea-pig outer ear and the human outer ear permitting comparisons between our experimental findings and similar published data for the human. Secondly, several middle-ear models have been derived for the guinea pig from available
experimental data. One such model (3) is used extensively in our computer simulation studies of the guinea-pig ear (Chapter 4).

3.2 The physiological parameters

In this study, the outer ear was divided into three parts. These are shown diagrammatically in Fig. 3.1. They are: (i) the pinna flap, which we define as the structure forming the outer rim of the pinna; (ii) the concha, or the well-like structure within the pinna; and (iii) the ear canal. The acoustic gain of the outer ear was determined by examining the individual contributions of each of these parts to the overall gain. In particular we determined:

1) The acoustic gain of the pinna flap ($G_{pf}$)
2) The acoustic gain of the concha ($G_c$)
3) The acoustic gain of the pinna ($G_p$)
4) The acoustic gain of the ear canal ($G_{ec}$)
5) The ratio of the pressure measured at the eardrum to the free-field pressure ($G_g$)
6) The phase difference between the sound measured at the entrance to the ear canal and the sound measured at the eardrum ($\phi_{ec}$).

The gain is a particularly useful parameter to measure because it can be readily used for the construction of electrical models representing the outer ear. Furthermore, since most previous investigators have also measured this parameter, a direct comparison of experimental results can be made.

3.3 Technique for measuring the physiological parameters

The various gain and phase parameters were measured using two acoustic probe-tubes (see section 3.4.3), mounted on 1/2" capacitor
Fig. 3.1 The three parts of the outer ear: the pinna flap, the concha, and the ear canal.
microphones. The two probes were placed at different positions within
the outer ear as shown in Fig. 3.2. One of these probes, the external
probe was placed so that its tip touched the entrance to the ear canal
while the other probe, the internal probe was surgically implanted in
front of the eardrum (see section 3.5). With this measuring arrangement
we recorded sound pressure levels (SPL's) from both probe-tube microphones
in the 1 kHz - 15 kHz frequency range.

To measure the gain of the pinna flap the following procedure
was followed. Pure tones of different frequencies were directed at the
guinea pig and the SPL's were measured from both probe-tube microphones
and stored on computer magnetic tape. The pinna flap was then surgically
removed and the measurements were repeated using the same acoustic
stimuli. The gain of the pinna flap at any frequency is defined as the
ratio of the sound pressure (SP) measured in the intact animal from
either probe to the SP measured in the surgically altered animal from the
same probe. Similarly, we were able to measure the acoustic gain of the
concha (G_c), and the acoustic gain of the pinna (G_p). The procedure
followed during an experiment is illustrated diagrammatically in Fig. 3.3,
along with the formulae used to determine the gain and phase changes.

To measure the gain of the ear canal (G_{ec}) surgical amputation
was unnecessary and a different procedure could be followed. In particular,
we found the ratio of the SP measured at the eardrum by the internal probe
(P_d) to the SP measured at the ear-canal entrance by the external probe (P_e).
Phase changes in the ear canal were determined by taking the phase
difference between the internal probe signal (\phi_d) and the external probe
signal (\phi_e).

In the experiments we also measured the directivity of the outer
ear and in particular, the directivity of the pinna. This was done by
Fig. 3.2 The position of the probe-tube microphones in the ear of the guinea pig.
Fig. 3.3 The three states of the external ear during an experiment:
(A) intact ear, (B) pinna flap removed, (C) concha removed (pinnaless).
(P, $\phi$ represents the SP and phase respectively measured by the
external probe and P, $\phi$ represents the SP and phase measured by the
internal probe)
measuring the gain of the various outer-ear structures for different orientations of the sound source with respect to the experimental animal.

3.4 Instrumentation and measuring scheme

The experimental apparatus (Fig. 3.4) can be divided into two parts: the sound generating system, and the sound recording system. The sound generating system was used to create pure tones in the audio frequency range, while the sound recording system was used to measure the SPL in the various parts of the outer ear. A PDP-12 computer was used to control both the sound generating system and the sound recording system. Thus, following an operator request during the course of an experiment, the computer initiated the acoustic stimulus, measured the resulting SPL in the ear of the guinea pig, and stored the data on magnetic tape.

3.4.1 The generation of the acoustic stimulus

Figure 3.4 shows in block form the sound generating chain. Sinusoidal signals originating in the audio oscillator (B & K model 1014) were amplified (MacIntosh 75-W), and delivered to an 8" speaker (RSC model WR8) located in the sound proof room (IAC model 401A). The orientation of the speaker with respect to the test ear of the animal was variable during an experiment. This allowed us to measure the directivity pattern of the guinea pig's body in general, and of the pinna in particular. We used four speaker positions, all in the same horizontal plane as the animal's head (Fig. 3.5). These positions, designated by 0°, 45°, 90°, and 180°, represent the inclination of the speaker axis with an imaginary vertical plane which contains the two ear canals. Thus a speaker azimuth of 0° corresponds to the speaker pointing directly into the test ear, whereas, a position of 180° corresponds to the speaker pointing at the non-test ear. For all speaker positions, however, the distance between the
Fig. 3.4 Block diagram of the instrumentation: measuring and recording channels.
Fig. 3.5 The four speaker positions relative to the test ear (probe-tube microphone).
speaker and the test ear remained constant (13")

This investigation of the outer-ear function was based on a frequency domain analysis of the system. Therefore, it was always necessary to vary the frequency while controlling the acoustic stimulus during an experiment. The audio oscillator has a built-in frequency sweep which eliminates the need for manual frequency changes. This sweep was controlled by the chart recorder through a mechanical coupling arrangement (Fig. 3.4). The control lines linking the recorder to the PDP-12 computer served to transfer the sweep control from the recorder to the computer.

Although using this oscillator arrangement it was possible to sweep through the entire audio range (20 kHz - 20 kHz), in our experiment we were only concerned with the 1 kHz - 15 kHz band. Below 1 kHz the ear of the guinea-pig is small compared to the wavelength of sound in air and hence it does not present any obstacle to the sound wave. Thus in this region the gain attributable to the outer-ear structures should always be 0 db. This was verified experimentally on live guinea pigs. Above 15 kHz, the instrumentation in general, and the speaker and microphones in particular, were not sufficiently accurate to allow measurement with any degree of confidence.

3.4.2 Measuring and data storing chain

The recording chain is shown as part of Fig. 3.4. The sound pressure measured by the two probe-tube microphones (B & K 4134) was amplified (B & K model 2603 or 2111), displayed on an oscilloscope, and entered into the computer via the chart recorder (B & K 2305). Although the oscilloscope served mainly to verify that the sinusoidal pressure variations were not distorted, phase differences between the internal-probe signal
and the external-probe signal were sometimes determined directly from the scope. Usually, however, the phase was measured with the phase meter (Phazor model 210AB) located in the circuit. The phase data was obtained for the 24 frequencies which are listed in table 3.1.

The chart recorder served two purposes. Firstly, it provided a permanent record of the SPL measured in the ear on a frequency scale, and secondly, it served as the interface between the analog instrumentation and the computer. This interface was in the form of a linear potentiometer (B & K model ZR0021) which provided a voltage directly proportional to the recorder pen deflection and thus to the SPL in decibels. This voltage was entered into one of the analog-to-digital channels of the computer where it was continuously sampled, displayed and stored in a buffer area. When the buffer was filled, its contents were transferred to magnetic tape for permanent storage. The recording system could measure 250 SPL's in the frequency range 1 kHz - 15 kHz with an accuracy of ± 0.3 db.

The software system for data manipulation was especially designed for the PDP-12 computer. The programs were divided into three categories: the supervisor, the analyzer, and the plotter. The supervisor program controlled the sound generating system and the sound recording system. Following a request from the operator, this program started the sweep of the oscillator at 1 kHz, sampled, displayed and stored the resulting SPL's measured in the sound proof room, and terminated the sampling when the last frequency (15 kHz) was reached. The analyzer program allowed the operator to manipulate, display, and smooth blocks of data (250 points). This program was also used to calculate the gain of the external ear structures from the raw data. The plotter program provided a permanent copy of the data.
Table 3.1

List of frequencies used to measure the phase data

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<td>4.5</td>
<td>8.5</td>
<td>15.0</td>
</tr>
</tbody>
</table>

3.4.3 The acoustic probe: construction and calibration

The acoustic probe (Fig. 3.6) is modelled after a probe unit described by Laszlo et al. (19). We modified Laszlo's probe by using cotton thread instead of steel wool tufts for acoustic damping. This modification was made only because it facilitated the job of constructing duplicate units. To measure the SPL's in the ear of the guinea pig a set of identical probes was always used. With identical probes, it was not necessary to correct for probe differences when comparing the SPL measured at the eardrum to the SPL measured at the ear-canal entrance.

To ensure that both probes had identical frequency responses in the audio range and to discard those probes whose response showed sharp peaks or dips, every probe was calibrated. For the calibration of the magnitude (gain), we measured the individual free-field acoustic characteristics
A - 15 mm, steel tubing 1 mm O D
B - 28-30 mm, PE100 polyethylene tubing
C - ring made of PE240 polyethylene tubing
D - approximately 24-26 mm long cotton thread for acoustic damping.

Fig. 3.6 The acoustic probe. (From Laszlo 19)
of each probe and compared the responses. For the phase calibration, the experimental set-up was similar to that shown in Fig. 3.4 but instead of placing the probes in the ear of the guinea pig, we arranged them so that the tips touched one another directly in front (13") of the speaker. Then at any particular frequency, the phase difference between the probes could be measured on the phase meter. If the magnitude response for a set of probes was within 1 db, and the phase difference between the probes less than $\pm 10^\circ$, the probes were considered to be identical. Only probe sets satisfying these criteria were used in these experiments.

3.4.4 Testing the system with a simple model

To test the reliability and accuracy of this system, a small pipe open at one end and closed at the other was placed in the sound field at a position corresponding to the center of the guinea pig's head. The speaker was pointed directly into the open end of the pipe. To determine the acoustic transmission characteristics of the pipe, duplicate acoustic probes were positioned at the entrance and at the closed end of the pipe. In order to position a probe at the closed end, a hole just large enough to accomodate the probe-tube was drilled through the closed end of the pipe and the probe tip was inserted into this opening. The other probe was placed so that its tip touched the open end of the pipe. Pure tones ranging in frequency from 1 kHz to 15 kHz were directed at the pipe and the resulting SPL's were measured from both probes. The acoustic transmission characteristics of the tube were calculated from the SPL's measured from both probes and compared to theoretically predicted values based entirely on the geometry of the pipe. The result indicated that the theoretical calculations and the measurements were in very good agreement (Fig. 3.7).

3.4.5 The guinea-pig support system

Once the surgical procedure was completed and the acoustic
Fig. 3.7 The acoustic transmission characteristics of a pipe 2.3 cm long and 1 cm in diameter: magnitude and phase response.
probe was implanted in front of the eardrum, the guinea-pig was placed on a cradle-like support especially designed to restrict any head movement (Fig. 3.8). This cradle was made of a wire frame covered with speaker cloth. The guinea-pig's head was kept fixed by means of a latch built into the frame at the front of the cradle. The animal's upper front teeth were placed in the latch while the rest of the body was left in a normal crouching position. Once the guinea pig was in place, the cradle was suspended in the middle of the sound proof room by fine nylon threads running from the corners of the cradle to the walls.

To prevent oscillations of the cradle it was attached by nylon threads to a rigid support on the floor. In this arrangement, the downward force created in the nylon thread quickly damped any oscillations arising from the movement of the animal. The support system was designed to present a minimal surface area for acoustic reflections while providing a stable suspension system for the guinea pig.

3.5 Surgical techniques

For this study, the guinea pigs were anaesthetised with Dial (Ciba) 0.5 mg/kg, injected intraperitoneally. The right bulla was exposed by a ventro-lateral approach (20). With the aid of an operating microscope, and a dental drill, a small hole (1 mm in diameter) was drilled through the wall of the bulla directly above the tympanic ring. The hole was made just large enough to accommodate the acoustic probe. Before the probe was fixed in place, the eardrum was examined under 40 X magnification in order to ensure that no physical damage had occurred. Having completed the operation, the probe was secured in place with dental cement and the guinea pig was ready for the experiment.
Fig. 3.8 The guinea-pig support system.
In several experiments it was necessary to change the impedance of the middle ear artificially. This was done by filling the middle ear cavities with water. The procedure consisted of drilling a small hole through the wall of the bulla, thus providing an entrance into the middle ear. With the use of a surgical syringe filled with water and a fine needle, water was injected drop by drop into the middle ear. When the middle ear cavities were completely filled, the hole in the bulla was hermetically sealed with dental cement.

Post-experimental examination was performed on every animal to examine the condition of the middle ear and to ensure that the eardrum was undamaged.

3.6 The experimental results

In this experimental study, 10 guinea pigs were used. Seven of these animals weighed between 500 and 750 gm, one animal weighed 259 gm and the remaining two weighed 845 gm and 960 gm respectively. The smallest guinea pig and the two largest guinea pigs were used mainly for purposes of comparison with the seven animals whose average weight was 630 gm. Results for the above three animals are within the range of variation of the results for the animals in the "norm" group. Hence, no differentiation with respect to weight will be made in the presentation of the results. One of the large animals (960 gm) had a severe case of middle ear disease; a condition we were particularly interested to study. The diseased condition was detected prior to surgical exposure, for the animal did not exhibit the pinna reflex and examination of the eardrum and the middle ear through a speculum inserted in the ear canal showed pronounced changes in the appearance of the middle ear. The post-experimental examination of the animal revealed a very advanced state of middle-ear infection (see section 3.6.6).
In the presentation of the results, we will first show the curves describing the gain of the pinna flap ($G_{pf}$), of the concha ($G_c$), and of the pinna ($G_p$). We will then compare the gain and phase responses of the ear canal ($G_{ec}$, $\phi_{ec}$) for normal and abnormal middle ears. In particular, the effects of two middle ear abnormalities are examined. These are (i) artificially induced disturbances in the middle ear and (ii) disease due to pathological conditions in the middle ear.

It should be noted that not all the animals survived the entire duration of the experiment. Firstly, respiratory failure resulting from the particular position of the animal on the cradle caused death in some cases. Secondly, it was necessary at times to give the animal an added dose of anaesthetic during the surgical removal of pinna. This added dose depressed respiration sufficiently to cause death in some animals. In all, four animals survived throughout the experiment. An investigation of the effect of death on the gain of the ear canal revealed that the gain did not change for at least two hours after death (Fig. 3.9). Since the experiments seldom lasted more than two hours, impedance changes in the middle ear due to death did not significantly alter the experimental results. The variability in the results are shown in the standard deviation of $G_{pf}$, $G_c$, $G_p$, and $G_{ec}$ in Figs. 3.13, 3.17, 3.21, and 3.26 respectively.

3.6.1 The acoustic gain of the pinna flap

The gain of the pinna flap was measured at two different positions in the outer ear. One measurement was made with the external probe (Fig. 3.10); the other measurement with the internal probe (Fig. 3.11). The gain was determined at each position by measuring the SP in the intact ear, resulting from the stimulus, surgically removing the pinna flap and performing the same measurement again. It is clear that the gain of the
Fig. 3.9 Variation in the gain of the ear canal with death.
(i) Guinea pig alive (solid line), (ii) half an hour after death (dashed line), and (iii) two hours after death (dot-dash line).
pinna flap should be independent of the point of measurement in the ear canal. As expected, Figs. 3.10 and 3.11 are very similar. Thus it was permissible to average these results (Fig. 3.12).

The pinna flap exhibits no significant gain below 3 kHz. This is easily explained from basic wave theory. In order for a structure to interfere with a progressive sound wave (reflections or diffractions), the average dimension of the body must be comparable to the wavelength of sound. For low frequencies the wavelength is very large compared to the dimensions of the pinna flap and hence the gain is predictably zero. As the frequency of sound increases, the wavelength decreases according to the relation:

\[
\lambda = \frac{c}{f} \quad (3.1)
\]

where: \( \lambda \) is the wavelength of sound
\( c \) is the velocity of sound
\( f \) is the frequency of sound

Thus above 3 kHz, the wavelength becomes comparable with the dimensions of the pinna flap and, hence, the gain varies with frequency.

Over most of the frequency range, the gain of the pinna flap is largest when the sound source is on the same side of the test ear. Thus, it appears that the pinna flap contributes to the directivity of the pinna.
Fig. 3.10 The ratio of the SP measured at the ear-canal entrance \( (P_e) \) for an intact ear to the SP \( (P_e) \) measured after surgical removal of the pinna flap. (Average of 8 animals)

Fig. 3.11 The ratio of the SP measured at the eardrum \( (P_d) \) for an intact ear to the SP \( (P_d) \) measured after surgical removal of the pinna flap. (Average of 8 animals)
Fig. 3.12  Gain of the pinna flap ($G_p$). An average of Figs 3.10 and 3.11. (16 curves from measurements performed on 8 animals).

Fig. 3.13  The standard deviation of the gain of the pinna flap (From Fig. 3.12 for $\theta = 0^\circ$).
3.6.2 The acoustic gain of the concha

The gain of the concha, as measured by the external probe, is shown in Fig. 3.14 and the gain measured by the internal probe in Fig. 3.15. In Fig. 3.16, an average of the results of Figs. 3.14 and 3.15 is shown.

The results indicate that the concha serves as an acoustic amplifier in the frequency range 4 kHz - 10 kHz with the gain reaching a maximum of 12 dB at about 7 kHz ($\theta = 45^\circ$). This result is consistent with observations on the human pinna by Shaw (11). He reported that the human pinna exhibits a broad resonance in the frequency range 4 - 6 kHz which is largely "controlled by the depth resonance in the concha". We cannot directly compare the results of the study on human subjects with our work on the guinea pig since, by necessity, Shaw used an intact pinna and could not therefore measure the acoustic gain of the concha alone. Our experimental results, however, strengthen the common belief that the resonance in the pinna is largely due to the concha.

Since the curves in Fig. 3.16 show that the gain of the concha is virtually independent of the location of the sound source in the horizontal plane, it appears that the concha in the guinea pig is not significantly directional.

3.6.3 The acoustic gain of the intact pinna

The acoustic gain of the pinna should equal the gain of the pinna flap plus the gain of the concha. This gain was calculated directly from the ratio of the SP in the intact ear to the SP in the pinnless ear (Fig. 3.3). As before, two sets of measurements were obtained: one from the external probe (Fig. 3.18), and one from the internal probe (Fig. 3.19).
Fig. 3.14 The ratio of the SP measured at the ear-canal entrance (P_e) for an intact concha to the SP (P_e) measured after surgical removal of the concha. (Average of 5 animals)

Fig. 3.15 The ratio of the SP measured at the eardrum for an intact concha to the SP measured after surgical removal of the concha. (Average of 4 animals)
Fig. 3.16  Gain of the concha ($G$). Average of Fig. 3.14 and 3.15. (9 curves from measurements performed on 6 animals)

Fig. 3.17  Standard deviation of the gain of the concha. (From Fig. 3.16 for $\theta = 0^\circ$)
The average of the internal and external probe measurements is shown in Fig. 3.20.

The guinea-pig pinna exhibits a broad resonance in the frequency range 3 kHz - 10 kHz with the gain in this region reaching a maximum of 15 db. This resonance is directly attributable to the 'depth' action of the concha while the 'broadness' of the curve (Fig. 3.20) is due to the combined action of the pinna flap and the concha. As expected, the gain is dependent on the relative position of the sound source with respect to the animal.

The gain curve for the guinea-pig pinna (Fig. 3.20, $\theta = 0^\circ$) and the human pinna (Fig. 2.4, solid line) are remarkably similar. The only difference is in the position of the resonance peak. This, however, is expected since the human pinna is larger than the guinea-pig pinna and, hence, resonance should occur at a lower frequency in the human pinna. The result shown in Fig. 3.18 ($\theta = 0^\circ$) was obtained with the probe at the entrance to the ear canal and is, therefore, appropriately comparable with Shaw's results (Fig. 2.4). However, the two experimental methods differed somewhat. Shaw calculated the gain by taking the ratio of the SP measured at a blocked ear-canal entrance to the SP measured in the reflecting plane of the sound wave, while we calculated the gain by taking the ratio of the SP measured at the open ear-canal entrance for a normal ear to the SP measured at the same place for a pinnaless ear. Nevertheless, in both cases, the methods give a true measure of the gain of the pinna regardless of the loading effects of the ear canal. Both the human and the guinea-pig gain curves exhibit zero gain at the low frequencies. As the frequency increases, the wavelength becomes comparable to the dimensions of the pinna and both curves exhibit a broad resonance. On the high-frequency side of the resonance peak, both curves exhibit a small
Fig. 3.18 The ratio of the SP measured at the ear-canal entrance ($P_e$) for an intact ear and for a pinnaless ear. (Average of 8 ears)

Fig. 3.19 The ratio of the SP measured at the eardrum ($P_d$) for an intact ear and for a pinnaless ear. (Average of 10 ears)
Fig. 3.20  Gain of the pinna ($G_p$). Average of Fig. 3.18 and 3.19. (18 curves from measurements performed on 10 animals)

Fig. 3.21  Standard deviation of the gain of the pinna. (From Fig. 3.20 for $\theta = 0^\circ$)
negative peak. In view of differences in the experimental methods, the results suggest very similar acoustic behaviour for the pinna of man and guinea pig.

3.6.4 The acoustic gain and phase of the ear canals. Normal middle ear

The acoustic transmission characteristics of the guinea-pig ear canal were determined by taking the ratio of the SP measured at the eardrum ($P_d$) to the SP measured at the ear-canal entrance ($P_e$) for all frequencies of interest. The resulting curves describing the gain of the ear canal for different conditions of the pinna are shown in Figs. 3.22, 3.23, and 3.24. In Fig. 3.25 we have averaged the results of Figs. 3.22, 3.23 and 3.24 while in Fig. 3.29 the phase shift contribution of the ear canal is shown for a normal and abnormal middle ear.

The ear canal is not directional in the frequency range of measurement. The gain was found to be the same regardless of the position of the sound source with respect to the experimental animal. This result is consistent with Wiener's observations for man (4) and for the cat (2). The shape of the gain curve, however, is not the same as that obtained from a tube model of the ear canal with a hard wall approximating the eardrum (Fig. 2.7). In addition, the experimental curve does not resemble the curve describing the gain of the human (Fig. 2.6) and the cat (Fig. 2.8) ear canals. In the guinea pig, the gain is greatly influenced by the termination since the input impedance curves for the middle ear (18) show a marked resemblance to the gain of the ear canal curve with respect to the position of the peaks and troughs in these curves. For the human and the cat the middle ear represents a very high impedance termination to the ear canal (4, 2) and, hence, there is no loading effect, and the gain is dependent only on the geometry of the ear canal.
Fig. 3.22 The ratio of the SP at the eardrum ($P_d$) to the SP at the ear canal entrance ($P_e$) for an intact ear. (Average of 7 animals)

Fig. 3.23 The ratio of the SP at the eardrum ($P_d$) to the SP at the ear-canal entrance ($P_e$) after surgical removal of the pinna flap. (Average of 6 animals)
Fig. 3.24 The ratio of the SP at the eardrum ($P_d$) to the SP at the ear-canal entrance ($P_e$) after surgical removal of the pinna. (Average of 4 animals)

Fig. 3.25 The gain of the ear canal. Average of Figs. 3.22, 3.23 and 3.24. (From 17 curves based on measurements performed on 7 animals)
3.6.5 The acoustic gain of the ear canal: Altered middle ear

To measure the effect of an abnormal middle ear on the gain of the ear canal, we altered conditions in the middle ear artificially. This was done by filling the middle-ear cavities with water (see section 3.5) thereby raising the acoustic impedance by several orders of magnitude. This particular method was chosen since it permitted us to simulate the altered middle ear by a very high impedance (open circuit) in the electrical model of the middle ear (see section 5.2). It was therefore possible to compare the experimental results with the corresponding theoretical behaviour of the models.

The acoustic gain for the middle ear filled with water condition is shown in Fig. 3.27 along with the normal middle ear curve. It is immediately apparent from the result that the SP in front of the eardrum in the guinea pig is strongly dependent on the condition of the middle ear. Furthermore, the curve for the middle ear filled with water condition which represents a high impedance termination to the ear canal, resembles the gain of the ear canal curve of both the human (Fig. 2.6) and the cat (Fig. 2.8). It appears therefore that in man and in the cat, the quality of the impedance match, between the outer and middle ear is different from that observed in the guinea pig. This question will be examined in more detail in Chapter 5.

3.6.6 The acoustic gain and phase of the ear canal: Diseased middle ear

Since, in the guinea pig, the condition of middle ear affects the gain of the ear canal, we decided that it would be interesting to examine the gain in an animal with advanced middle ear disease. For this animal, a post-experimental examination of the middle ear revealed that:
Fig. 3.26 The standard deviation of the gain of the ear canal. (From Fig. 3.25 for $\phi = 0^\circ$)

Fig. 3.27 The gain of the ear canal with different conditions of the middle ear. The 'normal middle ear' curve is based on 17 measurements on 7 animals (Fig. 3.25). The 'middle ear filled with water' curve is an average for two animals.
1) The animal was diseased in both ears.
2) Bony growth covered most of the middle-ear space.
3) The ossicles were fused together and barely distinguishable.
4) The wall of the middle ear and the wall of the inner ear was abnormally thick.

Even though we did not measure the impedance of the middle ear we can assume that it was significantly different from normal. The gain and phase responses for this animal are shown in Figs. 3.28 and 3.29 respectively. A comparison of the curves (gain and phase) for the normal and diseased middle ear shows a marked difference for these two conditions. This again demonstrates the strong influence of the guinea-pig middle ear on sound transmission in the outer ear.

3.6.7 The acoustic gain of the outer ear of the guinea-pig

In the frequency range 1 kHz - 15 kHz, the wavelength of sound is comparable to the largest dimension of the guinea pig's body and, hence, the animal's body impedes the motion of the sound wave. To measure the overall effect of the body and the outer ear on the sound wave, we determined the ratio of the SP measured at the eardrum to that measured in a position corresponding to the center of the animal's head in the absence of the guinea pig (Fig. 3.30).

The largest amplification occurs at $\theta = 0^\circ$. When the speaker is in this position, the body of the guinea pig offers the largest surface area to the sound wave and hence the obstacle effects are large. As the sound source is moved ($\theta = 45^\circ$), the effective obstacle surface area presented to the sound field by the body of the guinea pig decreases and
hence the gain decreases. For a speaker position corresponding to $\varphi = 90^\circ$ the effective area is just that of the front of the head and therefore the obstacle effects are smaller. For a speaker position of $\varphi = 180^\circ$, the body is effectively shadowing the test ear and hence we get a negative gain for most frequencies.

It is interesting to note that the combined effect of the pinna (Fig. 3.20, $\varphi = 0^\circ$), the ear canal (Fig. 3.25, $\varphi = 0^\circ$), and the body of the guinea pig act to maintain a high eardrum pressure over most of the frequency range (Fig. 3.30, $\varphi = 0^\circ$). Thus at the lower end of the frequency scale (1 kHz to 4 kHz), the gain is due mainly to the first resonance peak of the ear canal. Between 4 kHz and 15 kHz the trough in the ear-canal gain curve combines with the resonance in the pinna to maintain a relatively high eardrum pressure.
Fig. 3.28 The gain of the ear canal with different middle-ear conditions. The 'normal middle ear' curve is based on measurements performed on 7 animals (Fig. 3.22). The 'middle ear disease' measurement is from a single animal.

Fig. 3.29 The phase shift contribution of the ear canal (\( \phi \)) was obtained by taking the phase difference between the internal probe signal \( \phi \) and the external probe signal \( \phi_e \) for the frequencies listed in Table 3.1. Measurements were made on 4 animals in the normal group and on one abnormal animal (same ear as shown in Fig. 3.28).
Fig. 3.30 The ratio of the SP at the eardrum \( (P_d) \) to the SP in the free-field \( (P_{ff}) \).
(Average of 7 animals)
Chapter 4

MODELS OF THE OUTER AND MIDDLE EAR: MAN AND GUINEA PIG

Introduction

From the gain and phase results presented in Chapter 3, and by using anatomical data in conjunction with electroacoustic theory, it is possible to formulate electrical models of the outer ear of the guinea pig. To compare the performance of the human and guinea-pig ear, it is also necessary to derive a model of the human outer ear.

In this chapter, we describe models of the outer and middle ear of man and of the guinea pig. Models of the human middle ear and of the ear canal already exist, and therefore we need only formulate and add a pinna model to complete the model of the entire mechanonoacoustical part of the auditory system. Similarly for the guinea pig, a model of the middle ear already exists. It is only necessary, therefore, to derive models of the ear canal and of the pinna.

It is convenient to start our analysis by examining the middle-ear models for man and for the guinea pig. Then, a theoretical basis for modelling the ear canal is established and models of the human and guinea-pig ear canals are presented. Next, we examine the models of the human and guinea-pig pinnae which are based on both anatomical and experimental data.

In this formulation of the pinna and ear-canal models we will use the voltage-pressure and current-volume velocity analogy.
4.1 Human and guinea-pig middle-ear models

Middle-ear models exist for both the human (15, 16, 22, 23, 24), and the guinea pig (3). The model of Onchi (24), is a mechanical analog and hence not easily adaptable to our form of analysis. In a recent paper (21) Onchi, shows a conversion from his mechanical analog to an equivalent electrical analog but he does not present the numerical values of his circuit elements.

The earlier model of Zwislocki (15) will not be used in our analysis since more recent models (Moller (16), Zwislocki (22), and Glaesser (23) ) have been developed from additional experimental data. These are all in particularly convenient electrical analog forms, and after careful comparison, we have decided to use Zwislocki's analog.

The block diagram for the human middle-ear analog of Zwislocki (22) is shown in Fig. 4.1. The first series block (1) simulates the action of the middle-ear cavities. All the current flows through this block, indicating that the total volume velocity of the eardrum is the same as the rate of volume change of the air enclosed behind the eardrum. The second series block (3) represents the coupling between the eardrum and the ossicles. The input impedance of the inner ear is introduced in the third series block (5). The first shunt block (2) represents the parts of the eardrum which are not coupled to the ossicles. The second shunt block (4) represents the fact that not all the acoustic energy is transmitted across the incudo-stapedial joint.
Figure 4.4 shows Zwislocki's circuit model of the middle ear of the human. The values of $R_a$ and $R_m$ were not given in the paper describing the model, although in a subsequent paper, Ross (25) calculated values for these two elements from the input impedance data (Fig. 3 in Zwislocki's paper (22)). Using Ross's estimates for $R_a$ and $R_m$, we plotted the input impedance of the middle-ear cavities and found it to be in good agreement with Zwislocki's data. We will therefore use Ross's estimates of $R_a$ and $R_m$ in all the calculations involving the human analog.

The guinea-pig middle ear model is similar to man's as can be seen from the block representation of the middle ear in Fig. 4.2 and from the circuit diagram in Fig. 4.5. However, they differ in that the middle-ear cavities, the eardrum, and the inner ear in the guinea-pig analog are represented by somewhat simpler electrical networks.

### 4.2 A theoretical basis for modelling the ear canal

Electroacoustic theory provides the necessary basis for modelling simple geometric structures by equivalent circuit models. In particular the ear canal can be modelled directly from electroacoustic considerations. Mason (26) showed that any cylindrical structure, and hence a tube, can be represented by a lumped parameter model with resistive, inductive and capacitive elements provided that only fundamental mode propagation exists in the tube (Fig. 4.3). Furthermore, the values of the elements in the model depend only on the medium and on the dimensions of the tube. Thus, if we represent the human ear canal by a tube of appropriate dimensions, open at one end and closed at the other (after Wiener (4)), an electrical analog of the ear canal can be derived following Mason's work. This lumped parameter analog,
Fig. 4.1 Schematic block diagram of the human middle ear.
(From Zwislocki 22).

Fig. 4.2 Schematic block diagram of the guinea-pig middle ear
(From Zwislocki 3).
\( P \) is the perimeter of the tube
\( \rho \) is the density of the medium in the tube (air = 1.22 \times 10^{-3} \text{ gm/cc})
\( \gamma \) is a constant related to the viscosity of the medium (air = 4.25 \times 10^{-4} \text{ c.g.s})
\( \omega \) is the angular velocity
\( c \) is the speed of sound in the medium (air = 3.44 \times 10^{4} \text{ cm/sec})

Fig. 4.3 An electrical model of a tube. (From Mason 26)
however, is an electrical equivalent of a distributed system and, therefore, it is accurate only in a very limited frequency range. The upper frequency limit of this range is defined by the relation

\[ f = \frac{c}{4l} \quad \text{(4.1) (after Bauer (27))} \]

where:
- \( f \) is the upper frequency limit
- \( c \) is the speed of sound (344 m/sec in air)
- \( l \) is the length of the tube

If the tube representing the human ear canal is taken to be typically 2.3 cm in length (after Wiener (4)), the lumped parameter electrical model of the ear canal is accurate only up to 3.75 kHz (from eq. 4.1). Since man can hear sounds well above this frequency, Mason's model has limited utility.

To obtain an analog of a tube which is valid for the higher frequencies (i.e. \( f > 3.75 \text{ kHz} \)), Bauer (27) suggested that the tube be divided into several equal length segments (\( \Delta x \)) where each segment can be considered as a tube by itself. Thus, for example, if we divide the tube into five equal segments (\( \Delta x = 0.46 \text{ cm} \)), the upper frequency limit of each of these segments (from eq. 4.1) is 18.7 kHz or five times higher than the limit for the tube as a whole. If we model each segment by the T-section of Fig. 4.3, we will obtain a cascaded arrangement which represents a model of the tube valid up to 18.7 kHz. With this technique, we can model a tube-like distributed structure such as the ear canal by a lumped parameter model over any frequency range provided longitudinal propagation predominates in the tube. In the human, this is true up to about 20 kHz, and in the guinea pig up to 40 kHz.
4.2.1 A model of the human ear canal

Several investigators have derived human ear canal models from electracoustic theory. We will not examine these models individually since they are all essentially in the same basic form—a cascaded arrangement of T-sections similar to the circuit shown in Fig. 4.3. The differences between these models are in the values of the elements and in the number of cascaded sections used. These variations are due to the different estimates of the dimensions of the ear canal (length and diameter) and the different assumed upper frequency limits in calculating the number of T-sections required.

We will use Bauer's (17) ear-canal model (Fig. 4.4) because in his formulation he used an ear-canal length of 2.2 cm, which is very close to the value measured by Wiener (4) on real human ears (2.3 cm). Since we are comparing the model behaviour of the ear canal to the experimental data of Wiener, it is necessary that the length of the ear canal in the model be similar to that measured by Wiener. Bauer (17) assumed that the human ear canal resembles a "tube approximately 2.2 cm in length and 0.76 cm in diameter" and for these dimensions, he calculated the total inerance and the total compliance of the circuit model. He estimated that a three section "lumped" analog is a sufficiently accurate representation of the ear canal. The inductance and capacitance values for each of these sections were obtained by dividing the total inerance and total compliance by three. In addition, Bauer assumed that the ear canal can be represented by a lossless network (i.e. $R = 0$) on the basis that over most of the frequency range the resistance is small compared to the reactance of the inductor in the series branch.
Fig. 4.4 An electrical analog of the human outer-middle ear complex.
4.2.2 A model of the guinea-pig ear canal

In order to construct a circuit model of the guinea-pig ear canal from anatomical data, the geometry of the ear canal must be described quantitatively. From measurements performed on three animals whose weights ranged from 500 to 750 gm we calculated the diameter of the ear canal to be 0.25 cm. We also measured the length of the ear canal of eight animals whose weights ranged from 500 to 960 gm. This measurement was accomplished by inserting a thin graduated rod into the ear canal until the tip of the rod touched the malleus. When the rod was in place, the ear-canal length was read off from the scale on the rod. The measurements were performed through an operating microscope at a magnification of 20 X. Results are shown in Table 4.1.

<table>
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<tr>
<th>Experiment Number</th>
<th>Animal Weight (gm)</th>
<th>Reading on the graduated rod (cm)</th>
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<tbody>
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<td>700</td>
<td>1.1</td>
</tr>
<tr>
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<td>05</td>
<td>500</td>
<td>0.6</td>
</tr>
<tr>
<td>06</td>
<td>960</td>
<td>0.9</td>
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<tr>
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</tr>
<tr>
<td>08</td>
<td>835</td>
<td>1.1</td>
</tr>
<tr>
<td>09</td>
<td>588</td>
<td>0.7</td>
</tr>
<tr>
<td>10</td>
<td>700</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Mean of eight animals = 0.87 cm
Standard deviation = 0.187 cm
Although the readings were taken with a straight pin-like instrument, it must be noted that the ear canal is itself not straight but it contains several slight bends (see Fig. 3.1). The true length of the ear canal is therefore larger than the mean measured value (0.87 cm). However, it is convenient to assume that the guinea-pig ear canal can be modelled by a short tube 1 cm long and 0.25 cm in diameter.

We had originally planned to make a mold of the ear canal for each animal but we abandoned this approach after several unsuccessful attempts were made to fill the ear canal with an impression material. The problem was that we could not find any suitable material which would flow into the small opening of the guinea-pig ear canal and eventually harden to provide us with a solid replica of the ear canal.

The total inerance $L_T$ and the total compliance $C_T$ for a tube 1 cm long and .25 cm in diameter is

\[
L_T = \rho l/A = 25 \text{ mH} \quad \text{.............. (4.2)}
\]

\[
C_T = A l/ \rho c^2 = 34 \text{ nF} \quad \text{.............. (4.3)}
\]

where: $l$ is the length of the ear canal

$A$ represents the cross-sectional area

$c$ is the speed of sound ($3.44 \times 10^4$ cm/sec in air)

$\rho$ is the density of the medium ($1.22 \times 10^{-3}$ gm/cc in air)

The model is lossless (i.e., $R_e = 0$) because the resistance $R_e$ is negligible compared to the reactance of the inductance in the frequency range of interest (1 kHz - 15 kHz). It remains, therefore, to find the number of $T$ - segments required to accurately describe the guinea-pig ear canal by a
lumped parameter approximation. An estimate of the number of segments required can be obtained by considering the input impedance poles and the transfer function poles of our model under open circuit conditions. For a tube 1 cm long, the input impedance poles will occur at

\[ f = 8.6 \times n \text{ kHz} \quad \text{where } n = 0, 2, 4, 6 \ldots \quad (4.4) \]

Similarly, the transfer function poles will occur at

\[ f = 8.6 \times n \text{ kHz} \quad \text{where } n = 1, 3, 5, 7 \ldots \quad (4.5) \]

(for more detail see Beranek (5), pages 29 to 35)

In order to determine the desired frequency range of the model, we need an estimate of the upper frequency of hearing of the guinea pig. Miller (28) found that based on his immobility response testing "the guinea pig's upper limit of hearing extends to 32 kHz and perhaps as high as 50 kHz". Schleidt (29) reported that he could elicit the pinna reflex to a 40 kHz tone while Heffner et al (30) found that the audibility curve for the guinea pig extends from 86 Hz to 46.5 kHz.

Thus for an upper frequency limit of 46.5 kHz the poles (eq. 4.4, 4.5) will occur at 8.6 kHz, 17.2 kHz, 25.8 kHz, 34.4 kHz and 43.0 kHz. We shall use a five segment analog to describe the acoustic behaviour of the ear canal up to 46.5 kHz. The inerntance per section is \( L = \frac{L_i}{5} = 5 \text{ mH} \), and the total capacitance per section is \( C = \frac{C_i}{5} = 6.8 \text{ nF} \). The complete ear-canal model is shown in Fig. 4.5.

4.3 A theoretical basis for modelling the pinna

The pinna consists of a cavity (concha) which is surrounded by a baffle-like structure (pinna flap) containing several convolutions (see Fig. 2.1).
Fig. 4.5 An electrical analog of the guinea-pig outer-middle ear complex.
The concha is geometrically simple and hence it can be modelled by conventional electracoustic techniques. The analysis of the pinna flap, however, is much more complex. Since it is not our purpose to perform a detailed investigation of this structure, the acoustic relevance of the various convolutions within the pinna flap will be ignored. Our interest is in the gross action of the pinna flap and the derivation of an appropriate model to describe its behaviour.

Figure 4.6 shows a circuit equivalent of the pinna. Shaw, in a recent paper (11) suggested that because of its depth the concha acts as a "reservoir of acoustic energy". We have therefore modelled the concha by a shunt capacitor, $C_p$, since a capacitor is equivalent to a "reservoir of electrical energy". In the model there is no compliance in the series branch since a capacitor in series with the source is analogous to a membrane within the pinna. Since no such membrane exists, and because the pinna flap does not have any significant depth, the total compliance of the pinna is due entirely to the cavity of the concha. To simulate the resistive and inductive properties of the pinna, we have used a resistance, $R_p$, and an inductance $L_p$, in the series branch on each side of the shunt capacitor $C_p$. With this particular network form, it is always possible to construct a cascade of $T$-segments, as was done for the ear canal, to model the pinna over a wider frequency range.

The capacitance associated with a cavity (such as the concha) is defined by the relationship

$$C = V \rho c^2$$  

where:  
- $V$ represents the total volume of the cavity  
- $\rho$ is the density of the medium  
- $c$ is the speed of sound
Fig. 4.6 A model of the pinna.
It is clear, therefore, that the total capacitance \( C_p \) in the model depends only on the volume of the concha and not on its shape. Thus by measuring the volume of the concha we can obtain an estimate of the value of \( C_p \).

The values of the resistance \( R_p \) and the inductance \( L_p \) are calculated from the experimental data since it was not possible to estimate the values of these parameters from the anatomy. A computer program to fit the model response to the experimental gain was developed. In this program, both \( R_p \) and \( L_p \) were adjusted until an optimal 'fit' of the two curves was achieved. To obtain this fit, the program calculated (for every value of \( R_p \) and \( L_p \)) an error function \( F \) (eq. 4.7) which corresponds to the sum of the errors per point between the theoretical data and the experimental data. This function \( F(R_p, L_p) \) is defined by the relation

\[
F(R_p, L_p) = \sum_{i=1}^{n} (G^m_i - G^e_i)^2 \quad (4.7)
\]

where: \( n \) is the total number of frequencies in the measurement.

\( G^m_i \) is the gain of the pinna calculated from the model for the \( i \)th frequency using the current estimates of \( R_p \) and \( L_p \).

\( G^e_i \) is the experimentally measured gain of the pinna at the \( i \)th frequency.

\( F(R_p, L_p) \) is the total error in db between the theoretical curve and the experimental one.

Naturally, the optimum values of \( R_p \) and \( L_p \) were obtained for the smallest \( F \) value.
4.3.1 A model of the human pinna

In order to calculate $C_p$ for the human pinna model we first measured the volume of the human concha. This was done by making impressions of the right ear of six male subjects using ordinary play dough. The section of the impression due to the concha alone was then separated from the rest of the mold and dropped into a graduated cylinder filled with water. The fluid displacement was taken as a measure of the concha volume. Results are shown in Table 4.2.

Table 4.2

<table>
<thead>
<tr>
<th>Subject Code</th>
<th>Subject Weight (lbs)</th>
<th>Volume of Concha (cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>125</td>
<td>2.5</td>
</tr>
<tr>
<td>B</td>
<td>140</td>
<td>1.8</td>
</tr>
<tr>
<td>C</td>
<td>147</td>
<td>2.5</td>
</tr>
<tr>
<td>D</td>
<td>150</td>
<td>2.2</td>
</tr>
<tr>
<td>E</td>
<td>160</td>
<td>2.9</td>
</tr>
<tr>
<td>F</td>
<td>172</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Average value based on 6 ears = 2.4 cc
Standard deviation = 0.4 cc

Several investigators (Siebert (31), Shaw (10)) have suggested that the human concha can be represented by a short tube. Siebert modelled the concha by a tube 1.1 cm in radius and 1 cm long. Based on these dimensions, the volume of the concha is equal to 3.8 cc. Shaw, on the other hand,
estimated that the concha resembles a section 2.2 cm in height by 2.0 cm in breadth by 1.2 cm in depth. From these values, the concha volume is equal to 4.1 cc.

There are three different volume estimates for the human concha. We estimated the volume to be 2.4 cc from measurements performed on ear molds, while Siebert and Shaw's values of 3.8 cc and 4.1 cc are based on tube approximation models of the concha. The assumption in these approximations is that the concha has a constant cross-sectional area. This, however, is not true over the entire length of the concha. From the mold we get an accurate replica of the concha and hence we will assume that the volume of the concha is 2.4 cc. From eq. 4.6 we find that the total shunt capacitance in the model is \( C_p = 1.66 \mu F \).

Using this value for the capacitance and Shaw's experimental data describing the gain of the pinna (Fig. 2.4, solid line), we calculated optimum values for \( R_p \) and \( L_p \) from eq. 4.7. In the computer program, the resistance, \( R_p \), was varied from 1 \( \Omega \) to 20 \( \Omega \) in steps of 0.1 \( \Omega \), and the inductance, \( L_p \), was varied from 0.1 mH to 10 mH in steps of 0.01 mH. Outside these element ranges the total error, \( F \), diverged whereas inside these ranges \( F \) converged. The optimum values of \( R_p \) and \( L_p \) were found to be 4.2 \( \Omega \) and 0.52 mH respectively. In the calculation of \( R_p \) and \( L_p \) we used only the experimental data below 7 kHz. Above 7 kHz, transverse wave motion in the concha becomes predominant (11) and hence we can no longer represent the concha by a single capacitor. The upper frequency limit of the model is therefore 7 kHz. Fig. 4.7 shows a plot of Shaw's experimental data along with results obtained from the model under open circuit conditions.

### 4.3.2 A model of the guinea-pig pinna

The guinea-pig pinna can be modelled from the same analog
which we used to represent the human pinna. In order to calculate the element values for this model, it is necessary to know the volume of the guinea-pig concha and the gain of the pinna, $G^e_1$ (Fig. 3.20).

To calculate $C_p$ from eq. 4.6 we measured the volume of the guinea-pig concha by making outer ear impressions. Two impression materials were used: candle wax and ordinary play dough. Measurements were performed on four live guinea pigs using the play dough, and on three dead animals using the candle wax. For the set of live animals, two outer ear impressions were taken per animal and the mean volume was calculated. As before, the volume was determined by measuring the fluid displacement due to the concha mold. For the play dough impressions, water was used as the fluid, whereas for the candle wax impressions, we used alcohol as the fluid. Results of these measurements are shown in Table 4.3.

Table 4.3

<table>
<thead>
<tr>
<th>Animal Weight (gm)</th>
<th>Volume of Concha (cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Play dough</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>0.53</td>
</tr>
<tr>
<td>800</td>
<td>0.55</td>
</tr>
<tr>
<td>905</td>
<td>0.50</td>
</tr>
<tr>
<td>950</td>
<td>0.60</td>
</tr>
<tr>
<td>Candle Wax</td>
<td></td>
</tr>
<tr>
<td>249</td>
<td>0.50</td>
</tr>
<tr>
<td>655</td>
<td>0.60</td>
</tr>
<tr>
<td>835</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Mean of seven animals $= 0.55 \text{ cc}$
Standard deviation $= 0.05 \text{ cc}$
For a concha volume of 0.55 cc, $C_p = 0.4 \mu F$ from eq. 4.6.

To find optimum values for the resistance $R_p$ and the inductance $L_p$ in the model, we used the least square fit program (see section 4.3). In the guinea-pig ear, there is no significant transverse wave component in the frequency range 1 kHz - 15 kHz and hence, it is possible to model the pinna from the circuit of Fig. 4.6 over the entire frequency range.

It was found that a two-segment $T$ model of the pinna resulted in a better "fit" than a one segment model. Although a single $T$ network is an adequate circuit representation up to about 5 kHz, above this frequency, the behaviour of the one-segment model significantly differs from that of the experimental data. Since the pinna is a distributed system it is necessary to use more than one segment to model it over the wide frequency range covered by the guinea pig's ear.

In the two segment model, the capacitance per section is $C_p/2$ or 0.2 $\mu F$. The optimum fit to the experimental data, that is, the minimum value of $F$ was obtained when $R_p = 15 \Omega$ and $L_p = 0.85 \text{ mH}$. The complete analog of the guinea-pig pinna is shown in Fig. 4.4. The gain of this model under open circuit conditions is plotted along with our experimental results for the gain in Fig. 4.8.
Fig. 4.7 A comparison of the pinna model behaviour under open circuit conditions and the experimental result for man. Experimental data is from Fig. 2.4, solid line.

Fig. 4.8 A comparison of the pinna model behaviour under open circuit conditions and the experimental result for the guinea pig. Experimental data is from Fig. 3.20 for $\theta = 0^\circ$. 
Chapter 5

COMPUTER SIMULATION OF THE OUTER AND MIDDLE EARS

Introduction

In this chapter, we compare the behaviour of the guinea-pig and human ear models with the behaviour of their real ears to establish the range of applicability and the accuracy of these models. We also calculate two useful performance parameters for interspecies comparison; the reflection coefficient and the transmission coefficient at the eardrum.

In the remainder of the chapter, we summarize our most important findings, and discuss possible future applications of the models.

5.1 Model versus real ear: Human

In the comparison of the model behaviour with the behaviour of real ears we examine three parameters: the acoustic gain of the pinna (11), the acoustic gain of the ear canal (4), and the acoustic gain of the entire outer ear (4). In Chapter 4 we showed that the model provides results which are in good agreement with the experimental data for the pinna (Fig. 4.7). It remains therefore, to compare the behaviour of the model to existing data for the ear canal and the outer ear as a whole.

In Fig. 5.1 the theoretical and experimental gain of the human ear canal is shown. The agreement between the two curves is good although the response of the model is more sharply tuned and its 'quarter wavelength' resonance appears at a higher frequency than the resonance in the experimental data. The position of this peak will vary from
The ratio of the SP measured at the eardrum ($P_d$) to the SP measured at the ear-canal entrance ($P_e$). Experimental graph is based on 6 subjects (from Wiener 4). The theoretical curve is calculated from the model of Fig. 4.4 ($G_{ec} = 20 \log \frac{V_d}{V_e}$).
individual to individual although it will generally occur between 2.5 kHz and 4.5 kHz in adults. Hence, the model response is well within the range of individual variation.

In Fig. 5.2, the theoretical and experimental gain of the outer ear is shown. Over most of the frequency range, the agreement between the model response and Wiener's data on real ears is good. Although two distinct peaks are observable in both these curves, the low frequency peaks do not occur at the same frequency. Nevertheless, the model response is well within the range of variation among individuals (Fig. 5.3). The behaviour of the rubber-ear replica is also similar to the behaviour of the model although the low frequency (quarter wavelength) peak produced by the former is sharper than the one generated by the latter. This is to be expected however, since the replica is terminated by a hard wall which causes a sharper quarter wavelength resonance.

5.2 Model versus real ear: Guinea pig

In this section the theoretical and experimental gain of the ear canal and of the entire outer ear of the guinea pig is compared. This comparison has already been made for the pinna in Chapter 4 (Fig. 4.8).

As a check on the accuracy of the ear-canal model, we calculated the gain under open circuit middle-ear conditions and compared the result with the data obtained when the middle-ear cavities were filled with water (Fig. 5.4). The agreement between the two curves is excellent up to about 11 kHz. Above 11 kHz the effect of the differences in the geometry between the model and the actual ear canal is more pronounced than at the lower frequencies.
Fig. 5.2  The gain of the outer ear. Solid line is the model response (Fig. 4.4, \( G = 20 \log V_d/V_v \)). Dash-dot line is the result of Shaw's measurements on a rubber-ear replica (11). Broken lines are from Wiener's measurements on 6 human subjects (4). (Note, it was necessary to adjust the results of Wiener since he measured the ratio of \( P_d \) to \( P_{ff} \). To get the ratio of the SP at the eardrum \( (P_d) \) to the SP at the entrance to the pinna \( (P) \), we subtracted the acoustic effects of a sphere \( (G = 20 \log P_d/P_{ff}) \) representing the head (9) from Wiener's data.)
Fig. 5.3 The variation among three representative individuals (from Wiener 4)
The gain of the ear canal for an abnormal middle ear: Experimental ($G_{ec} = 20 \log \frac{P_j}{P}$) and theoretical ($G_{ec} = 20 \log \frac{V_j}{V}$). The experimental curve was obtained for two animals, the theoretical curve was calculated from the model of Fig. 4.5.
The next logical step in the comparison of the model behaviour with the experimental results is to examine the acoustic transmission characteristics of the ear canal under normal middle-ear conditions. In Fig. 5.5 the experimental and theoretical pressure responses of the ear-canal are shown while in Fig. 5.6, the corresponding phase results are given.

At first, it appears that there is little agreement between the response of the model and the behaviour of the guinea-pig ear. It should be noted, however, that there is a qualitative similarity between the experimental and the theoretical plots for both the magnitude and the phase curves. In particular, both magnitude plots (Fig. 5.5) exhibit a low frequency peak followed by a trough then a high frequency peak, and another trough. Similarly, both phase curves (Fig. 5.6) exhibit an initial drop followed by a small peak, and then a trough. The rough agreement of curve "shapes" indicates that the models are at least qualitatively representative of the physical system. The lack of agreement in quantitative detail is due to the variability of experimental data and can be eliminated by corresponding changes in the model parameters.

In particular, in our measurements of the acoustic gain of the ear canal of the guinea pig, we noticed large variations in the gain from animal-to-animal (Fig. 5.7). This was attributed to natural physiological differences in the middle ears since the removal of the loading effect of the middle ear by filling the middle-ear cavity with water, also removed the inter-animal variation. Our results are consistent with the observations of Mundie (18), Benson (34), and Funnell (35), all of whom reported a large variation in the middle-ear impedance between guinea pigs.
Fig. 5.5  The gain of the ear canal under normal middle ear conditions. The experimental curve is based on measurements performed on 7 animals (Fig. 3.25). The theoretical curve was calculated from the model of Fig. 4.5 ($G_{ec} = 20 \log \sqrt{V_d/V_e}$).

Fig. 5.6  The phase shift contribution of the ear canal. The experimental curve is based on measurements performed on 4 animals. The theoretical curve is calculated from the model of Fig. 4.5 ($\phi_{ec} = \phi_d - \phi_e$).
The gain of the ear canal of the guinea pig for four representative animals.

Fig. 5.7
The relevance of these middle-ear impedance variations is that the outer ear and middle-ear models used were based on two different sets of experimental data. Specifically, the ear-canal model of Fig. 4.5 is based on our own data but the middle-ear model is from Zwislocki's work. It will now be shown that this accounts for the quantitative dissimilarity between the experimental and theoretical curves of Figs. 5.5 and 5.6.

By changing the values of some elements in the middle-ear model, it is possible to obtain a better quantitative fit to our experimental data. The curves of Figs. 5.8 and 5.9 were obtained with $R_b = 150 \, \Omega$, $L_b = 43 \, \text{mH}$, $L_o = 14.5 \, \text{mH}$, and $C_o = 0.35 \, \mu\text{F}$ in the model of Fig. 4.5. The other parameters in the model were left unchanged. The new values of $R_b$ (150 $\Omega$) and $L_b$ (43 $\text{mH}$) do not differ significantly from those used by Zwislocki in his model. Based on an average of ten ears Zwislocki used $R_b = 100 \, \Omega$ and $L_b = 24 \, \text{mH}$ while for a "typical" animal he used values which are larger ($R_b = 190 \, \Omega$, $L_b = 50 \, \text{mH}$) than ours. The newvalues of $L_o$ and $C_o$ are also not unreasonable. Zwislocki's original estimates ($L_o = 31 \, \text{mH}$, $C_o = .8 \, \mu\text{F}$) were calculated from data obtained on only one animal which was not "entirely typical" and whose "results above 4 kHz cannot be considered reliable" (3). Because of the complexity of the middle-ear model, it is difficult to translate these parameter changes into corresponding anatomical and physiological changes. It should be noted that the variation between the model response and the experimental data (Fig. 5.8) is well within the variation in the response between animals (Fig. 5.7).

Next, we examine the acoustic transmission of the entire outer ear (pinna and ear canal). In Fig. 5.10 our experimental results are
Fig. 5.8 The gain of the ear canal (Fig. 4.5, $G = 20 \log \frac{V_o}{V_i}$) with $R_b = 150 \, \Omega$, $L_b = 43 \, \text{mH}$, $L = 14.5 \, \text{mH}$, and $C_b = 0.35 \, \mu\text{F}$. The experimental data is based on measurements performed on 7 animals.

Fig. 5.9 The phase shift contribution of the ear canal ($\phi = \phi_e - \phi_i$). The curve calculated from the model of Fig. 4.5 was obtained for $R_b = 150 \, \Omega$, $L_b = 43 \, \text{mH}$, $L = 14.5 \, \text{mH}$ and $C_b = 0.35 \, \mu\text{F}$. The experimental curve is based on 4 animals.
shown along with the results obtained from the model of Fig. 4.5 with the new parameter estimates for $R_b$, $L_b$, $L_o$, and $C_o$.

In our experiments we determined the ratio of the SP at the eardrum to the SP in the free field ($P_{ff}$) (Fig. 3.30). To compare this data to the response of the model ($P_d/P_s$) it was first necessary to account for the difference between the free-field pressure ($P_{ff}$) and the pressure at the entrance to the pinna ($P_s$). To do this, we assumed that the body of the guinea pig could be represented by a rigid cylinder and subtracted the acoustic gain effects of the cylinder (33) from our experimental data. The model behaviour and the real ear behaviour are similar at low frequencies ($f < 6$ kHz). At the higher frequencies, however, ($f > 6$ kHz) the wavelength of sound is comparable to the dimensions of the guinea pig's body and hence the "cylinder approximation" to the body is less accurate.

5.3 Reflection and transmission coefficients

It has already been shown (section 3.4.2) that in the guinea pig, the condition of the middle ear affects the quality of the impedance match between the outer ear and the middle ear. To compare the extent of 'mismatch' between the outer ear and the middle ear in man and in the guinea pig, it is useful to examine the reflection coefficient and the transmission coefficient at the eardrum.

In section 4.2 the ear canal was shown to behave as a transmission line. At any point in a transmission line, the reflection coefficient ($\rho$) is defined by the ratio of the reflected voltage ($E^-\nu$) to the incident voltage ($E^+\nu$). This coefficient is often used to determine the extent to which the load is matched to the line. When a transmission line (Fig. 5.11) is fed by a generator, the steady-state voltage at the load is a function of the
Fig. 5.10  The gain of the outer ear. The experimental plot is based on our adjusted results (see text) for 7 animals. The theoretical curve was calculated from the model of Fig. 4.5 ($G_{oe} = 20 \log V_d/V_e$).
Fig. 5.11  A transmission line system.
generator voltage $E_g$, the generator impedance $Z_g$, the characteristic impedance of the line $Z_o$, and the load impedance $Z_L$. The steady-state reflection coefficient at the load however, is a function only of $Z_L$ and $Z_o$ (see Johnson 36, pp. 93-100) and is defined by the relation

$$\phi = \frac{E^-}{E^+} = \frac{Z_L - Z_o}{Z_L + Z_o} \quad \text{............... (5.1)}$$

where:
- $Z_L$ is the impedance of the load
- $Z_o$ is the characteristic impedance of the line
- $E^-$ is the magnitude of the reflected voltage
- $E^+$ is the magnitude of the incident voltage
- $\phi$ is the reflection coefficient

The power transmission coefficient ($T$) at the load is a measure of the transmitted power to the incident power and is defined by the relation

$$T = 1 - |\phi|^2 \quad \text{............... (5.2)}$$

For a lossless transmission line, $Z_o$ is defined (36) by the relation

$$Z_o = \sqrt{\frac{L_T}{C_T}} \quad \text{............... (5.3)}$$

where:
- $L_T$ is the total inductance in the line
- $C_T$ is the total capacitance in the line

Substituting eqs. 4.2 and 4.3 for $L_T$ and $C_T$ respectively, we find that
\[ Z_o = \frac{\rho c}{A} \quad \ldots \ldots \ldots \ldots (5.4) \]

where \( \rho \) is the density (in air \( 1.22 \times 10^{-3} \text{ gm/cc} \))
\( c \) is the speed of sound (in air \( 344. \text{ m/sec} \))
\( A \) is the cross-sectional area of the ear canal

The human ear canal \((A = 0.38 \text{ cm}^2)\) typically has a characteristic impedance \((Z_o)\) of \(110. \Omega\) while in the guinea pig \(Z_o = 855. \Omega\) \((A = 0.05 \text{ cm}^2)\). The load impedance is analogous to the middle ear impedance and hence \(Z_L = Z_M\) (Figs. 4.4 and 4.5).

In Fig. 5.12 a plot of \(I \) vs \(\theta^2\) and \(T\) is shown for man and for the guinea pig and it appears that the impedance "match" between the outer and the middle ear is somewhat better in the guinea pig than in man. The significance of this is not clear; although presumably this apparent weakness in the human ear is a necessary result of the optimization of the overall auditory system for some other characteristics.

5.4 Discussion

In this study, the acoustic behaviour of the human and guinea-pig outer ear has been examined. From the experimental work on guinea-pigs, we have found:

(1) that the pinna serves as an acoustic amplifier and exhibits directional properties in the 3 kHz - 10 kHz frequency range. This amplification is due to the large cavity of the pinna (concha) whereas the directionality is due mainly to the outer portions of the structure (pinna flap).
Fig. 5.12  The power reflection and transmission coefficients at the eardrum for man and guinea pig.
(ii) that the ear canal behaves as a resonant tube
and its transmission characteristics are largely
dependent on the condition of the middle ear.

We have also formulated workable outer-ear models for man
and for the guinea pig and terminated them with existing middle-ear
models for our computer simulation studies of the ear. These models, can
be used to predict the behaviour of the mechano-acoustic part of the ear.
Furthermore, they are also useful for comparing the performance of the
human ear and the guinea-pig ear.

The specific objective of this study, was to examine the
acoustic behaviour of the ear from a pressure standpoint and to formulate
models which can be used to gain additional insight into the behaviour of
real ears. Although it is beyond the scope of this work, it is also possible
to calculate from the models many other useful performance parameters to
provide additional measures of the behaviour of the outer and middle ears.
For example, it would be useful to examine the change in volume velocity
due to the pinna, ear canal or the entire outer ear. In the study of the
acoustics of the outer ear, this parameter is as relevant as the gain but more
difficult to measure experimentally. Impedance studies should also be extended
to compare the impedance at the ear-canal entrance looking into the pinna
to the impedance looking into the ear canal. Similarly the impedance at
the eardrum looking into the ear canal and into the middle ear would also
provide information in regard to the quality of impedance "mismatch"
existing in the ear. The phase shift contribution of the outer ear to
the pressure, volume velocity, and impedance transfer characteristics
should also be examined.
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