Effects of tympanic-membrane perforations on middle-ear sound transmission: measurements, mechanisms, and models

by

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B.S., Brown University (1991)
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Submitted to the Harvard-MIT Division of Health Sciences and Technology
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Abstract

Tympanic-membrane perforations are a common sequela of middle-ear disease. However, the hearing loss associated with perforations of different sizes and locations is not well understood, largely because ears with perforations are often affected by additional pathology associated with the disease. The focus of this thesis is to determine how tympanic-membrane perforations affect sound transmission through the human ear. Measurements of sound transmission are made on fresh human cadaveric temporal-bone preparations before and after controlled perforations are made in the tympanic membranes. The results of these measurements are described, compared to previous estimates of perforation-induced loss, and used to develop a mathematical model of sound transmission through the perforated human middle-ear.

A laser-doppler vibrometer is used to measure stapes velocity before and after perforations. The measurements indicate that TM perforations result in frequency-dependent losses that: (1) are largest at low frequencies; (2) increase as perforation size increases; and (3) do not appear to depend on perforation location.

In order to describe the mechanisms of perforation-induced changes in sound transmission, we also measured middle-ear cavity sound pressures and the middle-ear input impedance before and after perforations. These measurements indicate that perforation-induced transmission changes result primarily from a change in driving pressure across the tympanic membrane and that perforation-induced changes in the structure of the tympanic-membrane and ossicles contribute little to the total loss. Additionally, measurements of middle-ear cavity pressures show that sound transmission via the direct acoustic stimulation of the oval and round windows is negligible with most tympanic-membrane perforations.

A quantitative model of the middle ear with a tympanic-membrane perforation is developed, in which perforation diameter is a parameter. The model is consistent with all of our measurements. Simplification of the model for low frequencies leads to an algebraic equation that predicts hearing loss as a function of frequency, perforation diameter, and middle-ear cavity volume. This equation should be useful to clinicians in determining when losses in a particular case result only from the perforation or other pathology is involved.

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Introduction

I.1 Motivation

The focus of this thesis is to describe sound transmission in the human ear with perforations of different sizes and locations in the tympanic membrane. Perforations can result from a variety of causes related to either middle-ear disease or trauma. Perforations are particularly common in ears with middle-ear disease and can occur via a variety of mechanisms that include: an abnormal static pressure or build up of fluid in the middle-ear air space, erosion of the tympanic membrane by noxious agents released in chronic otitis media, and surgical management of middle-ear disease with a tympanostomy tube in the tympanic membrane. In fact, it is estimated that 1.3% of American children (aged 8 months to 16 years) have tympanostomy tubes at a given time (Bright et al. 1993); since tubes are usually implanted for only 3 to 12 months, integration over the 16 year age span of the study suggests that about 10 to 15% of Americans have tubes at some point during their childhood. Additionally, Sadé (1982) claims that “0.5 to 30% of any community is afflicted with chronic otitis media”; by definition, chronic otitis media means a tympanic-membrane perforation exists. Thus, the combination of perforations that occur via disease processes and disease management constitutes a substantial fraction of the United States population.

Even though tympanic-membrane perforations are common, their effects on hearing are not well understood. According to Terkildsen (1976, p.83),

“There is no general agreement among clinicians about the magnitude and the configuration of the hearing loss that is caused by various types of tympanic-membrane perforations. Such defects are nearly always the result of severe middle ear infections and, concomitant with perforations, there will usually be other types of pathology which may contribute to the hearing loss.”

To determine the effects of tympanic-membrane perforations on hearing, we make measurements on human temporal-bone preparations with controlled perforations in otherwise normal ears. Our experimental results lead to both an estimate of hearing loss produced by perforations and a theoretical structure for how sound transmission is modified by perforations. These results are useful clinically because they provide a means to estimate whether a given hearing loss is the result of only a tympanic-membrane perforation or if additional
pathologies also exist. Currently, such determinations are often possible only after surgical exploration.

This introductory chapter provides background information about the human ear and the tympanic membrane. It also reviews the literature that pertains to tympanic-membrane perforations and concludes that many of the experimental findings contradict one another. Next, it summarizes our ideas about how perforations might affect middle-ear mechanics. Finally, a brief outline for the organization of this thesis is provided.

## I.2 The human-ear anatomy

### I.2.1 Overview of the human ear

Fig. I-1 shows a schematic of the human ear, which is commonly divided into three anatomical parts: the external ear, the middle ear, and the inner ear. The external ear is lateral to the tympanic membrane and includes the pinna and ear canal. The external ear filters the sound that reaches the tympanic membrane (ear drum). The middle ear is composed of the tympanic membrane, three middle-ear bones (ossicles) called the malleus, incus, and stapes, and the middle-ear air space (described below). The middle ear transmits sound from the ear canal to the inner ear. The inner ear, a fluid-filled space enclosed by bone, contains sensory receptor cells for both the vestibular and the auditory systems; the cochlea is the part of the inner ear that houses the auditory sensory cells. The cochlea and the middle ear communicate at the oval and round windows. The stapes attaches to the cochlea at the oval window, and the membrane-covered round window (not visible in Fig. I-1), which is inferior to the oval window, acts as a pressure release mechanism when the cochlear fluids are compressed.

Fig. I-1 does not describe features of the anatomy of the middle-ear air space which is composed of the tympanic cavity, the aditus ad antrum, and the mastoid cavity. Briefly, the tympanic cavity is the air space that contains the ossicular system and is shown in Fig. I-1. The volume of the tympanic cavity is from 0.5 cm³ to 1 cm³ (Gyo et al. 1986; Whittemore et al. 1998). The posterior-superior portion of the tympanic cavity opens into a passage called the aditus ad antrum which connects the tympanic cavity to the larger mastoid cavity. The mastoid cavity is composed of a network of air cells; a large air cell called the antrum sits on the mastoid side of the aditus ad antrum. Attached to the antrum are numerous smaller air cells that, together with the antrum, form the mastoid air space. Measurements of the volume of the entire air space (tympanic cavity, aditus ad antrum, and mastoid cavity) show large variation. Molvaer et al. (1978) measured an average volume from 55 specimens of 6.5 cm³, with a range from 2 cm³ to 22 cm³.
Figure I-1: Schematic of the human ear. White shading indicates air spaces, light gray indicates skin and soft tissue, and dark gray indicates bone. The cochlea is shaded light gray, but in fact it is surrounded by bone. Modified from Wilson and Nadol (1983, Fig. 1.1, p.2).

1.2.2 Sound transmission through the human middle ear

The middle ear transmits sound from the ear canal to the cochlea. The pressure difference between the sound pressure in the ear canal and the sound pressure in the middle-ear air space drives the tympanic membrane, which is coupled through the ossicles to the cochlea. Additionally, the tympanic membrane and ossicular system provides a pressure gain with a maximum of about 25 dB\(^1\). Most of the pressure gain is provided by the area ratio between the tympanic membrane and the footplate of the stapes at the oval window,\(^2\) and a small portion of the gain results from the lever action of the rotating ossicles, in which the longer rotational arm of the malleus is coupled to the shorter arm of the incus\(^3\). We use the term "ossicular route\(^4\)" to refer to sound transmission through the tympanic membrane and ossicles to the cochlea (Fig.I-2). Thus, in summary, the ossicular route of sound transmission includes (1) a drive to the tympanic membrane which is the pressure difference across the tympanic membrane and (2) the mechanical linkage providing sound-pressure gain from the tympanic membrane through the ossicular chain to the cochlea.

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\(^{1}\)In humans, at 1000 Hz, the tympanic membrane and ossicular chain provide 20-25 dB of pressure gain between the ear canal and the cochlea, and at higher and lower frequencies the gain decreases (Puria et al. 1997).

\(^{2}\)In human, the tympanic-membrane-to-footplate area ratio is about 21 (Wever and Lawrence 1954, p.113) to 26 (Békésy 1960, p.102).

\(^{3}\)Estimates of the human lever ratio range from 1.2 (Rosowsk 1996) to 1.9 (Gyo et al. 1987) for frequencies below 2000 Hz.

\(^{4}\)The terms ossicular and acoustic coupling were first introduced by Peake et al. (1992).
In addition to the ossicular route, sound can also reach the cochlea through direct acoustic stimulation of the oval and round windows (Békésy 1947; Schmitt 1958; Peake et al. 1992; Merchant et al. 1997a), with the cochlea responding to the difference in sound pressure between the windows (Voss et al. 1996). We use the term “acoustic route” to describe such sound transmission (Fig. I-2). Peake et al. (1992) show that the acoustic route is negligible in normal ears because the acoustically-coupled stimulus is much smaller than the ossicularly-coupled stimulus, but that sound transmission via the acoustic route can have significant contributions to hearing in some abnormal ears.

Figure I-2: Sound pressure in the ear canal, $P_{EC}$, is transmitted to the cochlea through two mechanisms: the ossicular and acoustic routes. In the ossicular route, $P_{EC}$ acts through the tympanic membrane, malleus, incus and stapes and produces a pressure $P_{ossicular}$ at the stapes footplate. In the acoustic route, the cochlea responds to the difference in sound pressure $P_{OW} - P_{RW} = \Delta P$ at the oval and round windows. The total stimulus to the cochlea is the sum of pressures transmitted via the two mechanisms: $P_{S} = P_{ossicular} + \Delta P$. Note, at low frequencies the acoustically-coupled stimulus $P_{OW} - P_{RW} = \Delta P$ is expected to be very small, as the oval and round windows are separated by only about 4 mm while the wavelength of sound at 100 Hz is about 3.5 m. In fact, the acoustically-coupled stimulus $\Delta P$ is generally only 0.01 to 0.001 of the ossicularly-coupled stimulus. As a result, pathologies that interrupt the ossicular route result in large hearing losses. After Merchant et al. (1996).
I.2.3 The tympanic membrane

I.2.3.1 Anatomy

The human tympanic membrane is a cone-shaped membrane, 55 to 85 mm² in area (Wever and Lawrence 1954, p.416), that attaches to the annulus of the tympanic bone (the tympanic ring) along most of the membrane's outer margin and to the manubrium of the malleus centrally. The tympanic annulus is absent superiorly at the notch of Rivinus. This notch helps separate the tympanic membrane into two components. In humans, the pars tensa makes up the 97% of the tympanic-membrane area inferior to the notch (Kohllöffel 1984). The pars tensa is cone-shaped, taut and tightly coupled to the manubrium at the umbo and the lateral process. The pars flaccida, which makes up the 3% of the tympanic membrane that is superior to the notch (Kohllöffel 1984), is wrinkled and loose. Both membrane components are composed of three tissue layers: an epidermal layer, a connective layer (lamina propria), and a mucosal layer. The epidermal layer is continuous with the ear-canal epidermis and the mucosal layer is continuous with the mucosal layer of the middle ear. The lamina propria of the pars tensa and flaccida differ in that the connective tissue of the pars flaccida is loose collagen and elastic fibers while that of the pars tensa is organized into a system of radial and circular fibers (Lim 1995; Schuknecht 1993, p.31; Donaldson et al. 1992, pp.147-148; Kirikae 1960, pp.36-46).

I.2.3.2 Perforations

Tympanic-membrane perforations (i.e., holes in the eardrum) can result from middle-ear disease or trauma. Perforations are common in ears with middle-ear disease and can occur via a variety of mechanisms that include: an abnormal static pressure or build up of fluid in the middle-ear air space, erosion of the tympanic membrane by noxious agents released in chronic otitis media, and surgical management of middle-ear disease with a tympanostomy tube in the tympanic membrane\(^5\). In addition to disease, perforations also occur as a result of trauma. Shulman (1979, pp.504-505) lists several common causes of traumatic perforations: "(1) direct injury by such "weapons" as cotton applicators, pencils, paper clips, flying objects (slag), irritation of the external auditory canal, etc.; (2) concussive injury from an explosion or from a blow to the ear, which suddenly compresses the air within the external auditory canal; (3) various types of barotrauma; (4) tears from temporal

\(^5\)A tympanostomy tube is a small tube that is implanted in the tympanic membrane. Typically, such tubes are used to manage middle-ear disease by equalizing the pressure between the middle-ear air space and the ear canal. When the tube is first implanted, middle-ear fluid is removed if it is present. The diseased ear is thought to heal faster when there is no static pressure build up in the middle-ear air space. Thus, tympanostomy tubes are a class of tympanic-membrane perforations. Surgeons can choose from more than 100 types of tympanostomy tubes (Cunningham and Eavey 1993); the typical tube has a circular cross section with an inner diameter of 1 to 1.5 mm.
bone fractures; and (5) lightning injury and other miscellaneous causes." For additional potential causes of traumatic perforations, see, for example, Bruins and Cawood (1991), Golka (1994), Patow et al. (1994), Vohra and Mason (1994), Gordon et al. (1995), and Berger et al. (1997).

For description, the tympanic membrane is divided into four quadrants: posterior inferior (PI), posterior superior (PS), anterior superior (AS), and anterior inferior (AI) (Fig. I-3). The anterior-posterior border is defined by a line through the handle of the malleus, and the superior-inferior border is defined by a line through the umbo that is perpendicular to the handle of the malleus (Fig. I-3). Tympanic-membrane perforations are described both by perforation location (i.e., quadrant(s) involved) and perforation type. A central perforation does not involve the tympanic annulus so that the tympanic membrane is intact at all borders; a marginal perforation includes the tympanic annulus; and an attic perforation refers to perforation of pars flaccida (Schuknecht 1993, p.194).

![Figure I-3: A schematic lateral view of the tympanic membrane in a right ear. The pars tensa is shaded white; the malleus is outlined in black and shaded dark gray; and the pars flaccida is shaded light gray. AS=Anterior-superior, AI=Anterior-inferior, PS=Posterior-superior, PI=Posterior-inferior.]

The experimental measurements of this thesis focus on perforations made in the pars tensa, since in humans the pars flaccida is very small and even difficult to identify. Fur-
thermore, most of our perforations are either in the posterior-inferior or anterior-inferior quadrants. We chose these two locations because they are the most common locations for tympanostomy tube placement. Tympanostomy tubes are rarely placed in the posterior-superior quadrant because of this quadrants proximity to the ossicular system.

I.3 Sound transmission with a perforated tympanic membrane: Literature review

Although middle-ear transmission and hearing levels with perforated tympanic membranes have been measured in both animal and clinical studies, no consensus has developed for how tympanic-membrane perforations affect middle-ear sound transmission. Specifically, these studies address questions of frequency dependence of hearing levels and the dependence on size and location of perforations on sound transmission. Here, we provide an overview of the important studies, and we note that many of the conclusions are contradictory. For example, the animal studies suggest a frequency-dependent loss while some human studies suggest a frequency-independent loss associated with perforations.

I.3.1 Animal Studies

In cat, Payne and Githler (1951) measured a reduction in cochlear potential as they increased the size of tympanic-membrane perforations, and they found these reductions were nearly frequency independent. McArdle and Tonndorf (1968) showed that the Payne and Githler (1951) results [which are still found in otology textbooks (e.g., Shambaugh and Glasscock 1980, p.372)] have methodological problems. In the Payne and Githler study, the pressure difference across the tympanic membrane was set-up between the ear canal and the middle-ear cavity which had been opened to surrounding space. The state of the middle-ear cavity caused the pressure on the middle-ear side of the tympanic membrane to be smaller than it would have been with an intact middle-ear cavity. McArdle and Tonndorf’s cochlear-potential measurements in cats with closed cavities showed that small superior quadrant perforations (less than 5% of the tympanic-membrane area) cause a change in cochlear-potential magnitude having a slope of +10.2 dB/octave for frequencies below 1000 Hz. Above about 1000 Hz the perforated and normal responses are within 5-10 dB of each other and the changes have no clear frequency dependence. McArdle and Tonndorf (1968) also showed small variations (5 dB) in cochlear potential with perforation location. However, McArdle and Tonndorf (1968) investigated only small perforations with diameters of either 0.9 mm or 1.65 mm. Later, Kruger and Tonndorf (1977,1978) made measurements on cats that were consistent with those of McArdle and Tonndorf (1968).

6The cochlear potential is an electric-evoked potential that can be measured with an electrode on or near the round window. The cochlear potential is often used as a measure of input to the cochlea (Wever and Lawrence 1954).
More recently, Bigelow et al. (1996) studied the effect of perforation size on umbo velocity in the rat at frequencies from 1000 Hz to 40000 Hz. Perforations of approximately 4, 20, 47, and 74% of the total tympanic-membrane area caused frequency-dependent decreases in umbo velocity. The lowest frequencies were affected most by perforations so that as the perforation size increased, the frequency range that was affected also increased. Additionally, increases in perforation size produced further decreases in umbo velocity.

To summarize, animal experiments suggest that: (1) tympanic-membrane perforations cause a reduction in hearing that varies inversely with frequency over some low-frequency range, (2) as perforation size increases, the sound transmission decreases and the high-frequency limit of the hearing loss increases and (3) the location of a perforation has only small effects on hearing levels.

1.3.2 Human Studies

Studies of sound transmission in human ears have been performed on both human temporal bones and human subjects with tympanic-membrane perforations. Clinically, it is difficult to study the effect of a tympanic-membrane perforation on hearing because middle-ear disease often affects other aspects of the ear.

Békésy, using a temporal bone preparation, studied the effect of an inferior tympanic-membrane perforation, with a diameter of 0.6 mm, on the vibratory amplitude of the malleus. He found no differences between the normal tympanic membrane and the perforated tympanic membrane at frequencies above 400 Hz. Below 100 Hz, the loss in motion with the perforation increased inversely with frequency with a slope of about 10 dB/octave (Békésy 1960, Fig. 5-14, p.109). Larger perforations were not studied.

Anthony and Harrison (1972) studied the effect of tympanic-membrane perforation size and location with audiograms of patients whose conductive hearing losses were eliminated through myringoplasty. A total of 103 perforated ears was included in the study. The maximum and average air-bone gaps are summarized in Table I.1. The authors concluded that “the average loss for all perforations was minimal in the order of 20 dB, being more marked in the lower frequencies and gradually becoming less in the high frequencies.” In general, small perforations (less than 2 mm in diameter) had somewhat smaller air-bone gaps than large perforations (greater than 2 mm in diameter), and the greatest loss occurred with posterior-inferior quadrant locations. However, definitive statements about how the size and location of tympanic-membrane perforations correlate with hearing loss are not available from this study. First, 91 of the 103 perforations were large while only 12 were small.

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7 Myringoplasty refers to surgical repair of a perforated tympanic membrane
8 Total hearing loss is the combination of conductive hearing loss and sensory-neural hearing loss. Conductive hearing loss includes loss caused by abnormalities in sound transmission through the external and middle ear. Sensory-neural hearing loss is caused by pathology of the cochlea or the central nervous system. The air-bone gap refers to the difference between the total hearing loss and the sensory-neural hearing loss and is a measure of conductive hearing loss. For more information see Katz (1994).
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Air-bone gap(^5) (dB)</td>
<td>60</td>
<td>55</td>
<td>55</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>Average Air-bone gap(^5) (dB)</td>
<td>25</td>
<td>22</td>
<td>17</td>
<td>17</td>
<td>13</td>
</tr>
</tbody>
</table>

Table I.1: Conductive hearing loss with perforated tympanic membranes. From Anthony and Harrison (1972).

Second, when perforation location (quadrant) was considered, the size of the perforation was not considered, and when perforation size was considered, the perforation quadrant was not considered. Thus, the observation that posterior-inferior quadrant perforations had the largest losses could be artifactual if the posterior-inferior perforations were larger than other quadrant perforations.

Austin (1978) presents measured air-bone gaps\(^8\) at 500, 1000, and 2000 Hz from patients with a variety of tympanic-membrane perforations. He concludes that the size of perforation is directly proportional to hearing loss, the location of the perforation has no effect on hearing loss, and the perforation has no effect on the frequency response of the ear (i.e., the perforation introduces a flat conductive loss).

Yung (1983) studied pre- and post-myringoplasty air-bone gaps of 100 patients with perforations greater than 25% of the total tympanic membrane. Only the average HTL (hearing threshold level, averaged across frequency) was reported so frequency dependencies are not known. Using the HTL, Yung concludes that “marginal and malleolar perforations had a greater hearing loss ... than central and non-malleolar perforations. It was also shown that posterior perforations had a greater hearing loss than anterior perforations.” Yung interprets the greater loss associated with posterior perforations to be caused by “round window exposure and a higher incidence of ossicular fixation.”

To summarize, the literature pertaining to perforations in humans indicates that hearing loss increases as tympanic-membrane perforation area increases, but there are conflicting data as to whether or not the location of the perforation affects the magnitude of hearing loss and whether or not the perforation introduces a frequency-dependent hearing loss.

### 1.3.3 Studies with tympanostomy tubes

The presence of a tympanostomy tube\(^5\) constitutes a perforation with a diameter of about 1 to 1.5 mm. Tavin et al. (1988) measured hearing levels before and after tympanostomy tube placement for 88 ears with functioning tympanostomy tubes (Table I.2). Fifteen different types of tubes were used among the 88 intubated ears. The average conductive hearing loss (air-bone gap) with a patent tympanostomy tube (15 tube types considered together; Table I.2) was greater at the lower frequencies.

Rosowski et al. (1996) collected air-bone gaps retrospectively from 88 ears with patent tympanostomy tubes and no other known middle-ear pathologies (Table I.2). In this study, all ears contained a Baxter grommet tube (inner diameter 1.25 mm and length 2 mm).
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-bone gap (dB)</td>
<td>12.9</td>
<td>10.7</td>
<td>8.9</td>
<td>5.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Tavin et al. (1988)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-bone gap (dB)</td>
<td>19.2</td>
<td>15.2</td>
<td>12.5</td>
<td>0.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Rosowski et al. (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Loss (dB)</td>
<td>22</td>
<td>12</td>
<td>4.5</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Nishihara et al. (1993)</td>
<td></td>
<td></td>
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<td></td>
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</table>


Again, the average air-bone gap was greater at the lower frequencies, and there was virtually no hearing loss above 1000 Hz.

Nishihara et al. (1993) report changes from normal in stapes displacement that occurred in human temporal bones with four types of tympanostomy tubes placed in the tympanic membrane. Differences between tube types were less than 5 dB. An estimate of the median loss for all four tube types appears in Table I.2. Again, the measured losses were larger at the lower frequencies, and transmission returned nearly to normal above 1000 Hz.

In the case of tympanostomy tubes, both the clinical studies and the temporal-bone study found a frequency-dependent reduction of sound transmission at frequencies below 1000 Hz and only small changes above 1000 Hz.

I.4 Mechanisms of sound transmission with tympanic-membrane perforations

Several mechanisms have been proposed to explain loss in sound transmission with tympanic-membrane perforations. However, a complete, coherent explanation of sound transmission with perforations does not exist. Here, we review mechanisms that have been suggested to explain sound transmission with perforations.

A decreased pressure difference across the tympanic membrane, in the presence of a perforation, has been suggested as an explanation for transmission loss with perforations by Mehmke (1962), McArdle and Tonndorf (1968) and Kruger and Tonndorf (1977, 1978). Mehmke (1962) measured sound pressure in the tympanic cavity of a fresh temporal bone with the tympanic membrane in the normal condition and with the tympanic membrane perforated, and he showed that the tympanic-cavity pressure is increased at low frequencies in the presence of a perforation when compared to normal; thus, the pressure difference across the tympanic membrane is decreased with perforations. From their studies on cat, McArdle and Tonndorf (1968) and Kruger and Tonndorf (1977, 1978) conclude that the frequency-dependent losses with tympanic-membrane perforations are a result of loss of pressure difference across the tympanic membrane. Kruger and Tonndorf (1977) show that,
with small perforations, the frequency dependence of the loss and the frequency dependence of the change in pressure across the tympanic membrane caused by the perforation are the same. However, when the sound pressure across the tympanic membrane required to produce a 10 μV cochlear potential for the perforated case relative to the normal case is plotted, a frequency-independent cochlear-potential loss of 10 dB remains. Kruger and Tonndorf (1978) do not offer an explanation for the 10 dB transmission loss other than it is larger than the loss in area ratio, which they estimate at about 5%, and the additional loss is perhaps from direct stimulation of the cochlea (i.e., stimulation via the acoustic route).

Two common themes tend to dominate the “common knowledge” amongst clinical texts associated with how perforations influence sound transmission: (1) the idea that the phase angle of the pressure outside the round window changes relative to that of the oval window so that the acoustic route of sound transmission is modified, and (2) the idea that the reduction in ratio of the tympanic-membrane area to stapes area is responsible for a large part of the change in sound transmission. The “textbook” explanations quoted below illustrate the common view found in otologic textbooks.

Hughes and Nodar (1985, p.72): “Perforations of the tympanic membrane alter the function of the middle ear transformer mechanism by decreasing the area effect of the drum and by producing abnormal phase on the oval and round windows. The size of the perforation is relatively more important than its location. A small central perforation may impair the area effect of the drum to produce a relatively small conductive hearing loss (e.g., 15 dB) primarily in the low frequencies. A large central perforation of the tympanic membrane may produce a greater (e.g., 30 dB) conductive hearing loss, due not only to further loss of area effect of the drum, but also to passage of sound directly to the round window membrane where the phase effect may be altered.”

Schuknecht (1993, p.196): “McArdle and Tonndorf (1968) have shown experimentally that hearing loss from a perforation is caused in great part by the canceling effects at the round window caused by the direct admittance of sound pressures into the middle ear. They noted that hearing losses were greatest for low frequencies but, other than that, the location of the perforation could not be correlated with any particular type of audiometric pattern. In clinical experience, however, it is well known that a posterior perforation, particularly if located over the round window niche, causes greater hearing loss than an anterior perforation of the same size.”

Austin (1978) argues that the loss of area ratio between the tympanic membrane and stapes footplate can explain all hearing loss with perforations (Austin 1978, p.376 Graph II). However, if Austin’s argument is correct, then a 50% perforation of the tympanic membrane, which reduces the tympanic membrane-to-stapes area ratio by one half, should correspond
to a 6 dB hearing loss. Instead, Austin predicts the hearing loss with a 50% perforation to be about 25 dB in human. Note, Austin’s theory contains no frequency dependence and no consideration of reduction in pressure across the tympanic membrane, loss in coupling between the tympanic membrane and malleus other than reduction in tympanic membrane area, or acoustic stimulation of the oval and round windows.

No quantitative theory exists of how tympanic-membrane perforations affect sound transmission through the ear. For example, McArule and Tonndorf (1968) and Kruger and Tonndorf (1977, 1978) have shown that the loss in pressure difference across the tympanic membrane is one important factor in how perforations affect middle-ear transmission, but they did not explore other factors. The quotations above communicate vague ideas about how changes in the tympanic membrane-to-stapes-footplate area ratio or alterations of the phase angle of sound acting on the oval and round windows may change sound transmission. However, there is no explanation of how sound is transmitted through the ear with a perforated tympanic membrane. The results of this thesis provide such an explanation and determine the relative importance of the mechanisms involved.

I.5 Sound transmission with a perforated tympanic membrane: Our approach

Perforations of the tympanic membrane may cause changes in middle-ear sound transmission by at least three mechanisms, where the first two mechanisms involve the ossicular route of sound transmission and the third involves the acoustic route of sound transmission.

1. Changes in the pressure difference across the tympanic membrane

2. Changes in the coupling between the tympanic membrane and ossicles (e.g., decreases in tympanic-membrane area, changes in the coupling between the malleus and tympanic membrane motion, or changes in tension on the tympanic membrane that may result from disruption of the circular and radial fibers that form the membrane)

3. Changes in acoustic coupling due to changes in the middle-ear sound pressures that act directly on both the oval and round windows.

Parts of this thesis focus directly on the three mechanisms listed here. Chapter 2 describes experiments that address the ossicular-route mechanisms [(1) and (2)] above, and chapter 3 describes experimental results that explain how tympanic-membrane perforations affect the acoustic route [(3) above]. In chapter 4, the ossicular-route mechanisms are represented by a mathematical model of the middle ear that is related to the models of both Zwislocki (1962) and Kringlebotn (1988). Note, this model ignores the effects of the acoustic route.
A model of the middle ear with a perforation\(^9\) is shown in Fig. I-4. In this model, an ear-canal air space accounts for the spatial variation between the measurement of the ear-canal pressure \(P_{EC}\) and the actual pressure at the tympanic membrane \(P_{TM}\). The middle-ear cavity impedance \(\hat{Z}_{CAV}\) is in series with elements that represent the impedance of the tympanic membrane, ossicles, and cochlea. The model includes representation of a perforation of the tympanic membrane by a volume velocity path \(\hat{Z}_{PERF}\) from the ear-canal side of the tympanic membrane to the middle-ear cavity. \(|\hat{Z}_{PERF}|\) is infinite under normal tympanic-membrane conditions (i.e., no perforation). In this model, the transfer function between stapes velocity \(\hat{V}_S\) and ear-canal sound pressure represents the total sound transmission to the cochlea. The model also represents two of the three mechanisms listed above for how perforations may affect sound transmission. In particular, mechanism (1), the pressure difference across the tympanic membrane per pressure at the tympanic membrane can be calculated as

\[
\hat{H}_{\Delta TM} \equiv \frac{\hat{P}_{TM} - \hat{P}_{CAV}}{\hat{P}_{TM}}. \tag{I.1}
\]

Additionally, mechanism (2) is represented by the two-port network which couples the tympanic membrane, malleus and incus to the stapes and cochlea. The transfer admittance of the two-port network terminated by \(\hat{Z}_{SC}\), the stapes and cochlear impedance, is the transmission through the ossicular system per pressure difference across the tympanic membrane, which represents mechanism (2) above.

\[
\hat{H}_{TOC} \equiv \frac{\hat{V}_S}{\hat{P}_{TM} - \hat{P}_{CAV}} \tag{I.2}
\]

Note, the transfer characteristics of this two-port network may depend on both perforation size and perforation location.

### I.6 Thesis organization

This thesis is organized into four chapters that focus on describing sound transmission with tympanic-membrane perforations through measurements made on a human temporal-bone preparation. Chapter 1 describes the methods developed for measurement of sound transmission on the temporal-bone preparation, provides several control experiments, and presents data taken from bones with normal tympanic membranes. Chapters 2 and 3 present the experimental results with tympanic-membrane perforations. Chapter 2 focuses on the ossicular route of sound transmission (Introduction, p. 13), and chapter 3 focuses on the acoustic route of sound transmission (Introduction p. 14). Chapter 4 uses the experimental results to develop a mathematical model of sound transmission in the human ear with tympanic-membrane perforations.

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\(^9\)All model elements, volume velocities, and pressures will be indicated with a hat \(\hat{\cdot}\) to distinguish them from measured values.
Figure I-4: Model of the human middle ear with a tympanic membrane perforation. The box labeled "ear-canal air space" is a two-port that transforms the ear-canal pressure measured a few mm from the tympanic membrane to the pressure at the tympanic membrane. The TM, malleus, incus two port represents tympanic-membrane-ossicular coupling from the ear canal to the stapes and cochlea. \( \hat{Z}_{SC} \) is the impedance of the cochlea and the stapes; \( \hat{Z}_{CAV} \) is the impedance of the middle-ear cavity; \( \hat{V}_{S} \) is the model stapes velocity; \( \alpha \) is a constant that relates the model stapes velocity to the model stapes volume velocity; \( \hat{U}_{TM} \) is the volume velocity on the ear-canal side of the tympanic membrane, and \( \hat{Z}_{PERF} \) is the impedance of a tympanic-membrane perforation. In cases where the tympanic membrane is normal, \( \hat{Z}_{PERF} \) is infinite. Sound transmission via the acoustic route is not included in this model.
Chapter 1

Measurement of stapes velocity in “normal” cadaveric human temporal bones

1.1 Introduction

The mechanics of middle-ear sound transmission cannot be determined with noninvasive measurements on live human ears. Thus, investigators study human middle-ear function in normal, diseased, and reconstructed states through measurements on cadaveric ears (e.g., Békésy 1960; Kringlebotn and Gundersen 1985; Vlaming and Feenstra 1986; Gyo et al. 1987; Nishihara et al. 1993; Kurokawa and Goode 1995; Merchant et al. 1996; Merchant et al. 1997a; Merchant et al. 1997b). The combination of measurements on both live human ears and cadaveric human ears then function to either support or suggest modifications to models of the normal, pathologic, and reconstructed human middle ear (e.g., Kringlebotn 1988; Rosowski and Merchant 1995; Rosowski et al. 1995; Merchant et al. 1995).

This chapter describes our methods of middle-ear measurements and presents measurements of sound transmission in human cadaver ears made with the middle ear in a normal condition. Later chapters report measurements on the same preparations with the tympanic membrane perforated.

Our measure of middle-ear sound transmission is the transfer function between stapes velocity and eardrum pressure, $V_S/P_{EC}$; we refer to $V_S/P_{EC}$ as the “middle-ear transfer function”. Other investigators have made measurements of stapes velocity (e.g., Kringlebotn and Gundersen 1985; Vlaming and Feenstra 1986; Gyo et al. 1987; Nishihara et al. 1993; Kurokawa and Goode 1995). Here, we provide controls that have not been previously reported, and we compare our measurements to those already in the literature. We also measure a mechanical artifact that results from the coupling between the sound source
and the temporal bone; this artifact places a frequency- and preparation-dependent lower limit on our stapes-velocity measurements. Finally, we provide evidence that the stapes translates with a piston-like, one-dimensional motion, in and out of the oval window, for frequencies up to 2000 Hz.

1.2 Methods

1.2.1 Subjects

Thirty-four temporal bones from 29 cadavers were acquired for measurements (15 female and 14 male). Measurements were made on 31 of the 34 bones (3 bones were damaged during preparation). The first several bones were used to develop measurement methods for three conditions: (1) Normal, (2) Middle-ear cavity under a static pressure, and (3) Tympanic membrane perforations. After the methods were developed, further study focused on how tympanic-membrane perforations affect middle-ear sound transmission. The perforation results are discussed in subsequent chapters. Here, we focus on the results without alteration of the static pressure or the tympanic membrane.

Specific information on each bone is contained within Appendix A. Fig. 1-1 summarizes (1) the age at death (mean ± std = 70 ± 13.6 years; range 42 to 103 years), (2) time between death and temporal-bone removal (mean ± std = 22 ± 9 hours; range 7 to 51 hours), and (3) time between death and measurements (mean ± std = 7.6 ± 3.7 days; range 2 to 19 days).

1.2.2 Temporal-bone preparation

Measurements were made on adult human temporal bones removed with an oscillating Stryker bone plug saw (Schuknecht 1968). Of the 31 bones on which measurements were made, 30 bones were fresh (i.e., not previously frozen) and one bone was previously frozen (bone 16). In each case, there was no evidence that the subject had suffered from otologic disease, as determined by a review of their medical chart. Furthermore, all bones appeared normal under a microscope. In order to retard putrefaction, the bones were refrigerated at 5 degrees C in approximately 300 cc of normal saline with 10 µl of 10% Betadine.

A schematic of our temporal-bone preparation is shown in Fig. 1-2. Several steps are required to prepare a bone. First, the bony ear canal is drilled away until the tympanic membrane is fully exposed. A bony rim of about 3 mm that extends laterally is left around the tympanic annulus. A brass ring is attached to the bony tympanic rim with carboxylate dental cement (ESPE, Durelon, Norristown, PA), and a sound source is later coupled to the brass ring.

Next, access to the stapes footplate is obtained through the facial recess using a posterior-tympanotomy approach (Shambaugh and Glasscock 1980, pp.704-705). Briefly, a canal-wall-
Figure 1-1: Information from each of the 29 cadavers whose temporal bones were used. When both ears from a single cadaver were obtained, the symbols R and L (for right and left) are used to distinguish between ears. AVE indicates the average. TOP: Age at death. MIDDLE: Time between death and temporal-bone harvest. BOTTOM: Time between death and measurements. In some cases, measurements were made on more than one day. Time reported refers to the first day that measurements were made.
Figure 1-2: Schematic of experimental set-up using a horizontal cross section through a human temporal bone. The transparent shapes between the tympanic membrane and the stapes represents the malleus and the incus.
up mastoidectomy is performed, in which the mastoid air cells are drilled away, and the bony covering of the semicircular canals, the short process of the incus, and the facial nerve are exposed. Next, the facial recess is opened and the middle ear is entered. The round window and stapes are visible through this circular opening of about 2-3 mm diameter. To increase visibility of the stapes footplate, (1) the stapedius tendon is cut with alligator surgical scissors, and the pyramidal process is curetted away, and (2) the mastoid segment of the facial nerve is removed. A 0.25 mm² reflector, composed of 50 μm polystyrene spheres packed side-by-side and weighing 0.05 mg, is placed on either the stapes footplate or the posterior crus of the stapes.

To test whether cutting the stapedius tendon affects stapes velocity, stapes velocity measurements were made both before and after cutting the stapedius tendon in two bones; the muscle was cut at its attachment to the posterior part of the stapes. The comparison is shown in Fig. 1-3. Since the before and after measurements are within 2 dB in magnitude and 0.05 cycles in angle, we conclude that cutting the stapedius muscle does not change the mechanics of the middle-ear system significantly in our cadaveric preparation. In general, we choose to cut the stapedius tendon in order to increase visibility of the stapes itself; when we seal the middle-ear cavity (described below) the visibility of the stapes is markedly reduced.

In 10 of the 31 bones, stapes velocity was measured with the middle-ear cavity open to the atmosphere. In the other 21 bones, the middle-ear cavity was sealed acoustically as follows. A cavity was constructed within the mastoid with gel foam and carboxylate dental cement to mimic the antrum, and this "artificial antrum" was then sealed with a plastic cover slip. The facial recess opening described above was also sealed with a plastic coverslip. Both cover slips were sealed with dental cement. Additionally, the entire bone was painted with dental cement to seal it acoustically. In cases where the cavity was sealed, care was taken to maintain a zero static pressure difference across the tympanic membrane. There was either (1) a piece of tygon tubing (length > 45 cm and diameter ≈ 1 mm) glued through the attic of the temporal bone into the middle-ear cavity or (2) a steel tube (id = 1.3 mm; length = 3 cm) glued through the facial recess opening that could be opened to equalize any static pressure build up. In the case of the steel tube, the tube was sealed just before any acoustic measurements.

The last step was to glue a brass rod, used to hold the bone for the measurements, into the carotid canal. All tissue and debris were removed from the carotid canal and the canal was coated with dental cement. Epoxy or dental cement was then used to glue the brass rod to the dental cement that coated the carotid canal. This brass rod was used to hold the bone in the measurement system.

The temporal bone must be kept moist in order to prevent measurement artifacts that result from the middle-ear components drying out (Rosowski et al. 1990a). Periodically, the bone was submerged in saline for several seconds, and the excess fluid removed with gentle suction.
Figure 1-3: Stapes velocity per ear-canal pressure both before and after cutting the stapedius tendon on bones 17 and 25. The middle-ear cavity was open. The measurement with the stapedius tendon intact was made. Next, the stapedius tendon was cut without moving the preparation. The measurement with the stapedius tendon cut was made within a few minutes of the original measurement. TOP: Magnitude. The left vertical axes correspond to the stapes velocity per ear-canal measurements, and the right axes indicate the ratio (in dB) between the measurements made before and after the stapedius tendon was cut. BOTTOM: Angle. Plotted are the angles that correspond to stapes velocity per ear-canal pressure and the difference between the angles before and after the stapedius tendon was cut.
1.2.3 Computer generated stimulus and response measurement

Measurements were made using the PC software package SYSid\(\oplus\)(SYsid Labs, Berkeley, CA) and an Ariel DSP-16+ digital signal processing board with two input and two output channels. The measurements used either a chirp signal or a tone signal as a stimulus, and the reported response is the 2048-point FFT (fast Fourier transform) of the time-domain average of N responses \((20 \leq N \leq 2000)\) sampled at 50 kHz; each time-domain sample has a duration of 41 ms. Note, all reported magnitudes are peak magnitudes, with the exception of magnitudes that are in dB SPL, which by definition are rms pressures.

1.2.4 Ear-canal sound pressure

A Radio Shack (40-137) sound source and either a Knowles hearing aid microphone (SK 497 3103) (bones 1 through 20) or a Larson Davis 2540 quarter inch microphone (bones 21 through 29) constituted the sound system used to generate and measure sound at the tympanic membrane. The sound source was coupled to a brass tube attached to the brass ring; the ring was was glued about 3 mm lateral to the tympanic membrane. A probe tube with the microphone at its lateral end ran down the center of the sound delivery tube so that the medial end of the probe tube was within about 3 mm of the tympanic membrane.

The sound-delivery system was calibrated with a second microphone called the reference microphone (a second Larson Davis 2540 quarter inch microphone). First, the sensitivity of the reference microphone was measured at 250 Hz by coupling the reference microphone to a Larson Davis acoustic calibrator \((114 \text{ dB SPL, 250 Hz})\). The frequency response of the reference microphone was flat \((\text{within 0.5 dB})\) from 12 Hz to 8000 Hz, as measured with an electrostatic actuator. Since the response was flat, the sensitivity measured at 250 Hz applies for all frequencies. Thus, the transfer function between pressure and reference microphone voltage becomes

\[
\frac{\text{Pressure}}{V_{\text{ref mic}}} = \frac{14.18 \text{ Pascals}}{V_{\text{ref mic}}|_{\text{acoustic calibrator}} \text{ Volts}} \tag{1.1}
\]

Next, the reference microphone was coupled to within 2 mm of the sound system described above that was used to generate and measure sound at the tympanic membrane, and the two microphone responses (i.e., reference microphone and sound system microphone) were measured simultaneously in response to a broad band chirp input to the sound source. The two responses are (1) the transfer function between the sound-source input voltage and the reference microphone voltage, \(\frac{V_{\text{source}}}{V_{\text{ref mic}}}\), and (2) the transfer function between the sound-source input voltage and the probe-tube microphone of the sound-delivery system, \(\frac{V_{\text{source}}}{V_{\text{probe mic}}}\). Finally, the pressure-per-volt for the probe-tube microphone, \(\frac{\text{Pressure}}{V_{\text{probe mic}}}\), was calculated as
the product of three measured ratios:

\[
\frac{\text{Pressure}}{V_{\text{probemc}}} = \left( \frac{\text{Pressure}}{V_{\text{refmic}}} \right) \left( \frac{V_{\text{refmic}}}{V_{\text{source}}} \right) \left( \frac{V_{\text{source}}}{V_{\text{probemc}}} \right) \cdot f
\]  

(1.2)

1.2.5 Stapes velocity measurements

Stapes velocity was measured with a laser vibrometer (Polytec OFV-501). The laser beam was aimed at the reflector placed on the stapes and the Doppler-shifted reflected signal was detected and decoded by the (OFV 2600) vibrometer controller to produce an output voltage that is proportional to stapes velocity. The reflector has an area of about 0.25 mm² and weighs about 0.05 mg. The stapes weighs about 2.5 mg (Wever and Lawrence, 1954; p. 417). To test whether or not the reflector affects the stapes motion, measurements were made with one, two, and three reflectors on the posterior crus. Comparisons are shown in Fig. 1-4. Since the measurements with one, two, and three reflectors are within 2 dB in magnitude and 0.05 cycles in angle, we conclude that the reflector does not change the mechanics of the middle-ear system significantly in our cadaveric preparation.

The laser vibrometer system measures velocity in the direction of the laser beam. The human-temporal-bone anatomy makes it impossible to focus the laser beam perpendicular to the plane of the stapes footplate, which is thought to be a plane perpendicular to the in-and-out, or piston-like, motion of the stapes. In our preparation, the laser beam is aimed through the facial recess at a reflector placed either on the posterior crus or the footplate of the stapes, and the view of the stapes leads to an angle between the laser beam and the expected piston-like stapes motion of about 20 to 50 degrees, depending on the individual anatomy. If the angle \( \phi \) between the laser beam and the stapes footplate is known, and the stapes motion is translational in and out of the oval window, then it is possible to correct the measured motion through division by \( \cos \phi \). It is difficult to estimate \( \phi \) in the three-dimensional space of our preparation, but crude estimates of \( \phi \) across our population of bones, using a protractor, indicate that \( \phi \) is typically between 20 and 50 degrees, which leads to systematic differences between the measured and actual stapes velocity of \( 20 \log(\cos \frac{20\degree}{180\degree}) = 0.5 \text{ dB} \) to \( 20 \log(\cos \frac{50\degree}{180\degree}) = 4 \text{ dB} \). However, for a given bone, the systematic error that may range from 0.5 to 4 dB will remain nearly constant, and since our ultimate goal is to measure changes in velocity that occur with tympanic-membrane perforations, absolute velocity calibration is not essential. Thus, we ignore the small effect of any angle correction and report velocity data that are not corrected for the angle of the laser beam relative to the stapes.

To test the velocity measurement system and whether the reflective tape follows the stapes motion, a stapes was removed from a temporal bone and glued to the surface of a shaker. Reflectors were placed both on the stapes footplate and glued to the surface of the shaker next to the stapes. Velocity measurements were made by relocating the laser beam to focus on each reflector; from 100 to 1000 Hz the ratio between the two measurements was
Figure 1-4: Comparison between measurements made with one, two, and three reflectors on the stapes (bone 26). For all three measurements, the laser was focused on the reflector attached to the stapes footplate. There were two additional reflectors on the posterior crus during the first measurement; there was one reflector on the posterior crus during the second measurement; and there was no extra reflector on the stapes during the third measurement. **TOP:** Magnitude. The left axis indicates the stapes velocity per ear-canal pressure for each individual measurement, and the right axis indicates the ratios between the measurements (in dB). **BOTTOM:** Angle.
less than 1 dB in magnitude and 0.01 cycles in angle, and from 1000 to 4000 Hz the ratio between the two measurements was less than 3 dB in magnitude and 0.05 cycles in angle. From these measurements we conclude that the reflector placed on the stapes footplate moves with the same motion as the stapes itself moves.

1.2.6 Mechanical artifact

Our middle-ear transfer function measurements of $V_S/P_{EC}$ are affected by a mechanical artifact, which appears to result from vibration of the sound source which shakes the entire bone. This mechanical artifact limits the measurement of the middle-ear transfer function $V_S/P_{EC}$ because the artifact-induced motion of the stapes adds to its sound-induced motion. We measure this artifact as the motion of the bony round-window niche (part of the petrous bone) in response to the sound stimulus in the ear canal. Specifically, we place a reflector on the bony round-window niche and we measure the transfer function between this temporal-bone velocity and the ear-canal pressure, $V_{BONE}/P_{EC}$. In figures that follow, measurements of $|V_{BONE}/P_{EC}|$ are plotted with the measurements of $|V_S/P_{EC}|$ in order to define regions where $V_S/P_{EC}$ is corrupted by the artifact. In most cases, $|V_S/P_{EC}|$ is more than 20 dB greater than $|V_{BONE}/P_{EC}|$, and therefore the artifact has little effect on the measured middle-ear transfer function.

Some features of the mechanical artifact are shown in Fig. 1-5. The velocity of reflector placed on the round-window niche was measured at three stimulus levels (A,B,C). The ratios of the velocity-magnitude measurements relative to the velocity-magnitude measurement at the mid-level B indicate that the mechanical artifact is stimulus dependent, i.e., as the stimulus increases the mechanical artifact increases proportionally. However, we are not able to measure this level-dependence of the artifact below about stimulus level C, where the noise-floor of the laser system and the mechanical artifact are similar. Although not plotted here, we also measured the mechanical artifact when the sound source was disconnected from the temporal-bone preparation. In this case, the velocity-magnitude decreased to the noise floor level, which indicates that the artifact results from the coupling of the sound source to the temporal-bone preparation and that the artifact is not strongly coupled through the table which holds the bone and measurement equipment.
Figure 1-5: The mechanical artifact measured as the velocity of a reflector placed on the round-window niche in response to ear-canal pressure $P_{EC}$ (TOP PLOT) at three levels: A, B, and C. The middle plot shows the velocity-magnitude in response to the three stimulus levels, and also the noise floor which is the velocity-magnitude in response to no input. The bottom plot shows the ratio of the velocity-magnitude measurements at stimulus levels A, B, and C relative to the velocity-magnitude measurement at stimulus level B.
1.3 Results

1.3.1 Linearity of the middle ear

In order to test whether the middle ear behaves linearly, we measured the middle-ear transfer function with ear-canal sound pressure levels that ranged from about 85 to 135 dB SPL. Measurements of $V_S/P_{EC}$ at several stimuli levels are plotted in Fig. 1-6, and $V_S/P_{EC}$ is nearly constant at levels up to about 130 dB SPL. Thus, the middle-ear system appears to be linear at least up to 130 dB SPL. Above 130 dB SPL we did not determine if the nonlinearities result from the middle-ear system or our instrumentation (e.g., our sound source or microphone), but in all cases the input stimulus to the ear canal appeared sinusoidal when monitored visually on an oscilloscope. (The measurements of Fig. 1-6 were all in response to a tonal stimulus.) All measurements presented in this chapter were made at levels below 130 dB SPL, and most measurements were in response to stimuli from 50 to 100 dB SPL (see Appendix B for ear-canal pressures).

1.3.2 Cavity sealed versus cavity open

Fig. 1-7 compares the middle-ear transfer function $V_S/P_{EC}$ with the middle-ear cavity closed (i.e., sealed acoustically) to $V_S/P_{EC}$ with the middle-ear cavity opened. Below 1000 Hz, the response is about 4 dB more sensitive when the cavity is open, and above 1000 Hz the differences between open and closed are smaller. Thus, sealing the middle-ear cavity reduces the magnitude of the middle-ear transfer function for frequencies below 1000 Hz. This result is consistent with the measurements and models of others (Onchi 1961; Zwislocki 1962; Gyo et al. 1986; Rosowski et al. 1990a; Rosowski and Merchant 1995; Whittemore et al. 1998). We address the effect of the middle-ear cavity further in chapter 4.4.
(D) Responses to a sweep of tone bursts.

Series of measurements. For each measurement, ear-canal pressure and shape velocity are the average of 50 (curves B and D) or 20 (curves A, C, and E) of which there are five measurements. Since these measurements are merely duplicates, the system appears to have been stable throughout the entire measurements, were made with the middle-ear cavity open. Both the first and the fund measurements were made at the 100 DB SPL input level (curve D) and the measurements at the other levels is plotted in the right column. All measurements were made at 6 input levels (from 20). Ear-canal pressure is plotted in the left column, and the ratio between ear-canal pressure and the shape velocity is plotted in the left-middle column, and the right-middle column of the transfer function. The shape velocity is plotted in the ear-canal pressure.

Figure 1. Measurements made at 6 input levels (from 20). Ear-canal pressure is plotted on the left, shape velocity is plotted in the left-middle, and angle difference (dB) and angle ratio (dB).
Figure 1-7: Magnitude and angle of $V_2/P_{EC}$ measured on bone 25 with the middle-ear cavity both closed and opened. First, the measurement with the cavity closed was made. Next, 3 glass coverslips – over the eustachian tube, the mastoid cavity, and the facial recess opening – were removed. The measurement with the cavity open was then made within minutes of the cavity closed measurement. TOP: Magnitude. The left axis indicates the magnitudes of the two stapes per ear-canal pressure measurements. The right axis indicates the magnitude ratio (in dB) between the cavity sealed and the cavity open measurements. BOTTOM: Angle.

1.3.3 Stability of measurements over time

Repeatability of measurements varied from bone to bone. For example, the transfer function $V_2/P_{EC}$ remained stable for several hours in some bones, but it decreased systematically in minutes in other bones. Typically, the decrease seemed to be associated primarily with the tympanic membrane, ossicular system, and annular ligament drying out. Moistening the system with saline and then using gentle suction to remove the saline almost always returned the response to its original level.
When the middle-ear cavity was not sealed, the bone appeared to dry out more rapidly than when the cavity was sealed. It seemed that a sealed cavity retained moisture for several hours while an open cavity did not. Fig. 1-8 shows two measurements separated by an hour. In this case, the cavity was sealed and the bone apparently did not dry out as the measurements are nearly the same at all frequencies, except for a narrow band near 1000 Hz where the peak magnitude differs by about 4 dB. In most bones, repeated measurements over at least 30 minute intervals showed similar stability to that in Fig. 1-8, even when the middle-ear cavity was open.

However, on some of our preparations, it was impossible to make repeated measurements that did not show systematic changes. For example, on both bone 21 Left and 21 Right, repeated measurements made within minutes of one another, showed a systematic decrease in the stapes velocity. It is not clear why these particular bones behaved differently; one hypothesis is that the time between death and stapes-velocity measurements was long relative to the times for other bones. In any case, when repeated measurements were not consistent with one another, the preparation was abandoned and not used for measurements with tympanic-membrane perforations.

1.3.4 Condition of the cochlea

Ideally, the cochleae on all of our bones remained filled with fluid for the measurement sessions. However, we have no way to confirm whether or not the cochleae did remain fluid filled. For example, damage to the endolymphatic sac during the removal of the temporal bone could create a leak of cochlear fluid. We suspect that freezing the cochleae may create cochlear-fluid leaks that result from fluid expansion while frozen. For this reason, we used fresh bones instead of frozen bones (with the exception of bone 16). As far as we could tell by examination under a microscope, the cochleae used here were normal at the oval and round windows. Additionally, measurements by Merchant et al. (1996, p.37) support the hypothesis that the cochleae of fresl temporal bones remain sealed.

Fig. 1-9 compares the transfer function $V_s/P_{EC}$ before and after purposely induced openings in the cochlea. A measurement was made with the cochlea normal. Next, the round window was punctured with a sharp instrument, and the measurement was repeated. Finally, the annular ligament was severed along its posterior edge. The round-window puncture leads to a systematic increase in $|V_s/P_{EC}|$ of about 1 to 2 dB at frequencies below 1000 Hz, and above 1000 Hz the round-window puncture results in larger increases of about 5 to 7 dB. Thus, air introduced into the cochlea seems to effect the stapes velocity, and the largest effects are above 1000 Hz. In contrast, damage to the annular ligament has the largest effects at the lower frequencies. Severing the annular ligament leads to a systematic increase in $|V_s/P_{EC}|$ of about 10 dB, up to about 1000 Hz, and above 1000 Hz, $|V_s/P_{EC}|$ reaches a maximum and then approaches the response measured with the
Figure 1-8: Comparison of $V_S/P_{EC}$ measurements made at an interval of one hour without moistening the bone. The cavity was sealed. **TOP:** Magnitude. The left axis indicates the magnitudes of the two stapes per ear-canal pressure measurements. The right axis indicates the magnitude ratio (in dB) between the two measurements. **BOTTOM:** Angle.
damage to the round window only. This result supports the hypothesis: when the annular ligament is severed, the low-frequency cochlear input impedance is reduced, and the stapes velocity increases. Thus, from Fig. 1-9, we conclude (1) stapes-velocity measurements that correspond to the normal ear require a fluid-filled cochlea and (2) our bones appear to be fluid filled because we measure changes in the stapes velocity when the round window is punctured.

1.3.5 Data from all bones

The middle-ear transfer function \( V_S/P_{EC} \) is plotted for each bone in Appendix B (Fig. B-1 to Fig. B-17). In most cases, several measurements were made, sometimes over the course of more than one measurement session. From the measurements on each bone, a representative measurement was selected; the selection process is further described in Appendix B. Fig. 1-10 plots both (1) one representative measurement of stapes velocity per ear-canal pressure for each bone and (2) the mean plus and minus the standard deviation of all representative measurements.

It is clear from Fig. 1-10 that the \( V_S/P_{EC} \) measurements vary substantially from bone to bone. All bones have a magnitude that increases at about 20 dB per decade at low frequencies. However, at any frequency, the magnitude ranges over an order of magnitude, and the peak magnitude occurs at frequencies as low as 480 Hz and as high as 2700 Hz, depending on the bone. Above about 1000 Hz, some measurements decrease in magnitude while other measurements show peaks and valleys. At low frequencies, the angle \( \angle(V_S/P_{EC}) \) is nearly 0.25 cycles, and as frequency increases, the \( \angle(V_S/P_{EC}) \) decreases such that it approaches 0 cycles near 1000 Hz and continues to decrease above 1000 Hz.

Fig. 1-10 separates measurements made with the middle-ear cavity sealed and open to the environment. The mean magnitude \( |V_S/P_{EC}| \) for the sealed-cavity condition is smaller than the mean magnitude for the open-cavity condition, which is consistent with the results presented above in chapter 1.3.2. Additionally, all bones were fresh except for bone 16, which had been previously frozen. The magnitude \( |V_S/P_{EC}| \) from bone 16 is identified on Fig.1-10 as the dashed line on the open-cavity plot. The measurement on this previously frozen bone shows similarities to the measurements made with the cochlea opened (chapter 1.3.4 ), which suggests that the cochlea on bone 16 may not have been sealed; thus, the measurement on bone 16 was not included in the displayed mean from the open-cavity measurements.

1.3.6 Modes of stapes motion

Our use of stapes velocity to define a middle-ear transfer function assumes that the stapes moves with a piston-like, translational motion in and out of the oval window. If instead of purely translational motion, the stapes moves with a more complex motion, such as rocking, then our use of velocity measurements at a single point on the stapes would not fully characterize the motion. For example, with the more complex motion, we would not
Figure 1-9: Effects of opening the cochlea on $V_s/P_{EC}$ (bone 25). First, $V_s/P_{EC}$ was measured with a normal cochlea. Next, a small hole was made in the round window, and the $V_s/P_{EC}$ measurement was repeated. Finally, the anterior portion of the annular ligament was severed, and the $V_s/P_{EC}$ measurement was again repeated. The middle-ear cavity was open for all the measurements. TOP: Magnitude. The left axis indicates the magnitudes of the three stapes per ear-canal pressure measurements. The right axis indicates the magnitude ratio (in dB) between each measurement and the measurement made with the cochlea normal. BOTTOM: Angle.
Figure 1-10: Stapes velocity per ear-canal pressure measured on all preparations. The thin lines indicate a single, representative measurement from each bone. The solid black line indicates the mean of the plotted representative measurements, and the gray shaded region is the mean plus and minus one standard deviation of the plotted representative measurements. All magnitude means and magnitude standard deviations were calculated in log base 10 domain, and all angle means and angle standard deviations were calculated in the linear domain. TOP: Magnitude. BOTTOM: Angle. LEFT: Representative measurements and the corresponding mean and standard deviation from the 21 bones in which the middle-ear cavity was sealed. RIGHT: Representative measurements and the corresponding mean and standard deviation from the 10 bones in which the middle-ear cavity was open. In this case, the dashed, black line is the measurement on bone 16, which was frozen prior to measurements. This measurement on bone 16 is not included in the mean.
know which component(s) of the stapes motion is (are) important for hearing, and we would not know which component we measure. However, if the stapes translates with a piston-like motion, then the velocity of any point on the stapes is equal to the velocity at any other point. Here, we make measurements of stapes velocity at different physical locations on the stapes in order to determine whether the stapes translates in one dimension or if the stapes motion is more complex.

Suppose the stapes does move with a translational motion in and out of the oval window. Under such a condition, even though each point on the stapes would move with the same velocity, our measurements of velocities at different locations may differ because our velocities are not corrected for the angle between the laser beam and the direction of translational motion (see chapter 1.2.5). Let us consider what we would expect to measure if we measure the velocity with our laser-doppler system at two different physical locations on the stapes, locations \( a \) and \( b \), assuming that the stapes moves with a translational motion. First, the phase angle of the stapes velocity (relative to the ear-canal sound-pressure angle) is independent of the location \( a \) or \( b \), because the entire stapes moves with the same motion. Second, the stapes-velocity magnitude could differ for the two locations \( a \) and \( b \). The magnitude depends on the cosine of the angle between the direction of translational motion and the incident laser beam. For example, if the angle between the translational motion and the laser beam was 0 degrees at location \( a \) and the angle between the translational motion and the laser beam was 45 degrees at location \( b \), then the magnitude ratio between the velocities at locations \( a \) and \( b \) would be \( 1/\sqrt{2} \). Thus, with a translational motion, velocity-magnitude measurements at two locations are related by a frequency-independent scale factor that results from different angles between the translational motion and the laser beam.

On five bones, measurements were made at different locations on the stapes in order to determine whether the stapes translates in and out of the oval window with a piston-like motion. For each bone, locations on the stapes were selected based on the individual anatomy. In some cases, it was possible to measure the velocity at more than one location on the footplate, while in other cases only part of the footplate was accessible by the laser beam. Thus, each of the five experiments has different measurement locations.

The measurements from the 5 bones are provided in Fig. 1-11, Fig. 1-12, and Fig. 1-13, and experiment-specific details are included in the captions. Plotted in each figure are the middle-ear transfer functions \( V_S/P_{EC} \), measured at different stapes locations, and the magnitude ratio and angle difference between the responses at the different locations (relative to a single location). In general, the angle differences at different stapes locations are nearly zero for frequencies up to 2000 Hz \(^1\), and above 2000 Hz, the angle differences rarely exceed 0.05 cycles. Likewise, the magnitude ratios are nearly constant with frequency, up to at least 2000 Hz, and above 2000 Hz, the changes in the magnitude ratio rarely exceed a few dB. As described above, a constant magnitude ratio is consistent with translational stapes motion.

\(^1\)See the caption of Fig. 1-11 for an explanation where the angle difference is zero only up to 1500 Hz.
motion in which the angle of incidence of the laser beam differed for different stapes locations. To summarize, the very small angle differences and the constancy of the magnitude ratio is consistent with a translational, piston-like motion of the stapes to frequencies of at least 2000 Hz. In other words, the measurements are consistent with the conclusion that translation in a frequency-independent direction describes the major features of the stapes motion. Above 2000 Hz, the motion appears to become more complex and perhaps different for different preparations, but even above 2000 Hz the magnitude ratios change by less than 5 dB and the angle differences can be nearly zero (depending on the bone). More measurements are needed to describe non-uniformities in stapes motion.

Figure 1-11: Measurements made by aiming the laser at 4 different locations on the stapes on bone 25. Reflectors were placed on the center of the footplate, at the anterior end of the footplate, at the posterior end of the footplate, and on the posterior crus of the stapes. LEFT: Magnitude and angle of $V_s/P_{EC}$ RIGHT: Magnitude ratio and angle difference relative to measurement at the center of the footplate. The first and final measurements were made with the laser aimed at the center of the footplate. In this bone, it appears that something changed during the time between the first and the final measurement. Specifically, the magnitude ratio and angle differences between the first and final measurements, both made at the center of the footplate, show variations from 0, especially between 1500 and 2000 Hz.
Figure 1-12: Measurements made by aiming the laser at different locations on the stapes of bones 26 and 27. LEFT: Bone 26. Reflectors were placed on both the posterior and the anterior most parts of the footplate. RIGHT: Bone 27. Reflectors were placed on both the posterior and the anterior most parts of the footplate, and on the posterior crus of the stapes. TOP: Magnitude of $V_s/P_{EC}$ for all reflector positions is plotted on the left-hand axis and the ratio between the measurements is plotted on the right-hand axis. BOTTOM: Angle of $V_s/P_{EC}$ for all reflector positions is plotted on the left-hand axis and the difference between the two measurements is plotted on the left-hand axis.
Figure 1-13: Measurements made by aiming the laser at 2 different locations on the stapes on bones 28 (Left) and 29 (Right). In both cases, reflectors were placed at the anterior end of the footplate and on the posterior crus of the stapes. On these bones, is was not possible to view the posterior end of the footplate. TOP: Magnitude of $V_s/P_{EC}$ for all reflector positions is plotted on the left-hand axis and the ratio between the measurements is plotted on the right-hand axis. BOTTOM: Angle of $V_s/P_{EC}$ for all reflector positions is plotted on the left-hand axis and the difference between the two measurements is plotted on the left-hand axis.
1.4 Discussion

1.4.1 Use of cadaveric temporal bones

Several investigators have used fresh\(^2\) human cadaver ears in order to study human middle-ear function. Two studies offer direct evidence that the acoustic properties of the middle ear of the cadaveric preparation are equivalent to those of the live middle ear. Specifically, Rosowski et al. (1990a) compared postmortem impedance measurements made at the tympanic membrane to measurements made on living human subjects; for postmortem ears with normal tympanograms, impedance measurement ranges were similar to those for living subjects. In a separate study, Goode et al. (1993) measured the magnitude of umbo velocity on both live and post-mortem human ears; again, the measurements for the two groups were similar. Even though it is currently difficult to test whether or not stapes motion is the same for the dead and live cases, the similarity in umbo motion and input impedance suggests that the stapes motion should also be similar. Thus, it appears that fresh human cadaver ears have acousto-mechanical properties that are similar to live human ears.

The state of the two middle-ear muscles, the stapedius and the tensor tympani, differs between our temporal-bone preparation and a live ear. These muscles are unable to contract in the temporal-bone preparation. However, in the live ear, the normal state for the muscles is relaxed and not tense, and the muscles contract when sound pressures are high (Silman 1984). Thus, our measurements with the muscles in either the relaxed or severed state serve to mimic the live middle-ear function, especially at lower sound pressure levels.

Even though the evidence described above supports the assumption that sound transmission is similar in fresh-cadaveric and live-human middle ears, special steps must be taken to maintain the normal function of the cadaver ears. First, the cadaver ears must be kept moist or else the middle-ear system becomes stiffer than normal (Rosowski et al. 1990a). We use an isotonic saline solution to keep our ears moist, and we hypothesize that the use of water for moistening purposes could lead to abnormal swelling from osmotic processes. Second, the cadaver ears probably should not be frozen and then thawed. It seems that the cochlear fluids could expand during the freezing process and in turn leak from the cochlea after thawing; such a process would alter the cochlear input impedance and probably affect the stapes velocity (Merchant et al. 1996) as a result of reduced fluid and entry of air bubbles within the cochlea. In fact, the middle-ear transfer function \((V_S/P_{EC})\) measurements we made on one previously-frozen bone (bone 16) are consistent with air in the cochlea; the magnitude of the frozen-bone measurement is greater than the magnitude of measurements made on similar fresh bones (Fig. 1-10), and our measurements of \(V_S/P_{EC}\) with a drained cochlea show that a reduction in cochlear fluid increases the magnitude of \(V_S/P_{EC}\) (Fig. 1-9). Furthermore, the reduction in damping and the sharp peak in our data with a drained

\(^2\)Fresh refers to bones that have not been frozen. The bones are typically refrigerated in a saline solution both before and between measurement sessions.
| Author                  | Method                        | $|V_s/P_{sc}|$ (mm/s/Pa) | Cavity State | Comments                                                                 |
|------------------------|-------------------------------|---------------------|--------------|--------------------------------------------------------------------------|
| Kringlebotn and Gundersen (1985) | Round-window volume displacement | 0.07                | open         | Average from 68 temporal bones. Condition of bones (i.e., fresh or frozen) not stated. Tones at 105 dB SPL. |
| Vlaming and Feenstra (1986) | Laser-Doppler                | .04 (range .015-.12) | open         | Average from 20 frozen temporal bones, defrosted in water. Tones at 80 dB SPL. No cos correction. |
| Gyo et al. (1997)       | Strobe and video              | 0.08                | sealed       | Average from 14 fresh temporal bones. Tones at 124 dB SPL.               |
| Nishihara et al. (1993) | Laser-Doppler                | 0.12                | sealed       | Average from 15 fresh temporal bones. Tones at 80 dB SPL. Cos correction applied. |
| Kurokawa and Goode (1995) | Laser-Doppler                | 0.04                | sealed       | Average from 6 fresh temporal bones. Tones at 105 dB SPL. Cos correction applied. |
| This work               | Laser-Doppler                | .03 (range .008 to 0.15) | sealed       | Average from 21 fresh temporal bones. No cos correction applied.         |

Table 1.1: Comparison of stapes motion measurements from the literature to those made here. All results converted to velocity per ear-canal pressure at 500 Hz.

cochlea are consistent with measurements made on cat (Lynch 1981; Allen 1986).

1.4.2 Comparison to measurements of others

Table 1.1 and Fig. 1-14 compare our stapes velocity measurements to other measurements reported in the literature. For the comparison to our data, we use our measurements on the 21 bones with the middle-ear cavity sealed (Fig. 1-10). All results plotted in Fig. 1-14 are similar in that: (1) below 1000 Hz, stapes-velocity magnitude increases with frequency at about 20 dB per decade, and stapes-velocity leads ear-canal pressure by almost 0.25 cycles and (2) above 1000 Hz, both the magnitude and angle of stapes velocity decrease with frequency.

The measurements compared in Fig. 1-14 contain differences in the range of mean magnitude, with the measurements reported here having the lowest mean magnitude. The measurements of Vlaming and Feenstra (1986), Kringlebotn and Gundersen (1985), and Kurokawa and Goode (1995) are mostly within the same range as the measurements reported here, while the measurements of Gyo et al. (1987) and Nishihara et al. (1993) are higher than the range reported here. These differences may involve combinations of several factors. First, both Kringlebotn and Gundersen (1985) and Gyo et al. (1987) used different methods from those used here (summarized in Table 1.1). While the measurements of Vlaming and Feenstra (1986) were made with similar methods to those used here, the temporal bones used by Vlaming and Feenstra (1986) were frozen prior to measurements and soaked in water during the defrosting process. Freezing the temporal bone could alter the cochlear load if fluid expansion while frozen creates a leak, and soaking the bones in water may change the acoustic properties if water is absorbed. Additionally, the measurements from Kringlebotn and Gundersen (1986) and Vlaming and Feenstra (1986) were made with the middle-ear cavity opened, which results in an increased stapes velocity (see Fig. 1-7
and chapter 4.4). An important difference between our reported stapes velocity and that of both Nishihara et al. (1993) and Kurokawa and Goode (1995) is that we do not correct for the angle between the laser beam and the expected direction of the piston-like motion of the stapes. The correction applied to these data for angles between 35 and 50 degrees make the Nishihara et al. (1993) and Kurokawa and Goode (1995) data systematically 1.7 to 3.8 dB greater than our data. In fact, if our mean magnitude data are increased by 3.8 dB, then below 1000 Hz they are nearly identical to those of Kurokawa and Goode (1995).

In summary, our measurements of stapes velocity are consistent with measurements in the literature that have been made by others. Our decreased magnitude, relative to these other measurements, may result from the combination of several factors that include (1) measurement technique (i.e., laser doppler as opposed to other methods), (2) condition of the temporal bone (i.e., fresh versus frozen), (3) state of the middle-ear cavity (e.g., open versus sealed or volume of cavity), and (4) correction for differences in angle between supposed stapes motion and the laser beam of a laser-doppler system.
The average of these four is the thick black line.

The average from 20 doses measured by Yimnag and Penelton (1996) was not reported. Individual measurements from four doses were reported. Here, the data were converted to dynamic pressure by multiplication by \( \frac{2}{\pi} \) for each peak and division by the appropriate pressure in each case. In cases where multiple measurements were reported the means of the measurements were reported. In cases where only one report for two of the cases was reported, the means of the two reports were reported for the cases in which one was reported. The mean measurements from the literature are shown in gray. The standard deviation is shaded in gray for the cases in which one was reported. The mean methods employed in each case. Our mean measurement is the gray line and the corresponding standard deviation is the dashed gray region. Mean values are employed for each set of measurements in the literature. Table 1.1 summarizes the

Figure 1-14: Comparison of our phase velocity measurements to five other sets of measurements reported in the literature.
1.4.3 Modes of stapes motion

Conflicting results exist on the mode of stapes motion. Some studies suggest that the stapes moves in and out of the oval window like a piston with one-dimensional translational motion (Guinan and Peake 1967; Dankbaar 1970; Gundersen 1972; Vlaming and Feenstra 1986) while others describe stapes motion with adjectives such as “rocking” and “hinge-like”, suggesting more complex stapes motion (Békésy 1960; Kirikae 1960; Gyo et al. 1987).

Evidence of complex (i.e., not translational) stapes motion comes from several sources. Békésy (1960, pp.112-114) claims that for intensities below the threshold of feeling, the stapes “executes a rotational movement about a vertical axis running through the posterior edge of the footplate,” and at intensities above the threshold of feeling, “the stapes rotates about an axis running longitudinally through the footplate.” It is not clear how Békésy drew these conclusions about the rocking motion of the stapes. Kirikae (1960) observed human-cadaver stapes motion with an optical system. For tones from 120 Hz to 2000 Hz, and stimulus levels from 110 to 140 dB (re sensation level), Kirikae (1960) concluded that “the vibration of the stapes is a complexity of three motions consisting of the hinging vibration round the minor axis of the foot plate, parallel (piston-like) movement of the foot plate and rotatory movement with the major axis of the foot plate as the rotation axis.” Later, Gyo et al. (1987, p.91) presented stroboscopic measurements made on human cadaver ears from which they conclude “at lower frequencies below 1 kHz, the stapes vibrated with a combination of piston-like and hinge-like movements, while at higher frequencies above 1.2 kHz, rotatory movement around the lengthwise axis was dominant.”

Support for a translating, piston-like stapes motion also includes several sources. Using measurements with stroboscopic illumination of live cat stapes, Guinan and Peake (1967) conclude “the stapes moves predominately in and out like a piston”. Dankbaar (1970) measured stapes footplate displacement at five footplate locations on a human cadaver ear from 25 to 2000 Hz. He placed a piezoelectric crystal pickup needle on the vestibular side of the footplate, which required removal of the cochlea. Dankbaar concluded that the footplate moves with a piston-like motion because all five footplate locations had identical displacements. A few years later, also using a pick-up needle on the vestibule side of a human-cadaver stapes, Gundersen (1972, p.422) concluded that “the stapes seems to move mainly as a piston in the oval window.” Vlaming and Feenstra (1986) used a laser-doppler vibrometer to measure stapes velocity at four points on the footplate. Since the velocity measurements were independent of footplate position, Vlaming and Feenstra (1986) conclude that the stapes moves in a piston-like manner, at least up to 5000 Hz. Most recently, Heiland et al. (1998) measured stapes motion on human temporal bones at three points on the stapes footplate and found a translational, piston-like motion up to at least 2000 Hz. Finally, measurements we made of stapes velocity at different footplate locations on five preparations (chapter 1.3.6) support a piston-like, translational stapes motion up to 2000 Hz.
We conclude that stapes motion appears translational (i.e., one-dimensional) below about 2000 Hz, and it is possibly more complex (multi-dimensional) above 2000 Hz. Thus, measurement of stapes velocity with a laser-doppler system (i.e., measurement in one dimension) is a reasonable method to describe sound transmission through the middle ear for frequencies up to 2000 Hz. Above 2000 Hz, more detailed study of stapes motion is needed to determine if measurements in one dimension are a reasonable measure of middle-ear sound transmission. Specifically, to study such motion, it seems necessary to develop a method for precise determination of the three-dimensional space in which the stapes sits and the laser beam travels. For example, in conjunction with laser-doppler measurements of stapes velocity at several locations on the stapes, knowledge in some coordinate system of the physical location of the stapes and the angle of the laser beam would allow for calculation of the precise motion of the stapes.
Chapter 2

Measurement of middle-ear sound transmission on a human temporal-bone preparation with tympanic-membrane perforations

2.1 Introduction

In this chapter, we present measurements of middle-ear sound transmission made on the same human temporal-bone preparations described in chapter 1. Measurements reported here were made with tympanic-membrane perforations of different sizes and locations. Specifically, our perforation sizes range from about 0.01% (diameter 0.1 mm) to 50% of the tympanic-membrane area, and we focus on the location differences between the anterior-inferior (AI) and posterior-inferior (PI) quadrants\(^1\). Our goal is to describe how such perforations affect sound transmission in terms of both (1) changes in sound transmission relative to the normal ear and (2) the mechanisms responsible for the measured transmission changes.

We present several types of measurements. First, we measure the middle-ear transfer function — i.e., stapes velocity per ear-canal pressure \((V_S/P_{EC})\) — described in chapter 1. This transfer function is a measure of sound transmission from the ear canal to the cochlea. Our measurements of the middle-ear transfer function include contributions from both the ossicular and acoustic routes of sound transmission described on page 13 and in Fig. I-2

\(^1\)We focus on the these two locations, AI and PI, because they are two common locations for placement of tympanostomy tubes, which can be considered surgically controlled perforations (Introduction, p. 15)
of the Introduction. The perforation-induced changes in the middle-ear transfer function measure the total changes in middle-ear sound transmission when the tympanic-membrane is perforated.

In addition to measurements of total changes in middle-ear sound transmission that result from perforations, we also make measurements to determine the mechanisms responsible for the transmission changes. As described on page 22 of the Introduction, one factor of sound transmission via the ossicular route is the pressure difference across the tympanic membrane, which drives the tympanic-membrane motion. We measure this pressure difference across the tympanic membrane in order to determine its importance in describing sound transmission with perforations. Specifically, we use sound-pressure measurements to calculate a transfer function $H_{\Delta TM}$ between the pressure difference across the tympanic membrane and the ear-canal pressure, and we examine how $H_{\Delta TM}$ changes with perforations.

Next, we examine how sound transmission is changed with tympanic-membrane perforations when the pressure-difference across the tympanic membrane is held constant. Here, we compute the transfer function between the stapes velocity and the pressure difference across the tympanic membrane, and we call this transfer function $H_{TOC}$, where $H_{TOC}$ is our measure of sound transmission through the middle-ear when the pressure difference across the tympanic membrane is held constant. In principle, $H_{TOC}$ is influenced by both the ossicular and acoustic routes of sound transmission, as $H_{TOC}$ is computed from the total stapes velocity. However, in chapter 3, we show that under most conditions with tympanic-membrane perforations, the acoustic route of sound transmission is negligible compared to the ossicular route. Thus, here, we interpret the transfer function $H_{TOC}$ as a measure of the ossicular coupling from the tympanic membrane ($T$), through the ossicles ($O$), and to the cochlea ($C$). In general, changes in $H_{TOC}$ represent changes in the mechanics of the ossicular system (e.g., changes in tympanic-membrane area or changes in the coupling between the malleus and the tympanic membrane).

The final measurement type presented here in chapter 2 is measurement of the acoustic input impedance of the middle ear, on the ear-canal side of the tympanic membrane. This impedance is the ratio of the ear-canal sound pressure to the volume velocity from both the tympanic-membrane motion plus flow through the perforation. Thus, the middle-ear input impedance at the tympanic membrane $Z_{TM}$ is an acoustical measurement of how the perforation affects the middle-ear input. Furthermore, the impedance measured with the tympanic membrane removed is a measure of the middle-ear cavity impedance. As we will see here in chapter 2 and also in chapter 4, the middle-ear cavity impedance plays an important role in the explanation of sound transmission with tympanic-membrane perforations.
2.2 Methods

2.2.1 Subjects and temporal-bone preparation

Perforations were made on 11 of the 34 bones discussed in chapter 1 (bones 8, 9, 13, 18, 19, 20, 22 Left, 22 Right, 23, 24 Left, and 24 Right). Experiment-related details, such as the sizes and locations of every perforation, are listed in Table 2.1. The temporal bone preparation was described in chapter 1. Additional measurement techniques are described below.

2.2.2 Perforation of the tympanic membrane

For each bone, perforations of different sizes and locations were made in the tympanic membrane. Typically, increasing-sized circular perforations were made in either the posterior-inferior (PI) or the anterior-inferior (AI) quadrant. In most cases, once an entire quadrant was perforated, a kidney-shaped perforation that included both inferior quadrants was made so that most of inferior half of the tympanic membrane was removed. A typical sequence of perforations is illustrated in Fig. 2-1.

![Figure 2-1: Schematic to demonstrate how increasing-sized perforations are made.](image)

The controlled tympanic-membrane perforations were made with a surgical Argon laser. The laser made it possible to control the location and size of a perforation. In order to measure the perforation sizes, an image of the tympanic membrane was video taped as each perforation was made, and a scale was placed next to the perforation. Later, the perforation was viewed with a video monitor and the perforation was traced and measured to obtain its area. We report a diameter that is calculated from the area measurement for each perforation. For kidney-shaped perforations that include more than one quadrant, we report the diameter that would be associated with the measured area even though the perforation is not circular.
<table>
<thead>
<tr>
<th>ID</th>
<th>Perforation size and location</th>
<th>Experiment notes</th>
<th>Volumes (cm³)</th>
</tr>
</thead>
</table>
| tb8 | Perf 1: Posterior-inferior; diameter=0.5mm  
Perf 2: Posterior-inferior; diameter=0.7mm  
Perf 3: Posterior-inferior; diameter=1.1mm  
Perf 4: Posterior-inferior; diameter=1.6mm  
Perf 5: Posterior-inferior; diameter=2.4mm  
Perf 6: Inferior-U-shaped; diameter=3.2mm | Perforation measurements (960806). Each measurement had only 16 frequency points from 25 Hz to 100000 Hz. | VCAV = 1.4 cm³  
VEC = 0.15 cm³ |
| tb9 | Perf 1: Posterior-inferior; diameter=0.1mm  
Perf 2: Posterior-inferior; diameter=0.8mm  
Perf 3: Posterior-inferior; diameter=1.1mm  
Perf 4: Posterior-inferior; diameter=1.9mm  
Perf 5: Posterior-inferior; diameter=3.3mm | Perforation measurements (961031). Tissue measurements had 25 points from 25 Hz to 10000 Hz. Artifact measurements were made only with the tympanic membrane normal with the low-impedance source. | VCAV = 3.3 cm³  
VEC = 0.16 cm³ |
| tb13 | Perf 1: Posterior-inferior; diameter=0.5mm  
Perf 2: Posterior-inferior; diameter=0.8mm  
Perf 3: Posterior-inferior; diameter=1.4mm  
Perf 4: Posterior-inferior; diameter=1.8mm | Perforation measurements (961219). Artifact was measured only with the tympanic membrane normal. Use this measurement for all perforations in order to eliminate data that is corrupted by the artifact. Tissue measurements had 25 points from 25 Hz to 10000 Hz. | VCAV = 3.7 cm³  
VEC = 0.16 cm³ |
| tb18 | Perf 1: Anterior-inferior; diameter=0.4mm  
Perf 2: Anterior-inferior; diameter=0.5mm  
Perf 3: Anterior-inferior; diameter=0.8mm  
Perf 4: Anterior-inferior; diameter=1.0mm  
Perf 5: Anterior-inferior; diameter=1.7mm  
Perf 6: Anterior-inferior; diameter=2.3mm  
Perf 7: Anterior-inferior; diameter=3.0mm  
Perf 8: Anterior-inferior; diameter=3.3mm | Perforation measurements (970407). Impedance measurements all have severe acoustic leaks that are most likely a result of the way the low frequency source was coupled to the bone. Thus, impedance measurements not presented for this bone. | unavailable |
| tb19 | Perf 1: Posterior-inferior; diameter=0.6mm  
Perf 2: Anterior-inferior; diameter=0.8mm  
Perf 3: Posterior-inferior; diameter=1.3mm  
Perf 4: Posterior-inferior; diameter=1.9mm  
Perf 5: Posterior-inferior; diameter=2.6mm | Perforation measurements (970426). The cavity pressures \(P_{CW}\) and \(P_{CW}\) for perforation 2 were not measured. | VCAV = 1.6 cm³  
VEC = 0.2 cm³ |
| tb20 | Perf 1: Margin, Posterior-inferior; diameter=0.7mm  
Perf 2: Central, Posterior-inferior; diameter=0.7mm  
Perf 3: Central, Posterior-inferior; diameter=1mm  
Perf 4: Posterior-inferior; diameter=1.7mm  
Perf 5: Posterior-inferior; diameter=3.0mm  
Perf 6: Posterior-inferior; quadrant; diameter=4.0mm  
Perf 7: Inferior half; diameter=5.6mm | Perforation measurements (970501). Perforation 4 expanded upon the central perforation. | VCAV = 1.6 cm³  
VEC = 0.2 cm³ |
| tb22L | Perf 1: Anterior-inferior; diameter=0.6mm  
Perf 2: Anterior-inferior; diameter=1.2mm  
Perf 3: Anterior-inferior; diameter=2.0mm  
Perf 4: Anterior-inferior; diameter=3.0mm  
Perf 5: Inferior-U-shaped; diameter=5.0mm | Perforation measurements (970518). The stapes-velocity measurements have problems for the fourth perforation - some aspect of the electronics may have been connected wrong. Thus, no Vw/Pw measurements for perforation 4. | VCAV = 1.5 cm³  
VEC = 0.18 cm³ |
| tb22R | Perf 1: Posterior-inferior; diameter=0.6mm  
Perf 2: Posterior-inferior; diameter=1.3mm  
Perf 3: Posterior-inferior; diameter=2.3mm  
Perf 4: Posterior-inferior; diameter=3.3mm  
Perf 5: Posterior-half; diameter=6.8mm | Perforation measurements (970522). The perforations began near the posterior-inferior margin. Perforation 4 included the entire posterior-inferior quadrant and perforation 5 included the entire posterior-inferior half. | VCAV = 1.5 cm³  
VEC = 0.15 cm³ |
| tb23 | Perf 1: Anterior-inferior; diameter=0.8mm  
Perf 2: Anterior-inferior; diameter=1.0mm  
Perf 3: Anterior-inferior; diameter=2.0mm  
Perf 4: Anterior-inferior; diameter=3.0mm  
Perf 5: Anterior-inferior; diameter=4.0mm  
Perf 6: Inferior-U-shaped; diameter=5.0mm | Perforation measurements (970626). The perforations began near the anterior-inferior margin. Perforation 5 included the entire anterior-inferior quadrant and perforation 6 included the entire inferior half. | VCAV = 1.3 cm³  
VEC = 0.14 cm³ |
| tb24L | Perf 1: Anterior-inferior; diameter=0.5mm  
Perf 2: Anterior-inferior; diameter=0.8mm  
Perf 3: Anterior-inferior; diameter=1.2mm  
Perf 4: Anterior-inferior; diameter=2.0mm  
Perf 5: Anterior-inferior; diameter=3.3mm  
Perf 6: Inferior-U-shaped; diameter=5.0mm | Perforation measurements (970630). Perforation 5 included the entire anterior-inferior quadrant and perforation 6 included the entire inferior half. | VCAV = 1.6 cm³  
VEC = 0.13 cm³ |
| tb24R | Perf 1: Anterior-inferior; diameter=0.5mm  
Perf 2: Anterior-inferior; diameter=0.6mm  
Perf 3: Anterior-inferior; diameter=1.2mm  
Perf 4: Anterior-inferior; diameter=2.3mm  
Perf 5: Posterior-inferior; diameter=4.0mm  
Perf 6: Inferior-U-shaped; diameter=5.0mm | Perforation measurements (970701). Perforation 5 included the entire Posterior-inferior quadrant and perforation 6 included the entire inferior half. | VCAV = 1.6 cm³  
VEC = 0.14 cm³ |

Table 2.1: Summary of all perforations.
2.2.3 Measurement of the middle-ear transfer function: Stapes velocity per pressure at the tympanic membrane

We use our measurements of the transfer function stapes velocity to ear-canal pressure, $V_S/P_{EC}$, as a description of the sound transmission through the middle ear. Our measurement technique and instrumentation was described in chapter 1.2. Specific details relevant to the measurements presented in this chapter are described here.

2.2.3.1 Acoustic stimuli for stapes-velocity measurements

Unless otherwise noted, the measurements of stapes velocity per ear-canal pressure reported in this chapter were made in response to tonal stimuli. For each tone, the two responses, ear-canal pressure and stapes velocity, were averaged as noted, typically the average of 1000 or 2000 41-ms-long responses for a total of 41 or 82 seconds of averaging. The frequency resolution for the first three bones with tympanic-membrane perforations was much smaller than that for the final eight bones. Measurements made on the final eight bones with tympanic-membrane perforations each have a frequency resolution of 68 logarithmically-spaced points from 25 to 10000 Hz, whereas the measurements on bones 8, 9, and 13 have only 16, 25 and 25 logarithmically-spaced points respectively. Due to the small frequency resolution on the first three bones, some of the reported means include only the final eight bones. Such cases are noted.

2.2.3.2 Correction for ear-canal air space

We measure the ear-canal pressure about 3 mm lateral to the tympanic membrane. When the tympanic-membrane is normal, this short distance is negligible and the sound pressure at our microphone ($P_{EC}$) is equal to the sound pressure at the tympanic membrane ($P_{TM}$). However, for large tympanic-membrane perforations, the impedance at the tympanic membrane decreases (chapter 2.3.5), and as a result, the pressure across the 3 mm distance between the microphone and the tympanic membrane can vary. To correct for the location difference, we use a lossless cylindrical-tube model to represent the residual ear-canal air space (Moller 1965; Rabinowitz 1981; Lynch et al. 1994; Huang et al. 1997), and we predict the pressure $P_{TM}$ at the tympanic membrane as

$$P_{TM} = \frac{P_{EC}Z_{TM}}{Z_{TM} \cos(kl) + jZ_o \sin(kl)},$$  \hfill (2.1)

where $P_{EC}$ is the measured pressure at the microphone probe-tube orifice, $Z_{TM}$ is the measured impedance at the tympanic membrane (chapter 2.2.6), $Z_o = \rho c/A$ is the characteristic impedance of the tube, $l = 3$ mm is the length of the tube, $A$ is the area of the tube, $k = 2\pi f/c$, $\rho$ is the density of air, $c$ is the velocity of sound in air, and $f$ is the frequency.
Figure 2-2: The ratio between $P_{EC}$ and $P_{TM}$ calculated for the data from bone 24L. $P_{EC}$ is the pressure measured in the ear canal, and $P_{TM}$ is the pressure at the tympanic membrane calculated from Equation 2.1.
We calculate the area $A$ as $A = V_{EC}/l$, where $V_{EC}$ is the ear-canal air volume between the microphone probe-tube orifice and the tympanic membrane, which is measured by filling the residual ear-canal air space with saline using a calibrated syringe; our measurements of $V_{EC}$ are included in Table 2.1.

Fig. 2-2 plots the ratio $P_{EC}/P_{TM}$ for the normal and perforated tympanic-membrane conditions. For perforations less than 1 mm in diameter, the ratio is less than 1 dB in magnitude and only a few hundredths of a cycle in angle. However, as the perforation diameter increases, and when the tympanic membrane is removed, the ratio $P_{EC}/P_{TM}$ can approach ±3 dB in magnitude and 0.1 cycles in angle for frequencies above 1000 Hz. Below 1000 Hz, the differences between $P_{EC}$ and $P_{TM}$ are small for all tympanic-membrane conditions.

In the following chapters, we apply the sound pressure correction of Equation 2.1, and the middle-ear transfer function $V_S/P_{EC}$ becomes $V_S/P_{TM}$. We note that we do not have measurements of $Z_{TM}$ on bone 18, which makes it impossible to calculate $P_{TM}$ for this preparation. However, since for many frequencies and for many perforation sizes, $P_{TM} \approx P_{EC}$, we use our measurements of $P_{EC}$ for all results that pertain to bone 18.

2.2.3.3 Removal of data affected by the mechanical artifact

Chapter 1.2.6 discusses the mechanical artifact that results from movement of the entire bone and not just the stapes. As perforations are made, the stapes velocity decreases for a constant pressure at the tympanic membrane, and the mechanical artifact interferes with measurement of the stapes velocity. As illustrated in Fig. 2-3, we removed data points that are within 20 dB of the artifact.

2.2.3.4 Definition of transmission loss

To study sound transmission with tympanic-membrane perforations, we compare the middle-ear transfer function, $\frac{V_S^{\text{norm}}}{P_{TM}}$, measured with a normal, intact tympanic membrane, to the same transfer function measured with a perforated tympanic membrane, $\frac{V_S^{\text{perf}}}{P_{TM}}$. The ratio between the transfer functions under the normal and the perforated conditions serves as our measure of transmission loss.

$$\text{Transmission Loss} \equiv \frac{V_S^{\text{norm}}}{P_{TM}} \div \frac{V_S^{\text{perf}}}{P_{TM}}. \quad (2.2)$$

Fig. 2-3 demonstrates the use of Equation 2.2.

2.2.3.5 Modes of stapes motion with tympanic-membrane perforations

In chapter 1.3.6, we presented measurements of stapes velocity made at different locations on the stapes in order to determine whether the stapes translates in and out of the oval
Figure 2-3: Example to demonstrate (1) elimination of data contaminated by the mechanical artifact and (2) calculation of transmission loss with tympanic-membrane perforations via Equation 2.2. LEFT: Transfer function magnitude between stapes velocity and pressure at the tympanic membrane for the tympanic membrane normal and with a 0.7mm diameter perforation (bone 20). Also shown is the measured mechanical artifact. Any data points that are within 20 dB (arbitrarily chosen) of the artifact are eliminated from the measurement. Here, for the perforation case, points that are more than 20 dB above the artifact are plotted in open triangles. RIGHT: Transmission loss calculated from left figure as the ratio between the measured transfer functions with the normal tympanic membrane and the perforated tympanic membrane. Only points that are 20 dB or more above the artifact are used for the calculation.
window with a piston-like motion or if the stapes has a more complex motion. Briefly, we argued that to be consistent with translational motion, the velocity ratio between two measurement locations has to (1) have a magnitude that is constant versus frequency, and (2) have an angle that is zero (see chapter 1.3.6 for further explanation). Figs. 1-11 to 1-13 show data from the five bones that suggests that up to at least 2000 Hz, stapes motion is translational, when the tympanic membrane is normal.

To determine whether the stapes motion is piston-like when the tympanic membrane is perforated, stapes-velocity measurements at two stapes locations were also made with tympanic-membrane perforations on two of the five bones presented in chapter 1.3.6. Fig. 2-4 shows the magnitude ratios and angle differences in stapes velocity for each perforation associated with these two bones. Below 2000 Hz, the magnitude ratios and angle differences with the tympanic-membrane perforations appear similar to those shown for a normal tympanic membrane in Figs. 1-11 to 1-13: below about 2000 Hz, the magnitude ratios are nearly constant and the angle differences are nearly zero, consistent with a translational motion. Above 2000 Hz, there is more variability in both the magnitude ratios and angle differences, suggesting a more complicated motion.

2.2.4 Pressure difference across the tympanic membrane

2.2.4.1 Calculation of the pressure difference

We calculate the pressure difference across the tympanic membrane from measurements of ear-canal sound pressure and middle-ear cavity sound pressure. The ear-canal sound pressure, $P_{EC}$, is generated and measured with the acoustic assembly described in chapter 1.2.4, and $P_{TM}$ is computed from $P_{EC}$ with Equation 2.1. (The same acoustic assembly is used for the measurements of stapes velocity per ear-canal sound pressure described above.) The middle-ear cavity sound pressure, $P_{CAV}$, is measured with a probe-tube microphone that is placed near the stapes footplate within the middle-ear cavity. Details of this probe-tube microphone and its calibration are contained in chapter 3.2.2.2, where the focus of chapter 3 is the measurement of sound pressures outside the oval and round windows. Here, $P_{CAV}$ is taken to be $P_{OW}$ of chapter 3. We compute $H_{\Delta TM}$, the transfer function between the pressure difference across the tympanic membrane and the tympanic-membrane pressure, as

$$H_{\Delta TM} = \frac{\Delta P_{TM}}{P_{TM}} = \frac{P_{TM} - P_{CAV}}{P_{TM}}.$$  \hspace{1cm} (2.3)

To examine how perforations affect $H_{\Delta TM}$, we also compute changes in $H_{\Delta TM}$ for the normal tympanic membrane relative to the perforated tympanic membrane as
Figure 2-4: Magnitude ratios and angle differences between $V_S/P_{EC}$ measured at two locations on the stapes of bones 28 and 29 with the tympanic membrane both normal and perforated. For both bones, the measurement locations were the anterior end of the stapes footplate (AF) and the posterior crus (PC). Thus, for each tympanic-membrane condition noted in the legends, the magnitude ratio refers to the ratio $|V_{PC}/P_{EC}|$, and the angle difference refers to the difference $\angle(V_{PC}/P_{EC}) - \angle(V_{AF}/P_{EC})$. The middle-ear cavities were open for the measurements on bone 28 and sealed for the measurements on bone 29. Measurement stimuli were chirps, and symbols to distinguish between measurements are plotted at every 30th data point.
\[ \Delta H_{\Delta TM} \equiv \text{Change in } H_{\Delta TM} = \frac{H_{\text{norm}}_{\Delta TM}}{H_{\text{per}}_{\Delta TM}}. \] (2.4)

### 2.2.4.2 Limits on the pressure-difference calculation due to calibration errors

With the tympanic membrane perforated, the middle-ear cavity pressure and the pressure at the tympanic membrane are nearly equal at low frequencies. Thus, small errors in the relative calibration of the two microphones that measure these two pressures introduce large errors in the computed pressure difference. The calibration procedure for the microphone that measures \( P_{CAV} \) is described in chapter 3.2.2.2. Briefly, this microphone is calibrated relative to the microphone that measures \( P_{EC} \) by coupling the two microphones together and comparing their responses to a common stimulus. The two microphones have two different calibration procedures. The microphone that measures the ear-canal pressure is calibrated by comparing its response to the response of a second quarter-inch microphone and an acoustic calibrator (chapter 1.2.4), and the microphone that measures the middle-ear cavity pressure is calibrated by comparing its response to the calibrated response of the ear-canal pressure microphone (chapter 3.2.2.2). Thus, we do not have an exact measure of the relative calibration errors that might exist between the two calibrations.

To estimate the variability in the relative calibrations between the two microphones, we examine repeated calibrations over the course of a single experiment for the microphone that measures the middle-ear cavity pressure. In general, the repeated calibrations during a single experiment vary by about 1 dB in magnitude and about 0.01 cycles in angle. A typical example of repeated calibrations is shown in Fig. 2-5.

If we assume an uncertainty in the relative calibrations for the two microphones of 1 dB in magnitude and 0.01 cycles in angle, we can set a lower limit on our ability to measure \( H_{\Delta TM} \). When \( P_{TM} \approx P_{CAV} \), a 1 dB error in magnitude corresponds to a factor of about 1.1. If we assume that \( P_{TM} \approx P_{CAV} \), then \( |H_{\Delta TM}| \approx 0 \). However, with an error in \( P_{CAV} \) of 1.1\( P_{CAV} \), the smallest \( |H_{\Delta TM}| \) that we can measure with \( P_{TM} \approx P_{CAV} \) is 0.1, where

\[
|H_{\Delta TM}| \text{ limit from 1 dB error} = \left| \frac{P_{TM} - 1.1P_{TM}}{P_{TM}} \right| = 0.1. \] (2.5)

Likewise, with \( P_{TM} \approx P_{CAV} \) and an angle error in \( P_{CAV} \) of \( P_{CAV} e^{2\pi \cdot 0.01 j} \), the smallest \( |H_{\Delta TM}| \) that we can measure with \( P_{TM} \approx P_{CAV} \) is 0.06, where

\[
|H_{\Delta TM}| \text{ limit from 0.01 cycles angle error} = \left| \frac{P_{TM} - P_{TM} e^{2\pi \cdot 0.01 j}}{P_{TM}} \right| = 0.06. \] (2.6)

Combination of both the factor of 1.1 in magnitude and the 0.01 cycles in angle leads to a limit of 0.12. Thus, based on our estimates of uncertainty in the relative calibration for the microphones that measure \( P_{EC} \) and \( P_{CAV} \), we impose the lower limit of 0.1 on the pressure...
ratio ($|H_{\Delta TM}|$) of Equation 2.3. In other words, we consider any $|H_{\Delta TM}|$ calculated from our pressure measurements that is below 0.1 to be inaccurate, and we eliminate it from the presented results.

We also note that the 0.1 cut off is supported by the pressure-difference data. Fig. 2-6 shows examples of $H_{\Delta TM}$ from two preparations. In general, with the tympanic membrane perforated, the low frequency $|H_{\Delta TM}|$ increases at about 40 dB/decade with increasing frequency. However, for the larger perforations and the lower frequencies, where the pressure differences are the smallest, the low frequency $|H_{\Delta TM}|$ cease to increase at 40 dB/decade. Instead, for these cases, $|H_{\Delta TM}|$ becomes irregular and for some regions constant with frequency. We suspect that this behavior results from errors in the calculation of the pressure difference.

Figure 2-5: Repeated calibrations ($N=5$) for the microphone that measures the middle-ear cavity pressure during the experiment on bone 19. LEFT: The top plot is repeated measurements for the magnitude calibration of the microphone that measures the middle-ear cavity pressure, $P_{CAV}$. The bottom plot is the ratio between each calibration measurement to the first calibration measurement. RIGHT: The top plot is repeated measurements for the angle calibration of the microphone that measures the middle-ear cavity. The bottom plot is the angle difference between each calibration and the first calibration measurement. Symbols are used to distinguish between measurements at intervals that vary between every 8th to 16th data point.
Figure 2-6: Examples of $H_{\Delta TM} = \Delta P_{TM}/P_{TM}$ from two preparations. The dashed line at 0.1 on the magnitude plot indicates our lower limit for accurate measurement of $\Delta P_{TM}/P_{TM}$. All points below this line are removed in future plots. Additionally, for each measurement curve, all points at frequencies below the highest frequency where $|\Delta P_{TM}/P_{TM}| < 0.1$ are also removed. Symbols to distinguish between measurements are plotted at every 20th data point. TOP: Magnitude. BOTTOM: Angle.
2.2.4.3 Acoustic Stimuli for cavity pressure measurements

The voltages that correspond to the pressures $P_{EC}$ and $P_{CAV}$ are measured simultaneously on two channels in response to a chirp stimulus. The chirp contains 1024 linearly spaced frequencies from 24 to 25000 Hz. The reported response is the average of 200 responses (8.2 seconds of averaging).

2.2.4.4 Spatial variations of cavity pressure

Our data analysis and interpretation assume that a tympanic-membrane perforation does not introduce spatial variations in the sound-pressure field of the middle-ear cavity. That is, we assume that our measured $P_{CAV}$ describes the pressure everywhere within the cavity. To check this assumption, we measured the spatial variation in middle-ear cavity pressure across the perforation to determine how much the sound-pressure varied with location near the perforation. Specifically, in one preparation (bone 18), we introduced a probe-tube microphone through the Eustachian tube and measured middle-ear cavity pressures at 5 locations, spaced 1 mm apart, across the middle-ear cavity side of the anterior portion of the tympanic membrane. The 5 locations swept across the first four perforations made in the tympanic membrane. The trajectory of the probe-tube microphone was almost parallel to the tympanic membrane so that the probe tip was within about 1 mm of the tympanic membrane at each pressure-measurement location. The probe-tube microphone was similar to the assemblies used to measure the pressures at the oval and round windows; a description of these microphone and the calibration procedure for these microphones can be found in chapter 3.2.2.2.

Fig. 2-7 shows the middle-ear cavity pressure measured at five locations for a normal tympanic membrane and four different perforations. Below about 1000 Hz, the spatial variation in pressure across the middle-ear cavity side of the tympanic-membrane perforation is small; pressure-magnitude ratios relative to position 0 mm are less than 1 dB, and above 1000 Hz the pressure magnitude ratios relative to position 0 mm rarely exceed 3 dB. Likewise, the angle differences are smallest below 1000 Hz (less than 0.005 cycles), and up to 4000 Hz the angle differences rarely exceed 0.01 cycles. In general, the largest magnitude ratios and angle differences occur for the largest perforations. For frequencies below about 3000 Hz, it appears that the middle-ear cavity sound pressure field is uniform even in the region near the tympanic-membrane perforation, but as frequency increases and perforation size increases, small nonuniformities become apparent.

2.2.5 Stapes velocity per pressure difference across the tympanic membrane

Perforation-induced changes in the stapes velocity per pressure difference across the tympanic membrane is a measure of sound transmission through the middle ear for a constant
Figure 2-1: Measurements of middle ear cavity pressure relative to ear canal pressure at 5 locations spaced 1 mm apart along the medial surface of the middle ear cavity.
pressure difference across the tympanic membrane. That is, this transfer function is a measure of sound transmission that eliminates the effects of changing pressure differences across the tympanic membrane with different perforations.

We refer to the transfer function between stapes velocity and pressure difference across the tympanic membrane as $H_{TOC}$, and we calculate $H_{TOC}$ from the measurements described above of stapes velocity per pressure at the tympanic membrane and pressure difference across the tympanic membrane per pressure at the tympanic membrane.

$$H_{TOC} = \frac{V_S/P_{TM}}{(P_{TM} - P_{CAV})/P_{TM}} \equiv \frac{V_S/P_{TM}}{H_{\Delta TM}}$$  \hspace{1cm} (2.7)

Changes in $H_{TOC}$ are also calculated as the ratio of the normal tympanic-membrane $H_{TOC}^{norm}$ to the perforated tympanic-membrane $H_{TOC}^{perf}$:

$$\Delta H_{TOC} \equiv \text{Change in } H_{TOC} \equiv \frac{H_{TOC}^{norm}}{H_{TOC}^{perf}}$$  \hspace{1cm} (2.8)

To calculate $H_{TOC}$ (Equation 2.7), some data manipulation was required. The measurements of $V_S/P_{TM}$ were made with a frequency resolution of 68 points from 24 to 10000 Hz (chapter 2.2.3), whereas the measurements of $H_{\Delta TM} = \Delta P_{TM}/P_{TM}$ (Equation 2.3) were made with a frequency resolution of 1024 points from 24 to 25000 Hz (chapter 2.2.4). Thus, the two kinds of measurements are not at exactly the same frequencies. We resolve this problem through interpolation of the $H_{\Delta TM}$ data to the frequencies of the $H_{TOC}$ data, where the $H_{\Delta TM}$ data has the larger frequency resolution of the two measurements. Data interpolation is done using cubic spline interpolation performed using the software package Matlab (The Mathworks, Inc.). Note, that the displayed $H_{TOC}$'s do not include points where either (1) $|V_S/P_{EC}|$ is within 20 dB of the mechanical artifact (chapter 2.2.3) or (2) $|\Delta P_{TM}/P_{EC}| < 0.1$ (chapter 2.2.4).

2.2.6 Impedance measurements at the tympanic membrane

We make measurements of the acoustic impedance at the tympanic membrane, $Z_{TM}$, with and without tympanic-membrane perforations. $Z_{TM}$ is a measure of the middle-ear load and is defined as the ratio between the volume velocity of the tympanic membrane to the pressure at the tympanic membrane. Here, we use measurements of $Z_{TM}$ to measure the acoustic effects of the perforations at the input to our system. In chapter 4, we make further use of the impedance measurements presented here to develop a quantitative model of the ear with a tympanic-membrane perforation.

2.2.6.1 Background on impedance-measurement method

Impedance measurements at the tympanic membrane were made with a method similar to that used by others (Lynch 1981; Rabinowitz 1981; Rosowski et al. 1984; Allen 1986;
Rosowski et al. 1990a; Ravicz et al. 1992; Lynch et al. 1994; Voss and Allen 1994; Teoh et al. 1997; Huang et al. 1997). Here, the Thévenin equivalent of the sound-delivery system (Fig. 2-8) is measured by making pressure measurements in two loads of known theoretical impedance: a tube with a rigid end (length=0.2 mm) that approximates an open circuit \(Z_{\text{open}}\) and a long tube with an open end with impedance \(Z_{\text{tube}}\) that is approximately resistive and smaller in magnitude than the source impedance. The two theoretical impedances, \(Z_{\text{open}}\) and \(Z_{\text{tube}}\), are calculated from the equations of Egolf (1977). The two pressure measurements made in the two loads, \(P_{\text{open}}\) and \(P_{\text{tube}}\), and the two theoretical impedances give two equations with two unknowns: the source Thévenin pressure \(P_{\text{source}}\) and the source Thévenin impedance \(Z_{\text{source}}\). The equations are

\[
\begin{align*}
P_{\text{open}} & = P_{\text{source}} \frac{Z_{\text{open}}}{Z_{\text{open}} + Z_{\text{source}}} \\
P_{\text{tube}} & = P_{\text{source}} \frac{Z_{\text{tube}}}{Z_{\text{tube}} + Z_{\text{source}}}.
\end{align*}
\]  

(2.9)

Simultaneous solution of Equations 2.9 provide estimates of \(P_{\text{source}}\) and \(Z_{\text{source}}\). The impedance of any load, \(Z_{\text{load}}\), can then be calculated from a pressure measurement in that load, \(P_{\text{load}}\), and use of the measured \(P_{\text{source}}\) and \(Z_{\text{source}}\):

\[
Z_{\text{load}} = Z_{\text{source}} \frac{P_{\text{load}}}{P_{\text{source}} - P_{\text{load}}}.
\]  

(2.10)

Figure 2-8: A schematic of the Thévenin equivalent for the sound delivery system. \(Z_{\text{source}}\) and \(P_{\text{source}}\) are calculated by measuring \(P_{\text{load}}\) in two loads of known impedance, \(Z_{\text{open}}\) and \(Z_{\text{tube}}\). \(P_{\text{source}}\) is proportional to the voltage input and is independent of the load, and \(Z_{\text{source}}\) is independent of both the voltage input and the load.

### 2.2.6.2 Acoustic assembly and stimulus

The acoustic assembly used to measure impedance in the ear canal was different from the one used to generate sound for the other ear-canal pressure (\(P_{EC}\)) measurements described above. Specifically, for an accurate impedance measurement, the source impedance mag-
nitude $|Z_{source}|$ must not be small compared to the magnitude of the impedance to be measured (e.g., input impedance of the middle ear). In other words, we require the opposite of an ideal pressure source in that the pressure across the load must be substantially dependent on the load impedance. The same point is made through examination of the circuit of Fig.2-8; if $|Z_{source}|$ were small relative to $|Z_{load}|$, as an ideal pressure source would be, then the measured pressure $P_{load}$ would always approximate the source pressure $P_{source}$, and there would not be measurable variations with different loads.

Our acoustic assembly for impedance measurements consists of a Knowles ED-1913 hearing aid receiver that acts as a sound source (Knowles Electronics, Elk Grove, IL) and a Knowles EK-3027 microphone for sound-pressure measurement. The source is further described by Ravicz et al. (1992).

All calibration and impedance measurements are made in response to a chirp stimulus. The chirp contains 1024 linearly spaced frequencies from 24 to 25000 Hz, and each reported measurement is an average of 200 responses.

2.2.6.3 Acoustic-source characteristics

The source's measured Thévenin-equivalent impedance is plotted in Fig. 2-9. Also plotted are representative measurements from one temporal bone. These plots show that the source impedance magnitude, ($|Z_{source}|$), is greater than either magnitude for our two extreme measurement cases, the normal tympanic membrane ($|Z_{TM}^{normal}|$) and the tympanic membrane removed ($|Z_{CAV}|$). Thus, pressures generated by this source will depend on the load impedance over the impedance range of interest. Although not shown in Fig. 2-9, we note that above about 4000 Hz, the impedance measurements become noisy due to the source's inability to generate substantial sound pressures at the higher frequencies.

2.2.6.4 Test loads

To check the measured $P_{source}$ and $Z_{source}$, we make pressure measurements in five additional loads with known theoretical impedances. We then calculate the measured impedances (from Equation 2.10) and compare them to the theoretical impedances predicted from equations from Egolf (1977). This method has been demonstrated to produce estimates of $Z_{load}$ that are accurate to within 10% in magnitude and 10 degrees in angle (Lynch 1981; Rabinowitz 1981; Rosowski et al. 1984; Allen 1986; Rosowski et al. 1990a; Ravicz et al. 1992; Lynch et al. 1994; Voss and Allen 1994; Teoh et al. 1997; Huang et al. 1997). Our five test loads are all tubes of diameter 4 mm and include: "Cavity B" with a rigid termination and length 6.8 mm, "Cavity C" with a rigid termination and length 29.6 mm, "Cavity E" with a rigid termination and length 11.7 mm, "Cavity LC" with a rigid termination with a 0.36 mm diameter hole through it and length 4.1 mm, and "Black tube" which is a 10 m long tube with an open termination.
Figure 2-9: Comparison of the source's Thévenin equivalent impedance to the two extreme impedances we measure experimentally. TOP: Magnitude. Note, the Thévenin equivalent magnitude, $|Z_{SOURCE}|$, is greater than the magnitude of both measured impedances. BOTTOM: Angle.
Figure 2-10: Comparison of measured and theoretical impedances of the five test loads described in the text. LEFT: Impedance magnitudes. LEFT-MIDDLE: Magnitude ratio (dB) of the magnitude of measurement to theory. RIGHT-MIDDLE: Impedance angles. Dotted lines represent ±0.25 cycles. RIGHT: Angle difference between measurement and theory.
Examples of the measured impedance in the five test loads compared to their theoretical impedance are shown in Fig. 2-10. Here, the magnitude ratios between the measurements and the theory are less than 1 dB at most frequencies between 100 and 4000 Hz, and the angle differences are less than 0.025 cycles at most frequencies between 100 and 4000 Hz. The largest variations between the theory and the measurements occur at resonant frequencies where there are large derivatives with respect to frequency; small errors in tube-length estimation have large effects at such frequencies. Such agreement between the measurement and the theory in the test loads is typical for all our impedance measurements on all the bones.

In general, these comparisons between measurements in the test loads and the observation that the sound source does not generate substantial sound pressures above about 4000 Hz suggest that our impedance measurements are valid up to about 4000 Hz. At higher frequencies there are errors larger than 1 to 2 dB in magnitude and 0.025 cycles in angle.

2.2.6.5 Measurement of impedance in the ear canal

Impedance was measured in the ear canal of each temporal bone when the tympanic membrane was both normal and perforated. The measurement location was about 3 mm from the tympanic membrane. In all cases, the air volume between the measurement location and the tympanic membrane was measured by filling the ear canal with saline using a calibrated syringe; measurements were made before the tympanic membrane was perforated. Across all preparations, the volumes ranged from 0.13 cm$^3$ to 0.20 cm$^3$ (see Table 2.1), and repeated volumetric measurements never differed by more than 0.02 cm$^3$. After the impedance was measured, the effect of the ear-canal volume was removed from the impedance measurement with the lossless cylindrical-tube model of the residual ear-canal air space that was described above in chapter 2.2.3.2. Here, $Z_{TM}$ is the impedance at the tympanic membrane and $Z_{EC}$ is the impedance measured at the probe-tube microphone orifice. In all cases, we report impedances at the tympanic membrane, $Z_{TM}$, where

\[
Z_{TM} = Z_0 \frac{Z_{EC} - jZ_0 \tan(kl)}{Z_0 - jZ_{EC} \tan(kl)} \quad \text{(2.11)}
\]

See chapter 2.2.3.2 above for variable definitions.

2.2.7 Frequency range of plotted results

Our measurements cover a range in frequency from either (1) 24 to 10000 Hz for stapes velocity and ear-canal pressure measurements made with tones (chapter 2.2.3) or (2) 24 to 25000 Hz for ear-canal and middle-ear cavity pressure measurements made with a chirp stimulus (chapter 2.2.4) and for impedance measurements (chapter 2.2.6). However, the entire measurement range is not useful. Below 100 Hz, many of the data have problems. Specifically, the mechanical artifact that corrupts the stapes-velocity measurements (chap-
ter 2.2.3) and the errors in calculating the pressure difference across the tympanic membrane (chapter 2.2.4) often make these lowest-frequency measurements meaningless. Thus, in order to improve visibility of our results for frequencies with meaningful data, the measurements below 100 Hz are not plotted. Likewise, we do not plot results at frequencies greater than 4000 Hz. First, due to the lack of understanding of the modes of stapes motion at higher frequencies (chapter 1.4.3), it is not clear how to interpret stapes-velocity measurements made in one dimension at frequencies above 4000 Hz. And second, our middle-ear impedance measurements are noisy at frequencies above about 4000 Hz because the sound source used for impedance measurements does not generate adequate sound pressures at higher frequencies; thus, calculation of $P_{TM}$ from $P_{EC}$ from Equation 2.1 for frequencies above 4000 Hz is not possible with our data.

2.3 Results

2.3.1 Organization

The results presented in this section are organized into five sections. The first four sections provide measurements and calculations for the middle-ear sound transmission measures discussed above in the Introduction (chapter 2.1). Specifically, we present measurements, (made with the tympanic membrane both normal and perforated), of (1) the middle-ear transfer function $V_s/P_{TM}$; (2) the transfer function between the pressure difference across the tympanic membrane and the pressure at the tympanic membrane, $H_{\Delta TM}$; (3) the transfer function between stapes velocity and the pressure difference across the tympanic membrane, $H_{TOC}$; and (4) the acoustic input impedance of the middle ear, $Z_{TM}$. For each of these four sections, we show example data from the same two temporal-bone preparations (bones 22R and 24L). The results from these two preparations are consistent with the results from all the preparations, and the interested reader is referred to appendices where all data from all bones are provided.

The final section presents results of one experiment designed to investigate the effect of extensive slits in the tympanic membrane on $H_{TOC}$. Specifically, the tympanic membrane was perforated with slits along the manubrium of the malleus in order to maximize the perforation's effect on $H_{TOC}$ and to minimize the perforation's effect on $H_{\Delta TM}$. The motivation for this experiment is discussed further in chapter 2.3.6.

2.3.2 The middle-ear transfer function: $V_s/P_{TM}$
2.3.2.1 Dependence on frequency and perforation size

Measurements of the middle-ear transfer function $V_S/P_{TM}$ (i.e., stapes velocity per pressure at the tympanic membrane), are shown as a function of frequency for two example bones in Fig. 2-11; the parameter is perforation size. All measurements of $V_S/P_{TM}$ made on all eleven bones are included in Appendix C (page 211). In every case, both the magnitude and angle of $V_S/P_{TM}$ display several consistent features. First consider the magnitude $|V_S/P_{TM}|$:

1. As perforation size increases, $|V_S^{\text{perf}}/P_{TM}|$ decreases systematically at frequencies below 1000 to 2000 Hz.

2. $|V_S^{\text{perf}}/P_{TM}|$ increases with increasing frequency such that in the 1000 to 2000 Hz range, $|V_S^{\text{perf}}/P_{TM}|$ approaches the normal value, and in many cases $|V_S^{\text{perf}}/P_{TM}|$ slightly exceeds $|V_S^{\text{norm}}/P_{TM}|$.

3. Above 1000 to 2000 Hz, the perforation generally has smaller effects than at lower frequencies.

Next, consider the angle $\angle(V_S/P_{TM})$. With the tympanic membrane normal, $\angle(V_S^{\text{norm}}/P_{TM})$ is flat at about 0.25 cycles at frequencies up to at least 500 Hz, and above about 500 Hz, $\angle(V_S^{\text{norm}}/P_{TM})$ decreases gradually with increasing frequency. When the tympanic membrane is perforated:

1. At low frequencies, $\angle(V_S^{\text{perf}}/P_{TM})$ is roughly constant with frequency but its value is typically between 0.25 and 0.75 cycles. Larger perforations result in larger low-frequency angle increases.

2. As frequency increases, $\angle(V_S^{\text{perf}}/P_{TM})$ decreases and approaches the value for the normal tympanic membrane $\angle(V_S^{\text{norm}}/P_{TM})$.

In Fig. 2-11 (and the figures of Appendix C, page 211) the magnitude of loss in the middle-ear transfer function defined by Equation 2.2 is also plotted. The characteristics of the transmission loss are the same as those described above for $|V_S/P_{TM}|$: the losses are greatest at the lower frequencies; the low-frequency losses increase with perforation size; and the losses are smaller above 1000 to 2000 Hz where there can also be small increases in transmission (negative losses).

Fig. 2-12 shows the mean magnitude losses computed from the final eight experiments. Perforations were grouped into five size categories shown as parameters in Fig. 2-12. The mean loss curves point out several features that are consistent with the individual measurements described above: (1) Loss in sound transmission with tympanic-membrane perforations is frequency dependent with the largest losses occurring at low frequencies; (2) Low-frequency loss increases with perforation size; (3) The slope of the low-frequency loss increases as perforation size increases; (4) Between 1000 and 2000 Hz, there can be increases
Figure 2-11: Stapes velocity per pressure at the tympanic membrane measured on bones 24 Left and 22 Right. Perforation size is the parameter. Perforation diameters d and perforation locations are noted within the plots. The smaller perforations on bone 24 Left were in the anterior-inferior (AI) quadrant and on bone 22 Right in the posterior-inferior (PI) quadrant. The largest perforation on bone 24 Left contained most of the inferior half of the tympanic membrane, and the largest perforation on bone 22 Right contained most of the posterior half of the tympanic membrane. Symbols are plotted at every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude of the Loss (Equation 2.2).
Figure 2-12: Mean loss magnitude in stapes velocity per pressure at the tympanic membrane (Equation 2.2). Losses from all perforations are included from the final eight bones. Each loss curve, with size as a parameter, includes all perforations made on the eight bones that fit the size category. The indicated N refers to the total number of perforations in each size category. N is the maximum number of measurements at each frequency, as individual frequency points where $V_S/P_{TM}$ is within 20 dB of the artifact are not included in calculation of the mean. There are five data points between symbols and 5 data points between error bars.
in transmission with perforations, where both the frequency location and the sharpness increase as perforation diameter increases; and (5) From about 2000 to 4000 Hz, loss of less than 15 dB occurs, which increases with perforation size.

2.3.2.2 Dependence on perforation location

The effects of perforation location on the middle-ear transfer function $V_S/P_{TM}$ were determined with two kinds of comparisons. For comparisons in the same ear, we first made a perforation in one location and measured $V_S/P_{TM}$; next we patched$^2$ the perforation and demonstrated that $V_S/P_{TM}$ returned to near its normal value; next we made a second perforation in a new location and measured $V_S/P_{TM}$. This method was satisfactory for perforation diameters less than about 1 mm. For perforations larger than 1 mm, we were unable to return $V_S/P_{TM}$ to its normal value with a patch. To compare locations for diameters greater than 1 mm, comparisons were made between different ears.

2.3.2.2.1 Small perforations: up to 1 mm in diameter. In three bones, we compared perforation-location effects using the patching paradigm described above. In two of the bones we compared perforations in the anterior-inferior quadrant to perforations in the posterior-inferior quadrant. These comparisons are shown in Fig. 2-13 and Fig. 2-14. There are no large differences between the results with the two locations; in fact, differences between the two locations are only a few dB in magnitude and generally less than 0.05 cycles in angle. Perforations located marginally and centrally are compared in Fig. 2-15. Again, there are no large differences between perforation locations.

We also compared effects of small perforations in the anterior-inferior and posterior-inferior quadrants between different bones. Using the results from the eight final experiments (where our frequency resolution was finest), we grouped all perforations less than or equal to 1 mm in diameter into one of two groups: (1) anterior-inferior (N=10) or (2) posterior-inferior (N=6). The loss from each of these perforations, at six selected frequencies, is plotted as a function of perforation diameter in Fig. 2-16. For these small perforations, at the lower frequencies, there is a clear trend of loss with perforation size. However, there are no obvious differences between the two perforation locations. Included in Fig. 2-16 are fits to each of the two sets of data that could be used to test for statistical differences between anterior and posterior. However, we do not apply such a test because the plotted data points are not independent, as there are different numbers of data points from each of the 8 bones. The problems with a statistical test are discussed below in chapter 2.3.2.2.2.

In summary, our measurements, both on single bones and across a population of 8 bones, do not show any differences in the middle-ear transfer function $V_S/P_{TM}$ for perforations in

$^2$ We used cigarette paper for the patch.
Figure 2-13: Comparison between perforations in the posterior-inferior and anterior-inferior quadrants (bone 19). Four measurements were made in the following order: 1. \( V_S/P_{TM} \) was measured with the tympanic membrane normal; 2. Perforation P (posterior-inferior perforation in schematic at top) with diameter 0.6mm was made, and \( V_S/P_{TM} \) was measured (indicated with circles at every fifth data point); 3. With perforation P patched, \( V_S/P_{TM} \) was measured; 4. A second perforation, perforation A (anterior-inferior perforation in schematic at top) with diameter 0.8mm was made, and \( V_S/P_{TM} \) was measured with the patch remaining over the posterior-inferior quadrant (indicated with squares at every fifth data point). LEFT: Magnitude \( |V_S/P_{TM}| \) and Angle \( \angle(V_S/P_{TM}) \). RIGHT: Losses in \( |V_S/P_{TM}| \) and \( \angle(V_S/P_{TM}) \). The losses in the first perforation P (posterior-inferior) and the patched tympanic membrane are both relative to \( V_S/P_{TM} \) measured with the normal tympanic membrane. The losses in the second perforation A (anterior-inferior) are relative to \( V_S/P_{TM} \) measured with the patched tympanic membrane so that we see the effect of the perforation and not the patch.
Figure 2-14: Comparison between perforations in the posterior-inferior and anterior-inferior quadrants (bone 24 Right). Four measurements were made in the following order: 1. \( V_S/P_{TM} \) was measured with the tympanic membrane normal; 2. Perforation A (anterior-inferior perforation in schematic at top) with diameter 0.5 mm was made, and \( V_S/P_{TM} \) was measured (indicated with circles at every fifth data point); 3. With perforation A patched, \( V_S/P_{TM} \) was measured; 4. A second perforation, perforation P (posterior-inferior perforation in schematic at top) with diameter 0.6 mm was made, and \( V_S/P_{TM} \) was measured with the patch remaining over the anterior-inferior quadrant (indicated with squares at every fifth data point). LEFT: Magnitude \( |V_S/P_{TM}| \) and Angle \( \angle(V_S/P_{TM}) \). RIGHT: Losses in \( |V_S/P_{TM}| \) and \( \angle(V_S/P_{TM}) \). The losses in the first perforation A (anterior-inferior) and the patched tympanic membrane are both relative to \( V_S/P_{TM} \) measured with the normal tympanic membrane. The losses in the second perforation P (posterior-inferior) are relative to \( V_S/P_{TM} \) measured with the patched tympanic membrane so that we see the effect of the perforation and not the patch.
Figure 2-15: Comparison between perforations near the tympanic membrane edge (margin) and near the malleus (central) in the posterior-inferior quadrant (bone 20). Four measurements were made in the following order: 1. $V_S/P_{TM}$ was measured with the tympanic membrane normal; 2. Perforation M (margin in schematic at top) with diameter 0.7 mm was made, and $V_S/P_{TM}$ was measured (indicated with circles at every fifth data point); 3. With perforation M patched, $V_S/P_{TM}$ was measured; 4. A second perforation, perforation C (central perforation in schematic at top) with diameter 0.7 mm was made, and $V_S/P_{TM}$ was measured with the patch remaining over the margin perforation (indicated with squares at every fifth data point). LEFT: Magnitude $|V_S/P_{TM}|$ and Angle $\angle(V_S/P_{TM})$. RIGHT: Losses in $|V_S/P_{TM}|$ and $\angle(V_S/P_{TM})$. The losses in the first perforation M (margin) and the patched tympanic membrane are both relative to $V_S/P_{TM}$ measured with the normal tympanic membrane. The losses in the second perforation C (central) are relative to $V_S/P_{TM}$ measured with the patched tympanic membrane so that we see the effect of the perforation and not the patch.
Figure 2-16: Losses from all perforations with diameter less than or equal to 1 mm plotted as a function of perforation diameter at six frequencies: 250, 500, 750, 1000, 1350, and 2200 Hz. Plotted in the red circles are the losses that correspond to perforations in the posterior-inferior quadrant, and plotted in the blue squares are the losses that correspond to perforations in the anterior-inferior quadrant. The solid (anterior-inferior perforations) and the dashed (posterior-inferior perforations) lines are fit to the data using the least-squares method.
either the posterior-inferior or the anterior-inferior quadrants when the perforation diameter is up to 1 mm.

2.3.2.2.2 Large perforations: 1 to 4 mm in diameter. Fig. 2-17 plots the losses from all perforations with diameters between 1 and 4 mm at six frequencies. Again, the data are grouped by perforation location as either (1) posterior-inferior or (2) anterior-inferior. At some of the frequencies where the losses are plotted in Fig. 2-17, the posterior and the anterior perforations appear to produce different losses. However, care must be taken in the analysis of this data. As an example, consider the frequency 750 Hz. Here, the least-squares fits for the two groups of data appear significantly different; in fact a student-T test suggests that the slopes of these two fits are different with a certainty of $p < 0.01$. However, such a test is not appropriate for this data. In particular, consider the data from the anterior-inferior perforations. There are seven perforations that fit this category, but these seven data points come from only three preparations; thus, they do not represent seven independent data points, but instead only three independent data points. If a single data point from each of the three bones with anterior perforations is considered, then there appears to be a difference between anterior and posterior perforations only one in three times; the anterior-perforation data from bone 24L does not differ from the posterior-perforation data while the anterior-perforation data from bones 22L and 23 might differ. Thus, while we do not observe obvious systematic differences between locations for larger perforations, we are unable, with our small number of independent data points, to make a definitive statement about the dependence of loss on perforation location for perforations greater than 1 mm in diameter.

2.3.3 Pressure difference across the tympanic membrane: $H_{\Delta TM}$

Measurements of the normalized pressure difference across the tympanic membrane, $H_{\Delta TM} = \Delta P_{TM}/P_{TM}$ (Equation 2.3), are shown in Fig. 2-18 for the two example bones; the parameter is perforation size. All measurements of $H_{\Delta TM}$ made on all eleven bones are included in Appendix D (page 219). Many of the features of $H_{\Delta TM}$ are similar to the features of $V_{S}/P_{TM}$ described above. In each case, as was observed with $V_{S}/P_{TM}$, the low-frequency magnitude of $|H_{\Delta TM}|$ decreases systematically as perforation size increases. In all cases with a perforated tympanic membrane, $|H_{\Delta TM}|$ has a maximum where the perforated tympanic-membrane measurement exceeds the normal tympanic-membrane measurement. The frequency of this maximum is usually between 1000 and 2000 Hz, and at the maximum frequency, the angle $\angle H_{\Delta TM}$ decreases from 0.5 cycles to 0 cycles. The combination of the magnitude maximum and the half-cycle angle change suggests a second-order resonant system at work in the transfer function $H_{\Delta TM}$. Also, as with $V_{S}/P_{TM}$, the frequency location and the sharpness of the maximum increase as perforation diameter increases.
Figure 2-17: Losses from all perforations with diameters between 1 mm and 4 mm plotted as a function of perforation diameter at six frequencies: 250, 500, 750, 1000, 1350, and 2200 Hz. Plotted in the red circles are the losses that correspond to perforations in the posterior-inferior quadrant, and plotted in the blue squares are the losses that correspond to perforations in the anterior-inferior quadrant. The solid (anterior-inferior perforations) and the dashed (posterior-inferior perforations) lines are fit to the data using the least-squares method.
Figure 2-18: The pressure difference across the tympanic membrane, $H_{\Delta TM} = \Delta P_{TM}/P_{TM}$ (Equation 2.3), measured on bones 24 Left and 22 Right. Perforation size is the parameter. Perforation diameters and perforation locations are noted within the figures. Perforations on bone 24 Left focused on the anterior-inferior quadrant while perforations on bone 22 Right focused on posterior-inferior quadrant. Symbols are plotted at every 25th data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal (Equation 2.4).
Figure 2-19: Magnitude of the means of changes in the normalized pressure difference across the tympanic membrane, $|\Delta H_{\Delta TM}|$ (Equation 2.4). Changes from all perforations are included from the final eight bones. Each curve, with size as a parameter, includes all perforations made on the eight bones that fit the diameter category. Individual frequency points where $|H_{\Delta TM}| < 0.1$ are not included in calculation of the mean. Symbols are plotted at every 20th data point, and error bars indicate the standard error at a subset of data points.
Above 1000 to 2000 Hz, the $H_{\Delta TM}$ measured on every bone exhibits the same systematic effects from perforations. Every perforated case for $|H_{\Delta TM}|$ has a minimum associated with a 0.5 cycle increase $\Delta H_{\Delta TM}$ between 2000 and 4000 Hz. In general, the effects from the perforation on $H_{\Delta TM}$ at frequencies above 2000 Hz appear to be more systematic and consistent across bones than the effects from the perforation on the middle-ear transfer function $V_S/P_{TM}$.

In Fig. 2-18 (and the figures of Appendix D, page 219), the perforation-induced changes in $|H_{\Delta TM}|$ defined by Equation 2.4 are also plotted. The characteristics of these changes are the same as those described above for $|H_{\Delta TM}|$. Fig. 2-19 shows the mean changes in $|H_{\Delta TM}|$ relative to normal from the final eight experiments. Perforations were grouped into five size categories shown as parameters in Fig. 2-19. The features listed above for the individual measurements are also seen in the mean measurements. In general, the minima and maxima seen above 1000 Hz are consistent across bones. Thus, these minima and maxima are apparent in the mean.

2.3.4 Stapes velocity per pressure difference across the tympanic membrane: $H_{TOC}$

The transfer function between stapes velocity and the pressure difference across the tympanic membrane, $H_{TOC} = V_S/\Delta P_{TM}$ (Equation 2.7), is computed from the measurements of stapes velocity per ear-canal pressure (chapter 2.3.2) and pressure difference across the tympanic membrane per pressure at the tympanic membrane (chapter 2.3.3).

For the two example bones of Fig. 2-20 the effect of perforations on $H_{TOC}$ is less than 10 dB in magnitude and less than 0.1 cycles in angle, at most frequencies. Changes in both the magnitude and angle of $H_{TOC}$ that result from a perforation appear frequency independent, small, and not clearly related to the perforation size. Additionally, $H_{TOC}$ with a normal tympanic membrane is almost identical to the middle-ear transfer function $V_S/P_{EC}$ with a normal tympanic membrane. This is a direct result of the large pressure difference across the normal tympanic membrane; that is the pressure difference across the tympanic membrane approximates the ear-canal pressure so that $\frac{V_S}{P_{EC}} \approx \frac{V_S}{\Delta P_{TM}}$ when the tympanic membrane is normal.

These two example bones of Fig. 2-20 do not represent the $H_{TOC}$ measured on all 11 bones. (See Appendix E, page 227, for $H_{TOC}$ measurements on all bones.) In eight of the eleven bones (bones 9, 13, 18, 19, 22 Left, 22 Right, 24 Left, and 24 Right), perforation-induced changes in $H_{TOC}$ are consistent with the description above: changes in $|H_{TOC}|$ tend to be frequency independent and less than 10 dB and changes in $\Delta H_{TOC}$ tend to be less than 0.1 cycles (at least up to 2000 to 3000 Hz). At higher frequencies, bone-dependent narrow bands of larger changes can occur.

In the remaining three bones (bones 8, 20, and 23), perforation-induced changes in
Figure 2-20: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bones 24 Left and 22 Right. Perforation size is the parameter. Perforation diameters $d$ and perforation locations are noted. Individual frequency points where either $|V_s/P_{BC}|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{BC}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. **TOP:** Magnitude and Angle of $H_{TOC}$. **BOTTOM:** Magnitude and angle of $\Delta H_{TOC}$. 
Figure 2-21: Mean of changes in the stapes velocity per pressure difference across the tympanic membrane, $\Delta H_{TOC}$ (Equation 2.8). Changes from all perforations are included from the final eight bones. Each curve, with perforation diameter as a parameter, includes all perforations made on the eight bones that fit the category. Individual frequency points where either $|V_s/P_{EC}|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{EC}|$ is less than 0.1 are not included in calculation of the mean. Symbols are plotted at every fifth data point, and error bars indicate the standard error at a subset of data points.
$|H_{TOC}|$ appear to be both frequency and perforation-diameter dependent (see Fig. E-1, Fig. E-3, and Fig. E-5). In these three bones, the largest changes in $|H_{TOC}|$ occur with the larger perforations, and the changes are largest at the lower frequencies. Furthermore, the low-frequency changes can exceed 20 dB with the larger perforations. In contrast to the changes in $|H_{TOC}|$, the changes in the angle $\angle H_{TOC}$ with perforations for these three bones are consistent with the description above for the other eight bones. In general, below 2000 to 3000 Hz, angle changes are less than 0.1 cycles. One exception occurs where bone 8 does show a consistent decrease in $\angle H_{TOC}$ of about 0.2 cycles around 1000 Hz.

We offer a possible explanation for the differences in $|H_{TOC}|$ between our group of eight bones and our group of three bones. $H_{TOC}$ is computed from the two measured quantities $V_s/P_{EC}$ and $H_{ATM}$ (chapter 2.3.3). Thus, errors in either of these measurements will result in errors in the calculation of $H_{TOC}$. We have discussed our difficulty in calculating small pressure differences across the tympanic membrane (chapter 2.2.4.2), where errors in the pressure difference lead to errors in $H_{ATM}$. Comparison of the $H_{ATM}$ data from the three bones (bones 8, 20, and 23) to the $H_{ATM}$ data from the other eight bones (Appendix D, page 227) reveals a subtle low-frequency difference. In particular, our measurements of $|H_{ATM}|$ on the subset of three bones are suggestive of pressure-difference calculation errors at the lowest frequencies because these measurements do not increase with a constant slope of 40 dB/decade; instead, many of these low-frequency $|H_{ATM}|$ measurements exhibit a more gradual change with frequency and are thus larger than the $|H_{ATM}|$ measurements that grow at 40 dB/decade. If our measurements of $H_{ATM}$ contain low-frequency errors that under-estimate the true $|H_{ATM}|$, our calculation of $|H_{TOC}| \propto \frac{1}{|H_{ATM}|}$ will be artifically decreased, and the computed change from normal will be increased. Thus, it is possible that the larger low-frequency changes observed in $|H_{TOC}|$ on the subset of three bones result artifically from measurement errors in $|H_{ATM}|$.

In Fig. 2-21 the mean changes in $H_{TOC}$ from our final eight experiments with the finest frequency resolution are plotted. Here, changes in $|H_{TOC}|$ are less than 5 dB for perforation diameters less than 3mm, and less than 10 dB for all perforations. Below 2000 Hz, changes in $\angle H_{TOC}$ rarely exceed $\pm 0.05$ cycles. In general, for perforations less than 3 mm in diameter, these means and the individual data described above show that perforation-induced changes in $H_{TOC}$ are small in both magnitude (less than 10 dB) and angle (less than 0.1 cycles), the changes are frequency independent, and the effect of perforation diameter on the changes is small (less than 5 dB in magnitude).

### 2.3.5 Impedance at the tympanic membrane: $Z_{TM}$

In Fig. 2-22, measurements of the acoustic impedance at the tympanic membrane (Equation 2.11) are plotted for our two example bones with normal ($Z_{TM}^{norm}$), perforated ($Z_{TM}^{perf}$), and removed tympanic membranes ($Z_{CAV}$). The impedance with the tympanic-membrane removed is the impedance of the middle-ear cavity, $Z_{CAV}$. Measurements made on all bones
are plotted in Appendix F (page 235).

Below 500 to 1000 Hz, $Z_{TM}$ appears compliant for all three conditions: tympanic-membrane normal, perforated, and removed. The low-frequency slope of the magnitude $|Z_{TM}|$ approximates -20 dB/decade, and the low-frequency angle of $\angle Z_{TM}$ is nearly $-0.25$ cycles. As frequency increases, the impedances both with and without perforations become less compliance-like. There is a slight magnitude maximum in $|Z_{TM}^{\text{norm}}|$ around 3000 Hz, and this maximum becomes more pronounced in $|Z_{TM}^{\text{perf}}|$ as the perforation size increases.

Next, we consider the perforation's effect on the impedance magnitude. At the lower frequencies, a perforation reduces the low-frequency $|Z_{TM}^{\text{norm}}|$ by a constant, frequency-independent factor of 10 to 20 dB. This reduction is independent of perforation size. Above about 500 Hz, $|Z_{TM}^{\text{perf}}|$ shows perforation-size dependent variations. First, $|Z_{TM}^{\text{perf}}|$ has a well defined local minimum that typically occurs between 500 Hz and 3000 Hz. As the perforation size increases, the frequency of the minimum increases; the magnitude $|Z_{TM}^{\text{perf}}|$ at the minimum frequency decreases; and the sharpness of the minimum (Q) increases. However, for the largest perforations, there is no apparent change in the frequency of the $|Z_{TM}^{\text{perf}}|$ minimum; as we will see in chapter 4, for these largest perforations, the cavity impedance dominates the total impedance at the tympanic membrane for the entire frequency range of 100 to 4000 Hz. Second, $|Z_{TM}^{\text{perf}}|$ has a well defined local maximum around 3000 Hz; the frequency of this maximum is not affected by the perforation size, but the sharpness (Q) of the maximum increases with increasing perforation size.

A perforation also affects the angle of the impedance at the tympanic membrane, $\angle Z_{TM}$. At low frequencies, the compliant-like angle approximates -0.25 cycles for both the normal and the perforated conditions. As frequency increases, the angle increases from -0.25 cycles to a positive value between 0 and 0.25 cycles. With perforations, the increase in angle occurs across the same frequency range as the first local minimum in magnitude, described above. Thus, as perforation size increases, the transition frequency from compliant-like to resistive and mass-like increases. Around 3000 Hz, corresponding to the local magnitude maximum described above, $\angle Z_{TM}^{\text{perf}}$ decreases; the decrease in angle becomes steeper as perforation size increases.

The measurements of $Z_{CAV}$ are included in Fig. 2-22. Comparison of the measurements of $Z_{TM}^{\text{perf}}$ to $Z_{CAV}$ indicate that (1) at the lowest frequencies $Z_{TM}^{\text{perf}} \approx Z_{CAV}$ for all perforation sizes, and (2) at higher frequencies, as the perforation size increases, $Z_{TM}^{\text{perf}} \approx Z_{CAV}$.

### 2.3.6 Effects of tympanic-membrane slits adjacent to the malleus

The results presented in chapter 2.3.2 to chapter 2.3.4 indicate that the effects of perforations are largely a consequence of changes in the pressure difference across the tympanic membrane, $H_{\Delta TM}$, and that perforations produce smaller changes in the mechanical coupling from the tympanic membrane to the cochlea, $H_{TOC}$. The specific effects of perforations on these two transfer functions, $H_{\Delta TM}$ and $H_{TOC}$, are plotted in Figures 2-19
Figure 2-22: Impedances at the tympanic membrane measured on bones 24 Left and 22 Right for the normal tympanic membrane ($Z_{TM}^{norm}$), perforated tympanic membrane ($Z_{TM}^{perf}$), and tympanic membrane removed ($Z_{CAV}$, plotted in red) conditions. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.
and 2-21 respectively.

The lack of effect that perforations have on $H_{TOC}$ seems to indicate that changes in the coupling between the tympanic membrane and the malleus, including the possible effects of tension in the tympanic membrane, the configuration of tympanic-membrane fibers with a perforation (Introduction, p. 15), and the tympanic-membrane area\(^3\), play a relatively small role in coupling the sound pressure at the tympanic membrane to the stapes. To test for dependence of tympanic membrane to mallear coupling on tympanic-membrane integrity, a perforation was designed to disconnect the tympanic membrane from the manubrium (handle) of the malleus mechanically, while changing the acoustics minimally. In other words, this perforation type might be expected to produce only small changes in the pressure difference across the tympanic membrane $H_{\Delta TM}$ while dramatically changing the coupling $H_{TOC}$.

This perforation involved slits in the tympanic membrane along the manubrium. In one experiment (bone 27), we slit the tympanic membrane with a myringotomy knife along the manubrium of the malleus, in stages as schematized in Fig. 2-23. Each slit completely severed the tympanic membrane, as it was possible to view the middle-ear cavity through the slit. However, for the smaller slits, after the knife was withdrawn, the slits appeared to close through surface tension that resulted from the moisture present on the tympanic membrane.

Fig. 2-24 shows sound-transmission measurements made with the conditions shown in Fig. 2-23. First, consider the single 2 mm slit along the posterior part of the manubrium, labeled 1 in Fig. 2-23. The left column of Fig. 2-24 indicates that there was no change in $V_S/P_{EC}$ from normal with this first slit. This slit certainly cut across numerous tympanic-membrane fibers, but after the slit was made the margins of the slit were observed under a microscope to be held together by moisture; essentially the slit patched itself. Fig. 2-24 (Column 2) shows that the pressure difference across the tympanic membrane, $H_{\Delta TM}$, was also not affected by this slit 1. The responses with slit 2 added were similar to those with slit 1 only: the middle-ear transfer function $V_S/P_{EC}$ and the pressure difference across the tympanic membrane $H_{\Delta TM}$ changed only a small amount from normal, and the second slit was held together by the moisture on the tympanic membrane. These results from the shorter two slits are consistent with the results from our circular perforations. Specifically, when the pressure difference across the tympanic membrane was not altered by the slits, the middle-ear transfer function did not change from normal. In other words, slits had little or no effect on either $H_{\Delta TM}$ or $H_{TOC}$.

Larger changes in $V_S/P_{EC}$ and $H_{\Delta TM}$ occurred with the addition of slits 3 and 4, in which the slits were longer and moisture did not close the entire length of the slit. With the

\(^3\)The tympanic membrane area would become important with a large enough perforation (i.e., a perforation that approaches 100% of the tympanic membrane). However, even if 50% of the tympanic membrane was perforated, the middle-ear pressure gain that results from the tympanic membrane to stapes area ratio would only decrease by 6 dB.
Figure 2-23: Schematic of connected slits made in the tympanic membrane (bone 27). Slit 1, indicated by a solid line, was made first along the posterior edge of the manubrium of the malleus. Slit 1 was about 2 mm. Next slit 2, also about 2 mm long and indicated by a solid line, was made along the anterior border of the manubrium. Next, slit 3, indicated by a dashed line, was made to connect slits 1 and 2. Finally, slit 4, with two components, was made so that the combined slit encompassed the perimeter of the manubrium and extended approximately to the pars flaccida.

Addition of the third slit, below 1000 Hz, the loss in $|V_S/P_{EC}|$ is relatively flat at about 10 dB, and for slit 4 the loss is between 10 and 25 dB and has some variation with frequency. Examination of the second and third columns of Fig. 2-24 show that for the longer third and fourth slits, there are changes in both the pressure difference across the tympanic membrane, $H_{\Delta TM}$, and also the stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$. For the longer slit 4, $|H_{TOC}|$ shows changes of up to 10 dB for frequencies from 400 to 2000 Hz. Even though we see changes in $H_{TOC}$ that are larger than with our circular perforations, the slit 4 changes of only 10 dB are relatively small when one considers that almost the entire manubrium is detached from the tympanic membrane. Thus, these slit experiments support the notion that perforations do not have large effects on $H_{TOC}$. We note that more measurements where the effects of $H_{TOC}$ are maximized and the effects of $H_{\Delta TM}$ are minimized could be helpful to examine this issue further.
Magnitude of change from normal:

H_{11M} = \frac{\Delta H_{11P}}{H_{11P}}$

COLUMN 3: Measurements of $H_{11C}$, $V_5/V_{11P}$

For all three columns, TOP: Measurements. MIDDLE: Angle. BOTTOM: Measurements made with the 4 ships in a line. COLUMN 1: Measurements of $V_{11P}$. COLUMN 2: Measurements of $V_{5}/V_{11P}$.

FIGURE 2-4: Measurements made with the 4 ships in a line.
2.4 Discussion

2.4.1 Comparison to other work

2.4.1.1 Frequency dependence of transmission loss with tympanic-membrane perforations

Our measurements of transmission loss with tympanic-membrane perforations (chapter 2.3.2) show a clear frequency dependence; Fig. 2-12 shows that for a given perforation size, the losses are greatest at the lowest frequency and decrease toward zero as frequency increases toward 1000 to 2000 Hz. There can be increases (0 to 20 dB) in transmission in the 1000 to 2000 Hz region. Above 2000 Hz, the losses are smaller than the low-frequency losses (< 10 dB).

Our result is consistent with the cat cochlear-potential measurements of McArdle and Tonndorf (1968) and Kruger and Tonndorf (1977,1978) (see Fig.2-25) and the umbo-velocity measurements of Bigelow et al. (1996)⁴, in rat, in all of which the perforation-induced loss was most prominent at the lowest frequencies and the loss decreased with increasing frequency. Our result is also consistent with the temporal-bone measurements of Nishihara et al. (1993) and the clinical measurements of both Tavin et al. (1988) and Rosowski et al. (1996) in which tympanostomy tubes in the tympanic membrane produced their largest losses at the lowest frequencies.

Our results disagree with the audiologic data of Austin (1978) (see Fig.2-25), in which the effect of a perforation on frequency-dependence is described as: “the presence of a perforation does not significantly affect the frequency response of the middle ear, since a flat hearing loss was observed for the three frequencies studied as well as for each size of perforation” (Austin, 1978; p. 372). Indeed, the means of audiograms at 500, 1000, and 2000 Hz that Austin (1978) presents do not show a clear frequency dependence. However, our measurements with perforation sizes similar to the perforations that correspond to Austin’s perforations show a clear frequency dependence (Fig. 2-25, Right). It seems possible that the clinical population of 13 ears that forms Austin’s mean audiogram may have suffered from other ear pathologies in addition to perforated tympanic membranes.

2.4.1.2 Effect of perforation size on transmission loss

Many studies of tympanic-membrane perforations, both animal and clinical studies, show that loss with tympanic-membrane perforations increases as perforation size increases (Anthony and Harrison 1972; Austin 1978; Bigelow et al. 1996). Our measurements of transmission loss with tympanic-membrane perforations (Fig. 2-12) show a clear dependence on

⁴We cannot compare our loss measurements to those of Bigelow et al. (1996). The low-frequency loss reported by Bigelow et al. (1996) is masked by their noise floor. Essentially, they show that a perforation results in their lowest frequency umbo-velocity measurements jumping from a measurable response to the noise floor, and as the perforation size increases, the frequency range where the the measurements are within the noise increases.
Figure 2-25: Comparison of our mean loss in the middle-ear transfer function $V_L/P_L$ to measurements of loss from Kruger and Tonndorf (1977) and Austin (1978). LEFT: Comparison of results of Kruger and Tonndorf (1977) to our mean loss with tympanic-membrane perforations of diameter $d$ such that $1 < d \leq 2$ mm (taken from Fig. 2-12). The perforation diameter of the Kruger and Tonndorf (1977) measurements was $d = 1.6$ mm, and their loss measurements were from cat cochlear potential data. RIGHT: Comparison of audioligic data from Austin (1978) with perforations that averaged about 3.4 mm in diameter. Here, we plot our mean loss with perforation diameter $d$ such that $3 < d \leq 4$ mm.

 perforation size. First, for frequencies below 1000 to 2000 Hz, the loss increases monotonically as perforation size increases, and as perforation size increases the slope of the loss approaches 40 dB per decade. Second, between 1000 and 2000 Hz, the loss is near zero or a slight increase in transmission may be present, and the frequency of this increased transmission increases with perforation size. Third, above 2000 Hz, the larger perforation sizes appear to show larger differences from 0 loss; both the gains and the losses increase with perforation size and can approach 10 dB.

2.4.1.3 Effect of perforation location on transmission loss

Our measurements show no apparent effects of perforation location on transmission loss. In patching experiments, we compare small perforations at different locations in the same temporal-bone preparation (Figures 2-13, 2-14, and 2-15), and show that for small perforations (up to 1 mm in diameter), there are no differences between central and marginal perforations or between anterior-inferior and posterior-inferior perforations. We also don’t observe any systematic differences in the losses associated with anterior-inferior and posterior-inferior perforations with larger perforations up to 1 quadrant in size (Fig. 2-17).

A systematic clinical study of how perforation location affects hearing loss has not been done. Such a study is difficult for numerous reasons, including: (1) additional affects of middle-ear disease other than a tympanic-membrane perforation and (2) difficulty in mea-
measurement of the perforation size. Austin (1978) analyzed the audiograms from 37 patients with perforated tympanic membranes. He found "the location of perforation ... [has] ...no effect on either hearing or on frequency response" (Austin 1978, p. 374). However, the details of Austin's analysis are not provided (e.g., number and sizes of perforations at different locations). Anthony and Harrison's (1972) analysis of audiograms from ears with tympanic-membrane perforations found "greater loss in the low frequencies in the posterior inferior quadrant when compared to the anterior inferior quadrant" (Anthony and Harrison 1972, p. 510). However, this conclusion is questionable as the analysis did not consider the perforation size.

Our results are inconsistent with the widely-held clinical view that a posterior-inferior perforation results in larger hearing loss than an anterior-inferior perforation (e.g., Schuknecht 1993, p.196; Glasscock and Shambaugh 1990, p.314; Pickles 1987, pp.60-61). The classic explanation for the location dependence is that a perforation over the round window affects the pressures acting on the oval and round windows differently than a perforation at other locations, and as a result, the pressure acting at the round window with posterior-inferior perforations "cancels" the motion of the round window more than the round-window pressure associated with perforations at other locations. In chapter 3, we use measurements of the oval and round window pressures with perforations at different locations to show that the perforation location has no effect on the pressure difference between the oval-window and round-window pressures. Thus, we show that the classic explanation of perforation-location effects is not supported by our results.

There may be physiologic mechanisms that affect how the perforation location influences hearing clinically. For example, perhaps posterior-inferior perforations tend to be larger than perforations at other locations. Or perhaps the ossicles tend to be damaged by middle-ear disease associated with posterior-inferior perforations more often than with perforations at other locations; such a possibility seems feasible since much of the ossicular chain is just medial to the posterior half of the tympanic membrane. Thus, while our temporal-bone measurements show no dependence on perforation location, it is possible that a location dependence results clinically from physiologic factors (e.g., related to middle-ear disease) that do no occur in our temporal-bone experiments.

2.4.2 A middle-ear model with a tympanic-membrane perforation

2.4.2.1 Description of the model

The model of the middle ear\(^5\) shown in Fig.2-26 is of the same configuration as the models of Zwislocki (1962) and Kringlebotn (1988) in that the middle-ear cavity impedance \(\hat{Z}_{CAV}\) is in

\(^5\)All model elements, volume velocities, and pressures will be indicated with a hat \(^\hat{\cdot}\) to distinguish them from measured values.
series with elements that represent the impedance of the tympanic membrane, ossicles, and cochlea. The model includes representation of a perforation of the tympanic membrane by a volume velocity path \( \hat{Z}_{PERF} \) from the ear canal to the middle-ear cavity. \( |\hat{Z}_{PERF}| \) is infinite under normal conditions (i.e., no perforation). The model also contains representations for the measurements presented here in chapter 2. In this model, an ear-canal air space accounts for the spatial variation between the measurement of the ear-canal pressure \( (P_{EC}) \) and the actual pressure at the tympanic membrane \( (P_{TM}) \) (chapter 2.2.3.2). The pressure difference across the tympanic membrane can be calculated as

\[
\hat{H}_{\Delta TM} \equiv \frac{\hat{P}_{TM} - \hat{P}_{CAV}}{\hat{P}_{TM}} \equiv \frac{\Delta \hat{P}_{TM}}{\hat{P}_{TM}}.
\]  

(2.12)

Additionally, the two-port network represents coupling through the tympanic membrane and ossicles to the cochlea. The model equivalent of the measured \( H_{TOC} \) is \( \hat{H}_{TOC} \) which is the transfer admittance of the two-port network terminated by \( \hat{Z}_{SC} \), the stapes and cochlear impedance:

\[
\hat{H}_{TOC} \equiv \frac{\hat{V}_S}{\hat{P}_{TM} - \hat{P}_{CAV}} \equiv \frac{\hat{V}_S}{\Delta \hat{P}_{TM}},
\]  

(2.13)

where \( \hat{V}_S \) is the model stapes velocity and \( \hat{\alpha} \) is a constant that relates the model stapes velocity to the model stapes volume velocity. Note, the transfer characteristics of this two-port network are perforation dependent.

![Figure 2-26: Model of the human middle ear with a tympanic membrane perforation. The box labeled “ear-canal air space” is a two-port that transforms the ear-canal pressure measured a few mm from the tympanic membrane to the pressure at the tympanic membrane. The two port labeled “TM, Malleus, Incus” represents tympanic-membrane-ossicular coupling from the ear canal to the stapes and coxhe. \( \hat{Z}_{SC} \) is the impedance of the coxhe and the stapes; \( \hat{Z}_{CAV} \) is the impedance of the middle-ear cavity; \( \hat{V}_S \) is the model stapes velocity; \( \hat{\alpha} \) is a constant that relates the model stapes velocity to the model stapes volume velocity; \( \hat{U}_{TM} \) is the volume velocity on the ear-canal side of the tympanic membrane, and \( \hat{Z}_{PERF} \) is the impedance of a tympanic-membrane perforation. In cases where the tympanic membrane is normal, \( \hat{Z}_{PERF} \) is infinite. Acoustic coupling is not included in this model.

As discussed in the thesis introduction and in chapter 2.1, tympanic-membrane per-
forations might affect middle-ear sound transmission through the combination of at least three mechanisms. In terms of the model of Fig. 2-26, two of these mechanisms are represented: (1) a perforation induced change in $\hat{H}_{\Delta TM}$, the pressure difference across the tympanic membrane, that results from changes in the magnitude of the parallel combination $\hat{Z}_{PERF} \parallel \hat{Z}_{TOC}$, where $\hat{Z}_{TOC}$ is the input impedance to the two-port network terminated by $Z_{SC}$; and (2) a perforation induced change in $\hat{H}_{TOC}$, the tympanic membrane-ossicular coupling, that occurs when the characteristics of the tympanic membrane-malleus-incus two-port network changes. The third mechanism which may change sound transmission with perforations, the acoustic coupling of sound via direct acoustic stimulation of the oval and round windows, is not included in the model of Fig. 2-26. Instead, the model focuses on the ossicular coupling mechanisms. In chapter 3, we show that under most conditions with tympanic-membrane perforations, the sound transmission via acoustic coupling is negligible compared to the sound transmission via ossicular coupling. Thus, we simplify our model by eliminating the acoustic coupling aspect of sound transmission. For an example of how acoustic coupling might be included in the model, see Peake et al. (1992).

2.4.2.2 Description of our measurements in terms of the model

To summarize our data in terms of the model, we note that our middle-ear transfer function ($V_S/P_{TM}$) can be represented as the product of the transfer functions that represent the two mechanisms (1) and (2) discussed in the proceeding paragraph. For both the model and the data,

$$\frac{V_S}{P_{TM}} = \frac{\Delta P_{TM}}{P_{TM}} \frac{V_S}{\Delta P_{TM}} = H_{\Delta TM} H_{TOC}.$$  \hspace{1cm} (2.14)

Changes in $H_{\Delta TM}$ between the normal and perforated conditions represent changes in sound transmission due to the change in pressure difference across the tympanic membrane. Changes in $H_{TOC}$ between the normal and perforated conditions represent changes in sound transmission due to changes in the coupling between the tympanic membrane, malleus, and stapes (i.e., changes in the transfer admittance of the two-port network in Fig. 2-26). If the perforation does not change the tympanic membrane, malleus, and incus coupling, the transfer function $H_{TOC}$ should be unchanged, i.e., all changes in the middle-ear transfer function (transmission loss) is explainable by decreased pressure difference across the tympanic membrane, or $H_{\Delta TM}$.

All four of our measurement types presented in chapter 2.3 can be interpreted in terms of the model of Fig. 2-26. First, perforations-induced changes in the model stapes velocity, $\hat{V}_S$, should reflect the perforation-induced changes we measured in stapes velocity: the model should predict that perforations cause the perforation-size dependent, low-frequency reduction in the model $\hat{V}_S$ that we see in the data $V_S$. Further analysis of the model gives insight into the mechanisms of sound transmission with tympanic-membrane perforations.

Consider $H_{\Delta TM}$, the pressure difference across the tympanic membrane per pressure at the tympanic membrane (chapter 2.3.3). The model $\Delta \hat{P}_{TM}$ is the pressure difference across
the perforation and also the pressure difference across the input to the tympanic membrane-malleus-incus two port. This pressure difference results from the pressure divider between the cavity impedance \( \hat{Z}_{\text{CAV}} \) and the parallel combination \( \hat{Z}_{\text{PERF}} \parallel \hat{Z}_{\text{TOC}} \), where \( \hat{Z}_{\text{TOC}} \) is the input impedance of the two-port network terminated by \( Z_{\text{SC}} \). Since \( \hat{Z}_{\text{CAV}} \) is not affected by tympanic-membrane perforations, the effects of tympanic-membrane perforations on the model \( H_{\Delta TM} \) are controlled by changes in the parallel combination \( \hat{Z}_{\text{PERF}} \parallel \hat{Z}_{\text{TOC}} \). Thus, if our model is valid, we expect the perforation induced changes in \( \hat{Z}_{\text{PERF}} \parallel \hat{Z}_{\text{TOC}} \) to account for the frequency and perforation-size dependent changes that we measured in the data \( H_{\Delta TM} \) (Fig. 2-19).

We also consider the stapes velocity per pressure difference across the tympanic membrane, \( H_{\text{TOC}} \). The model \( H_{\text{TOC}} \) is the transfer admittance of the two-port network of Fig. 2-26 and is analogous to the measurements shown in chapter 2.3.4. Perforation-induced changes in the measurements of \( H_{\text{TOC}} \) is a measure of how much the tympanic membrane-malleus-incus two port network of Fig. 2-26 changes with tympanic-membrane perforations. For example, if the tympanic membrane-malleus-incus two port does not change with tympanic-membrane perforations, then the measurements of \( H_{\text{TOC}} \) should be unaffected by tympanic-membrane perforations. Thus, we expect the perforation induced changes in the tympanic membrane-malleus-incus two port network to be comparable to the changes that we measured in stapes velocity per pressure difference across the tympanic membrane (Fig. 2-21).

Finally, our measurements of input impedance (chapter 2.2.6) at the tympanic membrane show that tympanic-membrane perforations reduce the impedance at the lower frequencies and have smaller effects on the impedance at higher frequencies. Again, since \( Z_{\text{CAV}} \) is unaffected by perforations, we expect the changes in our model input impedance \( \hat{Z}_{\text{TM}} \) with perforations to result from changes in the parallel combination \( \hat{Z}_{\text{PERF}} \parallel \hat{Z}_{\text{TOC}} \). Furthermore, since the low-frequency impedance measurements with tympanic-membrane perforations, \( Z_{\text{TM}}^{\text{per}} \), approximate the measurements of \( Z_{\text{CAV}} \), it appears that \( |\hat{Z}_{\text{PERF}}| \) must be much smaller than either \( |\hat{Z}_{\text{TOC}}| \) or \( |\hat{Z}_{\text{CAV}}| \).

In chapter 4 we develop a model of the tympanic-membrane perforation \( \hat{Z}_{\text{PERF}} \). We combine the model of the perforation with the model topology of Fig. 2-26 in order to describe the data presented here in chapter 2.3. We use the impedance measurements presented in chapter 2.3.5 in order to place specific constraints on the model with the perforation. With some simplifying assumptions to our perforation model, we present a simple algebraic equation (Equation 4.33) that predicts sound-transmission loss with tympanic-membrane perforations, with the parameters perforation diameter, frequency, and middle-ear cavity volume.
2.4.2.3 Consistency of model with measurements

We can use our measurements to check the general topology of the model shown in Fig. 2-26. For example, the model topology predicts that the impedance at the tympanic membrane $Z_{TM}$ has zeros at frequencies that correspond to the poles of $H_{\Delta TM}$. Specifically, for the model topology,

$$\hat{Z}_{TM} = (\hat{Z}_{PERF} \parallel \hat{Z}_{TOC}) + \hat{Z}_{CAV}$$  \hspace{1cm} (2.15)

and

$$\hat{H}_{\Delta TM} = \frac{\hat{Z}_{PERF} \parallel \hat{Z}_{TOC}}{(\hat{Z}_{PERF} \parallel \hat{Z}_{TOC}) + \hat{Z}_{CAV}} = \frac{\hat{Z}_{PERF} \parallel \hat{Z}_{TOC}}{\hat{Z}_{TM}}$$ \hspace{1cm} (2.16)

where $\hat{Z}_{TOC}$ is the input impedance of the two-port network terminated by $\hat{Z}_{SC}$. Thus, Equations 2.15 and 2.16 suggest that the minima in $|Z_{TM}|$ (along the real axis) will occur near the maxima in $|H_{\Delta TM}|$ (along the real axis).

Fig. 2-27 shows that our data taken with tympanic-membrane perforations fit this prediction as the measured maxima of $|H_{\Delta TM}|$ are at nearly the same frequencies as the measured minima of $|Z_{TM}|$. Specifically, for each bone we show a scatter plot of the frequency of the first maximum in $|H_{\Delta TM}|$ versus the frequency of the first minimum in $|Z_{TM}|$. The figure shows that for the 10 bones on which we measured both $H_{\Delta TM}$ and $Z_{TM}$, the model topology is consistent with the measurements.
Figure 2-27: Comparison between the frequencies for the first maximum in $|H_{\Delta TM}|$ and the first minimum in $|Z_{TM}|$. For each bone, a point is plotted for each perforation that was made and for the condition of tympanic membrane removed.
Chapter 3

Measurements of sound pressures at the cochlear windows with normal and perforated tympanic membranes

3.1 Introduction

Sound can be transmitted though the middle ear to the cochlea via two routes: the “ossicular route” and the “acoustic route” (Békésy 1947; Schmitt 1958; Peake et al. 1992; Merchant et al. 1997a) (see page 13 and Fig. I-2 of the Introduction). Briefly, the ossicular route is driven by the pressure difference across the tympanic membrane, and it refers to sound transmission to the cochlea through motion of the tympanic membrane, malleus, incus, and stapes. In addition, ear-canal sound pressure also generates a sound-pressure field in the middle-ear cavity. The sound pressures at the oval and round windows are nearly equal, but the approximately 4 mm separation between the two windows allows for a small pressure difference between them. The cochlea responds to this difference in sound pressures at the oval and round windows (Voss 1995; Voss et al. 1996), and we use the term acoustic route to refer to this mechanism. When the ear is normal, the “acoustically coupled” stimulus is negligible compared to the “ossicularly coupled” stimulus, but the acoustic route can become important when sound transmission through the ossicular system is decreased (Békésy 1947; Schmitt 1958; Peake et al. 1992; Merchant et al. 1997a).

The effect of tympanic-membrane perforations on the acoustic route has been discussed in the literature, but no direct measurements have been made. In 1947, Békésy measured the pressure difference between the oval and round windows in one temporal-bone preparation,
and later, Peake et al. (1992) used these window pressure-difference measurements with their middle-ear model to predict the hearing loss with a total perforation (i.e., tympanic-membrane removed). Peake et al. (1992) conclude that even with a total perforation, which eliminates the ossicular route, sound transmission via the acoustic route may allow for hearing levels of 40 to 60 dB, from 250 to 3000 Hz.

A second connection of the acoustic route to sound transmission with perforations is the common view that perforations alter the magnitude and phase angle of the sound pressures at the oval and round windows, and in particular the magnitude and phase are affected differently for different perforation locations. Schmitt (1958) introduced the theoretical idea that both the magnitude and phase-angle of the sound pressures at the two windows could be important. Subsequently, with no direct measurements to support Schmitt’s theoretical treatment, a common view developed that a perforation over the round window affects the pressures acting on the oval and round windows differently than perforations at other locations (e.g., Schuknecht, 1993, p.196; Glasscock and Shambaugh, 1990, p. 314; Pickles, 1987, pp. 60-61). Specifically, the explanation purports that the sound-pressure phase angle at the round window that results from posterior-inferior perforations “cancels” the motion of the round window more than the round-window sound pressures associated with perforations at other locations.

In this chapter, we use sound-pressure measurements at the oval and round windows on our temporal-bone preparation in order to describe sound transmission via the acoustic route with perforations. The total acoustic-route stimulus, $\Delta P_{\text{win}}/P_{TM}$, is the pressure difference between the oval and round windows normalized by the pressure at the tympanic membrane.

$$\frac{\Delta P_{\text{win}}}{P_{TM}} \equiv \frac{P_{\text{OW}} - P_{RW}}{P_{TM}}$$

(3.1)

In order to interpret how perforations affect $\Delta P_{\text{win}}/P_{TM}$, we break $\Delta P_{\text{win}}/P_{TM}$ into two factors: the middle-ear-cavity-pressure transfer function $H_{PCAV}$ and the window-pressure-difference transfer function $H_{WPD}$, where

$$\frac{\Delta P_{\text{win}}}{P_{TM}} = \frac{P_{\text{OW}} - P_{RW}}{P_{TM}} = \frac{P_{\text{CAV}}}{P_{TM}} \cdot \frac{P_{\text{CAV}}}{P_{CAV}}$$

(3.2)

Thus, the acoustic-route sound transmission depends on the product $H_{PCAV}$ and $H_{WPD}$. $H_{PCAV}$ is a measure of the acoustic processes that lead to a sound pressure in the middle-ear cavity caused by the pressures in the ear canal, and $H_{WPD}$ is a measure of the acoustic processes that set the relationship between $P_{OW}$ and $P_{RW}$. We note that, theoretically, both $H_{PCAV}$ and $H_{WPD}$ could depend on both perforation location and size.

In this chapter, we present measurements of the sound pressures at the oval and round
windows made on human temporal bones with normal and perforated tympanic membranes. In particular, we measure the oval-window, round-window, and ear-canal sound pressures, and we use these measurements to compute $H_{PCAV}$, $H_{WPD}$, and $\frac{\Delta P_{\text{in}}}{P_{TM}}$, described above. From these calculations, we determine how the perforation size and location affect sound transmission via the acoustic route. We use these measurements to predict the stapes velocity that results from sound transmission via the acoustic route. This acoustically coupled portion of the stimulus is then compared to the measured stapes velocity (from chapter 2) in order to place a bound on sound-transmission loss with tympanic-membrane perforations.

3.2 Methods

3.2.1 Calculation of the acoustic-route transfer functions and the window-pressure difference

We use our measurements of the oval- and round-window pressures, $P_{OW}$ and $P_{RW}$, and the ear-canal pressure $P_{EC}$ transformed to pressure at the tympanic membrane $P_{TM}$ via Equation 2.1, to calculate the components of the acoustic route. The middle-ear-cavity-pressure transfer function, $H_{PCAV}$, is calculated from our pressure measurements as

$$H_{PCAV} = \frac{P_{CAV}}{P_{TM}} = \frac{P_{OW}}{P_{TM}},$$

(3.3)

where we assume that the cavity pressure $P_{CAV}$ is uniform throughout the cavity and can be approximated by the pressure measured near the oval window, $P_{OW}$. Since this transfer function is used to describe the middle-ear cavity pressure field as a whole, and not a small difference in pressure between two locations, the assumption $P_{CAV} \approx P_{OW}$ is reasonable for frequencies for which the dimensions of the middle-ear cavity are much smaller than the wavelength of sound; thus the assumption seems reasonable up to about 2000 to 4000 Hz, where the largest cavity dimensions are about 0.1 the wavelength of sound.

The window-pressure-difference transfer function $H_{WPD}$ is also computed from our measurements of sound pressure:

$$H_{WPD} = \frac{(P_{OW} - P_{RW})/P_{TM}}{P_{OW}/P_{TM}} = 1 - \frac{P_{RW}/P_{TM}}{P_{OW}/P_{TM}} = 1 - \frac{P_{RW}}{P_{OW}}.$$  

(3.4)

We note that $H_{WPD}$ depends on the ratio of sound pressures between the two windows:

---

1The pressure at the tympanic membrane $P_{TM}$ is computed from the pressure measured in the ear canal 3 mm from the tympanic membrane as described in chapter 2.2.3.2.
Finally, we compute the difference in pressure between the oval and round windows per pressure at the tympanic membrane, which results from the product of the factors $H_{PCAV}$ and $H_{WP}$ and is the stimulus to the cochlea that results from the acoustic route of sound transmission.

\[
\frac{\Delta P_{\text{win}}}{P_{TM}} = \frac{P_{OW}}{P_{TM}} \left(1 - \frac{P_{RW}}{P_{OW}}\right) \tag{3.5}
\]

We note that the use of the approximation $P_{CAV} \approx P_{OW}$ is entirely arbitrary, and we could have alternatively used $P_{CAV} \approx P_{RW}$ without affecting our results. To demonstrate, example measurements of $\frac{P_{OW}}{P_{TM}}$ and $\frac{P_{RW}}{P_{TM}}$ are shown in Fig. 3-1 for both the normal and the tympanic-membrane-removed cases. For both tympanic-membrane conditions, $\frac{P_{OW}}{P_{TM}}$ and $\frac{P_{RW}}{P_{TM}}$ have nearly indistinguishable magnitudes and angles.

### 3.2.2 Measurement of the oval and round-window pressures

Pressures at the oval and round windows were measured on eleven of the bones described in chapters 1 and 2 (bones 8, 9, 13, 18, 19, 20, 22 Right, 22 Left, 23, 24 Right, 24 Left). Most of the measurement techniques were described in chapters 1.2 and 2.2. The additional details for measurement of the two pressures outside the oval and round windows are described here, along with our estimates of errors in these measurements.

#### 3.2.2.1 Placement of the oval- and round-window probe-tube microphones in the temporal-bone preparation

Probe-tube microphones were secured at the oval and round windows in order to measure the sound pressures outside each window. In both cases, the probe-tube microphone consisted of a Knowles hearing aid microphone coupled to one end of a 33 mm long steel tube of id = 0.8 mm and od = 1.1 mm; the other end of the probe tube was open and was positioned near the appropriate cochlear window. Attachment of each probe microphone to the temporal bone occurred as follows. First, a guide tube (id = 1.2 mm), through which the probe tube could slide, was carefully positioned and glued to the temporal bone. The guide tube provided a straight and repeatable path for the probe tube to reach its respective window. Next, under the view of a dissecting microscope, the open end of the probe tube was inserted through the guide tube until it was as close as possible to its respective cochlear window (0.5 to 2 mm). Finally, with the position of the probe tube set within the guide tube, a rubber stopper was positioned between the probe tube and the guide at the non-window side so that the probe tube was held at a constant location. This arrangement made it simple to remove the probe-tube microphone assemblies in order to calibrate them repeatedly throughout an experiment. Generally, the oval-window probe tube rested at the posterior-most edge of the footplate, and the round-window probe tube rested adjacent and lateral to the round.
Figure 3-1: Transfer functions between the oval- and round-window pressures to the pressure at the tympanic membrane, with the tympanic membrane normal and perforated. TOP: Magnitude. BOTTOM: Angle.
window.

### 3.2.2.2 Calibration of the oval- and round-window probe-tube microphones

Each probe-tube microphone was calibrated by coupling it to the sound source and microphone assembly (described in chapter 1.2) that is used to generate and measure a sound stimulus at the tympanic membrane. A cavity coupled each probe-tube tip to within 1 mm of the calibrated Larson Davis microphone (calibration described in chapter 1.2). The sound pressure was assumed equal at the Larson Davis microphone and the orifice of the probe-tube microphone. This procedure was repeated for both the oval-window and the round-window microphones so that two independent calibration ratios were measured: the ratio of sound pressure to the oval-window probe-microphone voltage \( \frac{p_{mic}}{V_{OW}} \) and the ratio of sound pressure to the round-window probe-microphone voltage \( \frac{p_{mic}}{V_{RW}} \).

![Figure 3-2: Pressure ratios measured between the oval window and the ear canal when (1) the oval-window microphone probe tube is normal and (2) the oval-window microphone probe tube is plugged with cotton.](image)

### 3.2.2.3 Do the probe-tube microphones measure the window pressures?

Since the microphones used to measure the window pressures are coupled to the windows via 33 mm long probe tubes, as described above, it is possible that the microphones also pick up sound from locations other than the probe tip (e.g., the ear-canal sound pressure). To test this possibility, we measured the cavity pressure with the probe tube normal and also with the window end of the probe tube plugged with cotton. Fig. 3-2 shows that, for most
frequencies, the probe-tube normal condition is at least 40 dB greater than the probe-tube plugged with cotton condition. Thus, based on the measurements shown in Fig. 3-2, we conclude that the probe-tube microphones do measure the window pressures.

3.2.2.4 Errors in relative calibration between the oval- and round-window microphones

The absolute calibration for the oval- and round-window microphones is not critical for our interest in the window-pressure differences. Instead, it is essential for the relative calibrations between the oval- and round-window microphones to be determined as precisely as possible. For example, consider the pressure difference between the oval-window pressure \( P_{OW} \) and the round-window pressure \( P_{RW} \).

\[
P_{OW} - P_{RW} = P_{OW} \left(1 - \frac{P_{RW}}{P_{OW}}\right). \tag{3.6}
\]

As Equation 3.6 shows via the term \( \frac{P_{RW}}{P_{OW}} \), since \( |\frac{P_{OW}}{P_{RW}}| \approx 1 \), errors in the relative sensitivity of the two microphones (\( \frac{V_{mic \ OW}}{V_{mic \ RW}} \) from chapter 3.2.2.2 above), which lead to errors in the relative measurement of \( P_{OW} \) and \( P_{RW} \), will have big effects on the measured difference in pressure. However, small absolute errors that are common to the calibration ratios for both microphones will not have substantial effects on the calculation of the pressure difference; these absolute errors are “divided out” in the ratio \( \frac{P_{RW}}{P_{OW}} \) and only account for a very small percentage of the remaining \( P_{OW} \) (Voss 1995).

The calibration procedure, discussed above in chapter 3.2.2.2, was repeated several times during each experiment. We use changes in the measured calibration ratios, \( \frac{P_{mic \ OW}}{V_{mic \ OW}} \) and \( \frac{P_{mic \ RW}}{V_{mic \ RW}} \), as a measure of error that exists in the measurements of \( P_{OW} \) and \( P_{RW} \). Specifically, we use the changes in the relative calibration of the two microphones, \( \frac{V_{mic \ OW}}{V_{mic \ RW}} \), measured throughout the experiment, to estimate the possible range of errors in the relative calibration between the two microphones.

The stability of the relative calibrations between the oval- and round-window microphones varied from experiment to experiment. The process of coupling the probe microphones to the sound-source assembly seemed to be the major source of variability in the calibration. For example, if a probe-tube microphone was attached to the sound-source assembly, and was left undisturbed, repeated measurements made over several hours showed changes that were less than 0.05 dB in magnitude and less than 0.001 cycles in angle. In contrast, if the sound-source assembly was moved, and the coupler that was used to attach it to the probe tubes was removed and then replaced, the changes in the measured absolute calibrations increased substantially. However, the relative calibrations remained more stable since it was possible to calibrate both probe-tube microphones, one at a time, without moving the sound source or coupler. Thus, while the absolute calibration of the
two microphones can change by 1 dB from calibration to calibration, the relative calibration between the two microphones exhibits less variability.

Repeated calibrations during the eleven experiments contained different levels of variability. In three of the eleven experiments (bones 23, 22 Right, and 8), the relative calibrations of the oval- and round-window microphones varied by more than 1 dB in magnitude and 0.01 cycles in angle. We considered this level of uncertainty in the calibrations unacceptable for computation of the window-pressure difference (see chapter 3.2.2.5 below). However, in the remaining eight (of eleven) experiments, the relative calibrations of the oval- and round-window microphones varied up to only 0.25 dB in magnitude and 0.005 cycles in angle. Thus, we focus our attention on the results from the subset of eight bones with the small variability in oval- and round-window microphone calibrations. Additionally, there was a dramatic change (2-3 dB) in round-window microphone calibration midway through the experiment on bone 18. It is not clear what happened to the microphone, but any measurements made after the change are not included here.

Fig. 3-3 shows a typical example of repeated calibrations throughout an experiment. For this example, the absolute calibrations of the oval- and round-window microphones changed by more than ±0.5 dB in magnitude and more than 0.01 cycles in angle, but at most frequencies the relative calibrations are all within 0.25 dB in magnitude and 0.005 cycles in angle of each other.

3.2.2.5 Lower limits for accurate calculations of $P_{RW}/P_{OW}$, $H_{WPD}$, and $\Delta P_{\text{min}}/P_{TM}$

Errors in the relative calibration between the microphones that measure the pressures at the oval and round windows limit the calculations of $P_{RW}/P_{OW}$, $H_{WPD}$, and $\Delta P_{\text{min}}/P_{TM}$. In this section, we estimate limits for the calculation of each of these quantities, based on our estimate of relative errors of 0.25 dB in magnitude and 0.005 cycles in angle between our measurements of $P_{RW}$ and $P_{OW}$ (chapter 3.2.2.4).

First consider how relative errors of 0.25 dB and 0.005 cycles in $P_{RW}$ and $P_{OW}$ affect the ratio $P_{RW}/P_{OW}$ when $P_{RW} \approx P_{OW}$. In this case, a 0.25 dB error in magnitude corresponds to a factor of 1.03. Thus, when $P_{RW} = P_{OW}$, our measurement of the magnitude ratio $|P_{RW}/P_{OW}|$ could range from 0.97 to 1.03. Likewise, our angle measurement could range from -0.005 to 0.005 cycles when the actual angle $\angle (P_{RW}/P_{OW}) = 0$.

Next, consider how the relative errors of 0.25 dB and 0.005 cycles in $P_{RW}$ and $P_{OW}$ affect the transfer function $H_{WPD} = 1 - P_{RW}/P_{OW}$ when $P_{RW} \approx P_{OW}$. In this case, the ratio $P_{RW}/P_{OW}$ has a maximum value of 1.03$e^{\pm0.0052\pi}$, which limits $|H_{WPD}|$ to 0.04. Such an error also introduces variation in the angle $\angle (H_{WPD})$ of up to ±0.37 cycles. Thus, we conclude that our measurements of $\angle (H_{WPD})$ are not useful.

\footnote{For the group of eight bones, there exists an occasional frequency band where the variation exceeds 0.25 dB in magnitude and 0.005 cycles in angle, but such bands are rare and narrow.}
Figure 3-3: Repeated calibrations (1, 2, and 3) of the oval- and round-window microphones from the experiment on bone 24 Left. Over the course of the experiment, three calibrations were made of each microphone. The left column pertains to the oval-window microphone, the middle column pertains to the round-window microphone, and the right column pertains to the ratio of the oval-to-round-window microphones. The top row plots the magnitude of the calibration for the oval-window (left-top) and the round-window (middle-top) microphones, and the magnitude ratio between these two calibrations (right-top). The middle-top row plots the respective magnitudes relative to calibration 1. The middle-bottom row plots the corresponding angles, and the bottom row plots the angles relative to calibration 1. The two shaded plots show that, at most frequencies, the relative calibrations between the oval- and round-window microphones do not change by more than 0.25 dB in magnitude and 0.005 cycles in angle.
<table>
<thead>
<tr>
<th>Calculated quantity</th>
<th>Measurement uncertainty or lower limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>P_{RW}/P_{OW}</td>
</tr>
<tr>
<td>$\angle(P_{RW}/P_{OW})$</td>
<td>Uncertainty $\pm 0.005$ cycles</td>
</tr>
<tr>
<td>$</td>
<td>H_{WPD}</td>
</tr>
<tr>
<td>$\angle(H_{WPD})$</td>
<td>Uncertainty $\pm 0.37$ cycles</td>
</tr>
<tr>
<td>$</td>
<td>\Delta P_{sin}\left/ P_{TM}\right</td>
</tr>
<tr>
<td>$\angle(\Delta P_{sin}\left/ P_{TM}\right)$</td>
<td>Uncertainty $\pm 0.37$ cycles</td>
</tr>
</tbody>
</table>

Table 3.1: Measurement uncertainties or lower limits for calculation of $P_{RW}/P_{OW}$, $H_{WPD}$ and $\Delta P_{sin}/P_{TM}$, based on the assumption that relative errors in the measurements of the oval- and round-window sound pressures are 0.25 dB in magnitude and 0.005 cycles in angle.

Finally, consider how the relative errors of 0.25 dB and 0.005 cycles in $P_{RW}$ and $P_{OW}$ affect the pressure-difference calculation $\Delta P_{sin}/P_{TM}$. If we assume that measurement errors in the ratio $P_{OW}/P_{TM}$ are negligible, then from Equation 3.5, our measurements of $\Delta P_{sin}/P_{TM}$ are limited by the same amount as our measurements of $H_{WPD}$ scaled by the factor $P_{OW}/P_{TM}$. Thus, the errors in the measurements of the magnitude $|\Delta P_{sin}/P_{TM}|$ are expected to be large when $|\Delta P_{sin}/P_{TM}| < 0.04 |P_{OW}/P_{TM}|$, and our measurements of the angle $\angle(\Delta P_{sin}/P_{TM})$ are not useful due to uncertainties of up to $\pm 0.37$ cycles.

Table 3.1 summarizes the ranges of limits we predict for our ability to measure the quantities $P_{RW}/P_{OW}$, $H_{WPD}$ and $\Delta P_{sin}/P_{TM}$. In the results that follow, we plot all our magnitude measurements, but we indicate regions of uncertainty based on the limits listed in Table 3.1. We do not plot the angles $\angle(\Delta P_{sin}/P_{TM})$ and $\angle(H_{WPD})$, due to the large errors we expect in them.

### 3.2.3 Statistical test to compare two groups of data

We use a statistical test to determine if there are differences between different populations within our data. Specifically, we compute probability values ($p$ values) to test the null hypothesis that two means are from the same population. In particular, we test to determine the $p$ values associated with the means for $|P_{RW}/P_{OW}|$, $\angle(P_{RW}/P_{OW})$, $|H_{WPD}|$, and $|\Delta P_{sin}/P_{TM}|$ when there are (1) different sized perforations and (2) perforations at different tympanic-membrane locations.

Our $p$ values are computed with a permutation test (Efron and Tibshirani 1993). For each permutation test, we test the null hypothesis $H_0$: Mean $\mu_1$ is equal to mean $\mu_2$. Since the sample sizes used to compute the means are small (range N=2 to N=16), we choose to compute the corresponding $p$ values using a bootstrap permutation test (Efron and Tibshirani 1993); this method makes no assumptions about characteristics of the distributions, such as a normal distribution.

The permutation test is performed computationally as follows.

1. Calculate the mean $\mu_1$ from data set $1 \ D_1 = d_1, d_2, ... d_{N_1}$ and the mean $\mu_2$ from data set $2 \ D_2 = d_1, d_2, ... d_{N_2}$ where $N_1$ and $N_2$ are the number of data points in data set...
1 and data set 2, respectively.

2. Calculate the difference in the data means: \( X_{data} = \mu_1 - \mu_2 \).

3. Form a sample data set \( D_{sample} \) from the \( N_1 + N_2 \) total data points. At random, form two new data sets from \( D_{sample} \) such that \( D_{sample} \) contains \( N_1 \) of the points and \( D_{sample} \) contains the remaining \( N_2 \) points.

4. Calculate the difference between the means for \( D_{sample} \) and \( D_{sample} \): \( X_{test} = \mu_{sample} - \frac{\mu_{sample}}{\mu_{sample}} \).

5. Repeat steps 3 and 4 \( Y \) times.

6. Calculate \( y \), the number of times \( |X_{test}| \geq |X_{data}| \).

7. \( p = \frac{y}{Y} \).

The computed \( p \) value depends on the particular randomizations of the test data. Thus, repeated calculations of the \( p \) value can show slight differences. However, if the total number of permutations \( Y \) is large enough, the computed \( p \) values from different trials differ by only a small degree. Here, we use \( y = 10000 \). A specific example of how much the \( p \) values may change involves a test performed on the data in Table 3.2. For these data, the \( p \) values were computed, with \( Y=10000 \), two times. Changes in the \( p \) values between the two trials ranged from 0 to 0.0202. The largest variations occurred when the \( p \) values were near 0.5; both large and small \( p \) values showed much less variation than 0.0202.

### 3.3 Results

#### 3.3.1 Organization

The results presented in this section are organized into three sections. Each section presents measurements of quantities involved in our interpretation of sound transmission via the acoustic route. Specifically, we present measurements, made with the tympanic membrane both normal and perforated, of (1) the middle-ear-cavity transfer function \( H_{PCAV} = \frac{P_{OW}}{P_{TM}} \), (2) the ratio between the oval- and round-window pressures \( \frac{P_{RW}}{P_{OW}} \) and the window-pressure-difference transfer function magnitude \( |H_{WP}| = |1 - \frac{P_{OW}}{P_{RW}}| \), and (3) the magnitude of the pressure difference between the oval- and round-window pressures per pressure at the tympanic membrane, \( \left| \frac{\Delta P_{win}}{P_{TM}} \right| \). For each of these quantities, we examine the effects of both perforation size and perforation location. In general, within this section we present results from one of our bones (bone 24 Left) as a typical example followed by the mean measurements calculated across the eight bones. Results from all eight bones are in appendices.
3.3.2 Effects of tympanic-membrane perforations on the middle-ear-cavity-pressure transfer function: \( H_{PCAV} \)

3.3.2.1 General behavior of \( H_{PCAV} \)

We examine how tympanic-membrane perforations affect the middle-ear cavity pressure by calculating the middle-ear-cavity-pressure transfer function \( H_{PCAV} = P_{OW}/P_{TM} \) (Equation 3.3). Measurements of \( H_{PCAV} \) made on the example bone 24 Left, and the mean measurement for five size categories calculated from all the data, are plotted in Fig. 3-4; these measurements are typical of all measurements of \( H_{PCAV} \) on all eleven bones (Appendix G, page 243). When the tympanic membrane is normal, \(|H_{PCAV}| \approx 1\) at the lowest frequencies; in other words, the ear-canal and middle-ear cavity pressures are nearly equal at the lowest frequencies. As frequency increases, with a perforated tympanic membrane, \(|H_{PCAV}|\) shows a peak followed by a decrease which, for the smaller perforations, approaches the normal \(|H_{PCAV}|\). There is a minimum around 2500 Hz, which is sharper and more pronounced as the perforation size decreases; the frequency of the minimum appears to be independent of perforation size.

At the lowest frequencies, the angle \( \angle H_{PCAV} \) is about zero when the tympanic membrane is normal, indicating that the cavity and ear-canal pressures are in phase. As frequency increases, \( \angle H_{PCAV} \) decreases so that the middle-ear cavity pressure lags the ear-canal pressure by up to 0.25 cycles. When the tympanic membrane is perforated, the angle \( \angle H_{PCAV} \) is also nearly zero at the lowest frequencies. As frequency increases, \( \angle H_{PCAV} \) begins to decrease at a frequency that increases with increasing perforation size. The frequency where the angle decrease begins corresponds to the frequency of the first increase in \(|H_{PCAV}|\), and this frequency increases as perforation diameter increases. For both the normal and perforated conditions, \( \angle H_{PCAV} \) increases to about zero near 2500 Hz (in conjunction with the local minimum frequency for \(|H_{PCAV}|\)), and at higher frequencies \( \angle H_{PCAV} \) again decreases at the frequency of the local maximum in \(|H_{PCAV}|\).

In summary, perforations have dramatic effects on the middle-ear-cavity transfer function \( H_{PCAV} \). For the lowest frequencies, all perforations equalize the ear-canal and middle-ear-cavity pressures so that \( H_{PCAV} \approx 1 \), and at the higher frequencies the perforation appears to introduce a perforation-size-dependent resonance that allows the cavity pressure to exceed the ear-canal pressure.

3.3.2.2 Effects of perforation size on \( H_{PCAV} \)

As described above and seen in Fig. 3-4, the perforation size has substantial effects on the transfer function \( H_{PCAV} \). In particular, the larger the perforation, the larger the
Figure 3-4: Measurements of the transfer function $H_{PCAV} = P_{DW}/P_{TM}$ with a normal tympanic membrane and with increasingly larger perforations. Symbols are at every 20th data point. LEFT: Bone 24 Left RIGHT: Means and standard errors from all measurements. TOP: Magnitude. BOTTOM: Angle.
low-frequency range over which the middle-ear cavity and the ear-canal cavity pressures are equal. Additionally, smaller perforations correspond to larger and sharper extrema in $|H_{PCAV}|$.

### 3.3.2.3 Effects of perforation location on $H_{PCAV}$

To compare the effect of perforation location on $H_{PCAV}$, we use measurements of $H_{PCAV}$ made on two of the three bones discussed in chapter 2.3.2.2 (bones 20, 24 Right), in which we compared measurements made with perforations at two locations on one bone by patching the first perforation. Fig. 3-5 compares the effects of perforation location on $H_{PCAV}$ for these two bones. Both the magnitude and angle of $H_{PCAV}$ appear to be independent of perforation location for the locations marginal versus central (Fig. 3-5, Left column) and anterior-inferior versus posterior-inferior (Fig. 3-5, Right column). We do not have measurements to demonstrate that the patch returned $H_{PCAV}$ to the $H_{PCAV}$ measured with a normal tympanic membrane; however, in chapter 2.3.2.2 we showed measurements that the patch did return our middle-ear transfer function between stapes velocity and pressure at the tympanic membrane to normal within a few dB. Here, slight differences between the $H_{PCAV}$ measured on the same bone in two locations could result from either true differences in $H_{PCAV}$ or effects of the patched tympanic membrane. Either way, the differences are small. Thus, we have no evidence for a location dependence in $H_{PCAV}$, at least for small perforations.

### 3.3.3 Effects of tympanic-membrane perforations on the window-pressure-difference transfer function: $H_{WPD}$

#### 3.3.3.1 General behavior of $H_{WPD}$

Measurements of the pressure ratio $P_{RW}/P_{OW}$ and the transfer function $H_{WPD} = 1 - P_{RW}/P_{OW}$ are plotted in Fig. 3-6 for the example bone 24 Left. Measurements on all eight bones in which the window-pressures were measured most accurately (chapter 3.2.2.4) are in Appendix H (page 251). All means presented in this section are calculated from measurements on this subset of eight bones.

First consider the pressure ratio $P_{RW}/P_{OW}$ (left column of Fig. 3-6). In all cases, at the lower frequencies, the magnitude $|P_{RW}/P_{OW}| \approx 1$ and the angle $\angle(P_{RW}/P_{OW}) \approx 0$, which indicates that $P_{RW} \approx P_{OW}$. Furthermore, this behavior seems to be uniform across all perforation sizes. Between 2000 and 3000 Hz, $|P_{RW}/P_{OW}|$ has a minimum that is followed by a maximum; associated with these extrema is a rapid increase in $\angle(P_{RW}/P_{OW})$ to about 0.05 cycles and then a rapid decrease back to 0 cycles. The behavior described here for the ratio $P_{RW}/P_{OW}$ measured on bone 24 Left is consistent across all of our bones. In all cases, for all tympanic-membrane conditions, between about 1000 and 3000 Hz, the ratio exhibits
Figure 3-5: Comparison of $H_{PCAV}$ (1) between perforations in the marginal versus central part of the posterior-inferior quadrant (LEFT) and (2) between perforations in the posterior-inferior and anterior-inferior quadrants (RIGHT). Symbols are at every 20th data point. TOP: Magnitude. BOTTOM: Angle.
a local magnitude minimum followed immediately by a local magnitude maximum, and a corresponding increase and decrease in angle.

The sources of the features of $P_{RW}/P_{OW}$ can be seen in individual oval- and round-window pressures $P_{RW}$ and $P_{OW}$. Fig. 3-1 shows that, although for most frequencies $P_{RW}$ and $P_{OW}$ are nearly indistinguishable, between 1000 and 3000 Hz $P_{RW}$ and $P_{OW}$ exhibit large derivatives with respect to frequency, and the biggest differences between $P_{RW}$ and $P_{OW}$ occur at the frequencies where $P_{RW}$ and $P_{OW}$ change rapidly. Interestingly, all of our measurements indicate that the frequency region where $P_{OW}$ changes most rapidly with frequency begins at a slightly lower frequency than the frequency region where $P_{RW}$ changes most rapidly with frequency. Thus, the the local minimum in the pressure ratio $|P_{RW}/P_{OW}|$ always occurs at a frequency below the local maximum in $|P_{RW}/P_{OW}|$. It is not clear what mechanism(s) may be responsible for this behavior, but the fact that it occurred consistently on all of our preparations suggests that the mechanism(s) are consistent from bone to bone.

As discussed in chapter 3.2.2.5, we estimate that errors in the measurements of the oval- and round-window pressures lead to uncertainties of $\pm 0.03$ in magnitude and $\pm 0.005$ cycles in angle for the calculation of $P_{RW}/P_{OW}$. These regions of uncertainty are shaded in gray in Fig. 3-6, such that the region is centered at $P_{RW} = P_{OW}$; though the region indicates the total range of uncertainty and could be centered at any value. For frequencies below 1000 Hz, the region of uncertainty indicates that if differences between tympanic-membrane conditions do exist, we are unable to detect them because they vary by a factor of less than 0.06 in magnitude and their differences are less than 0.01 cycles in angle.

Next, we consider the window-pressure-difference transfer function $H_{WPD}$ (right column of Fig.3-6). This transfer function is related to the pressure ratio discussed above in a simple manner: $H_{WPD} = 1 - (P_{RW}/P_{OW})$. Thus, when $P_{RW}/P_{OW} \approx 1$, the magnitude $|H_{WPD}|$ approaches zero and the angle $\angle H_{WPD}$ can be either positive or negative, depending on whether $|P_{RW}/P_{OW}|$ is greater than or less than 1. There is variability in our low-frequency measurements of $|H_{WPD}|$ both in bone 24 Left (Fig. 3-6) and in the other seven bones (Appendix H, page 251). However, the variability does not seem to be systematically related to perforation size; instead, we suspect it results from small errors in our pressure measurements when $P_{OW} \approx P_{RW}$. Indeed, our estimate of the lower limit to which we can accurately measure $|H_{WPD}|$ is 0.04 (chapter 3.2.2.5), which is indicated on the plot in Fig.3-6. Thus, our calculations of $|H_{WPD}|$ below about 1000 Hz suffer from our inability to measure the relative pressure between the oval and round windows with greater accuracy than 0.25 dB in magnitude and 0.005 cycles in angle.

In general, most measurements of $|H_{WPD}|$ increase with frequency above 800 Hz to a local maximum between 1000 and 3000 Hz. This local maximum is related to the local maximum described above for the pressure ratio $|P_{RW}/P_{OW}|$. In particular, when $|P_{RW}/P_{OW}|$ exhibits either a local minimum or a local maximum, $|1 - (P_{RW}/P_{OW})|$ will have a local maximum. However, in general, the maximum in $|P_{RW}/P_{OW}|$ exceeds 1 by a greater
Figure 3-6: $P_{RW}/P_{OW}$ and $|H_{WPD} = (1 - P_{RW}/P_{OW})|$ from bone 24 Left. The parameter is perforation size, and symbols are plotted at every 20th data point. LEFT: Magnitude and angle of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$. The gray region indicates the range of variation that is expected to result from our maximal errors of 0.25 dB in magnitude and 0.005 cycles in angle between the oval- and round-window pressures. Here, the gray region is centered at 1 in magnitude and 0 in angle. However, the total range of 0.06 in magnitude and 0.01 in angle is the important feature, not the centering location. In general, any variations by factors of up to 0.06 in magnitude and 0.01 cycles in angle may result from measurement errors. RIGHT: The transfer-function magnitude $|H_{WPD} = (1 - P_{RW}/P_{OW})|$. Points below 0.04 (gray region) probably suffer from large effects of measurement errors (see chapter 3.2.2.5). Thus, an upper limit of 0.04 probably best defines $|H_{WPD} = (1 - P_{RW}/P_{OW})|$ for frequencies below about 1000 Hz; in other words, our measurements indicate that below about 1000 Hz, $0 < |H_{WPD} = (1 - P_{RW}/P_{OW})| < 0.04$. 

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amount than the minimum in $|P_{RW}/P_{OW}|$ falls short of 1; thus, the maximum apparent in
the transfer function $H_{WPD}$ results from the maximum in $|P_{RW}/P_{OW}|$. Similarly, in some
of the data there is an additional local maximum that can be associated with the local min-
imum in $|P_{RW}/P_{OW}|$, but this finding is less consistent across bones. Note that the angle
$\angle H_{WPD}$ is not plotted. As discussed in chapter 3.2.2.5, we estimate that our measurement
errors lead to variations of $\pm 0.37$ cycles in this angle. Thus, for our measurements, we
conclude that the angle of the pressure ratio $\angle(P_{RW}/P_{OW})$ is a more robust quantity to
consider when describing how the sound-pressure angles at the windows are affected by
perforations.

3.3.3.2 Effects of perforation size on $H_{WPD}$

Qualitatively, our measurements of the window-pressure ratio $P_{RW}/P_{OW}$ and the window-
pressure-difference transfer function $H_{WPD}$ do not have features that show dependence on
perforation size (Fig. 3-6 and Appendix H, page 251). Here, we examine any potential
dependence on perforation size in a more quantitative manner. We note, that due to
measurement errors, our measurements are limited by the values listed in Table 3.1, and as
a result of these limits, most of our measurements below about 1000 Hz are more-or-less
at the level of a noise floor. Thus, we don’t expect to determine quantitative differences
between the measurements, even if they do exist. However, we do perform a statistical
analysis across our entire frequency range.

First, we group all our measurements of $P_{RW}/P_{OW}$ and $H_{WPD}$ into seven different
groups depending on the tympanic-membrane condition, where $d$ corresponds to perforation
diameter: (1) normal tympanic membrane, (2) $0.1 \leq d \leq 1.0$ mm, (3) $1.0 < d \leq 2.0$ mm,
(4) $2.0 < d \leq 3.0$ mm, (5) $3.0 < d \leq 4.0$ mm, (6) $4.0 < d \leq 7.0$ mm, and (7) tympanic
membrane removed. Next, we compute the means for each of the seven groups for the three
quantities $|P_{RW}/P_{OW}|$, $\angle(P_{RW}/P_{OW})$ and $|H_{WPD}|$. These means are plotted in Fig. 3-7.
There is no clear dependence on the perforation size.

Second, we perform a probabilistic analysis to determine if the small differences between
the means plotted in Fig. 3-7 are significant. Our analysis is performed for six frequencies:
125, 250, 500, 1000, 2000, and 4000 Hz. Using the “resampling-permutation” methodology
described in chapter 3.2.3, we compute $p$ values for each mean measurement relative to
all other mean measurements. In other words, for each possible combination of two mean
measurements, we test the null hypothesis that the two means are from the same population.
The resulting $p$ values to test for differences in the means are reported in Table 3.2 for
$|P_{RW}/P_{OW}|$, Table 3.3 for $\angle(P_{RW}/P_{OW})$, and Table 3.4 for $|H_{WPD}|$.

In general, almost all of the computed $p$ values for all three quantities ($|P_{RW}/P_{OW}|$,
$\angle(P_{RW}/P_{OW})$, $|H_{WPD}|$) are such that $p > 0.05$, indicating that the differences between the
means are not significant. There do exist a few comparisons where $p < 0.05$, but these compar-
isons are few and do not suggest any trends with perforation size. For example, there are
Figure 3-7: Means computed for the indicated tympanic-membrane conditions with measurements grouped together from the subset of eight bones. Symbols indicate every 20th data point. LEFT: Magnitude and angle of the pressure ratio between the round and oval windows. The gray shaded region indicates the range of variation that is expected to result from our maximal errors of 0.25 dB in magnitude and 0.005 cycles in angle between the oval- and round-window pressures. Here, the gray region is centered at 1 in magnitude and 0 in angle. However, the total range of 0.06 in magnitude and 0.01 in angle is the important feature, not the centering location. In general, any variations by factors of up to 0.06 in magnitude and 0.01 cycles in angle may result from measurement errors. The circles indicate measurements from Békésy (1947) of the angle between the oval- and round-window pressures one temporal bone with the tympanic membrane removed. RIGHT: Magnitude of the window-pressure-difference transfer function. Any points below 0.04 (gray shaded region) probably suffer from large measurement errors (see chapter 3.2.2.5). In general, for both $H_{WPD}$ and $P_{RW}/P_{OW}$, the standard errors of the means are about equal to the total ranges of all seven measurements at a given frequency.
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<th>Number in Category</th>
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<th>1 ≤ d ≤ 2</th>
<th>2 ≤ d ≤ 3</th>
<th>3 ≤ d ≤ 4</th>
<th>4 ≤ d ≤ 7</th>
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Table 3.2: Computed probabilities (p) that test the null hypothesis that any two means of |\(P_{RW}/P_{OW}\)|, plotted in Fig. 3-7, for different perforation diameters are from the same population. Values where p ≤ 0.05 are underlined and bold. Perforation diameter d in mm.

Four comparisons (of a total of 147 comparisons) for |\(P_{RW}/P_{OW}\)| (Table 3.2) where p < 0.05. In particular, two of these occur at 125 Hz and the other two at 250 Hz, both frequencies for which our measurement errors are suspected of making it impossible to determine true differences between measurements. Similarly, occasional values where p < 0.05 occur in the calculations for \(\angle(P_{RW}/P_{OW})\) (Table 3.3) occur at the lower frequencies. Finally, there are no values cases where p < 0.05 for |\(H_{WPD}\)| (Table 3.4). Thus, in general, we conclude that the quantities |\(P_{RW}/P_{OW}\)|, \(\angle(P_{RW}/P_{OW})\), and |\(H_{WPD}\)| do not depend on perforation size for frequencies greater than 1000 Hz where we are less limited by measurement errors. For frequencies less than 1000 Hz, we have no indication of a size dependence. If a size dependence does exist, the effects are smaller than our measurement limits allow us to measure.
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<td>0.5933</td>
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Table 3.3: Computed probabilities (p) that test the null hypothesis that any two means of \(\mathcal{L}(P_{RW}/P_{OW})\), plotted in Fig. 3-7, for different perforation diameters are from the same population. Values where \(p \leq 0.05\) are underlined and bold. Perforation diameter \(d\) in mm.
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<td>0.9408</td>
<td>0.9408</td>
<td>0.9408</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.0</td>
<td>1.0</td>
<td>0.1915</td>
<td>0.9408</td>
<td>0.9408</td>
<td>0.9408</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.0</td>
<td>1.0</td>
<td>0.1915</td>
<td>0.9408</td>
<td>0.9408</td>
<td>0.9408</td>
</tr>
</tbody>
</table>

Table 3.4: Computed probabilities (p) that test the null hypothesis that any two means of log |H WPD|, plotted in Fig. 3-7, for different perforation diameters are from the same population. There are no cases where p ≤ 0.05. Perforation diameter d in mm.
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>0.1 ≤ d ≤ 1</th>
<th>1 &lt; d ≤ 2</th>
<th>2 &lt; d ≤ 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 Posterior</td>
<td>7 Posterior</td>
<td>6 Posterior</td>
</tr>
<tr>
<td></td>
<td>8 Anterior</td>
<td>6 Anterior</td>
<td>2 Anterior</td>
</tr>
<tr>
<td>125</td>
<td>0.5707</td>
<td>0.2178</td>
<td>0.9606</td>
</tr>
<tr>
<td>250</td>
<td>0.2948</td>
<td>0.4311</td>
<td>0.7864</td>
</tr>
<tr>
<td>500</td>
<td>0.1767</td>
<td>0.0929</td>
<td>0.9271</td>
</tr>
<tr>
<td>1000</td>
<td>0.5518</td>
<td>0.8614</td>
<td>0.8244</td>
</tr>
<tr>
<td>2000</td>
<td>0.0753</td>
<td>0.2017</td>
<td><strong>0.0380</strong></td>
</tr>
<tr>
<td>4000</td>
<td>0.1240</td>
<td>0.7007</td>
<td>0.9622</td>
</tr>
</tbody>
</table>

Table 3.5: Computed probabilities (p) that test the null hypothesis that the means of |P_{RW}/P_{OW}| for the two perforation locations anterior-inferior and posterior-inferior are from the same population; values where p ≤ 0.05 are underlined and bold. Diameter d in mm.

### 3.3.3.3 Effects of perforation location on H_WPD

We compare the effects of perforation location on the quantities |P_{RW}/P_{OW}|, \( \angle(P_{RW}/P_{OW}) \), and |H_{WPD}| in a similar manner to our comparison of perforation size performed above in chapter 3.3.3.2. In particular, we compare perforations in the anterior-inferior quadrant to those in the posterior-inferior quadrant. First, we form three perforation-size categories - (1) 0.1 ≤ d ≤ 1 mm; (2) 1 < d ≤ 2 mm; and (3) 2 < d ≤ 4 mm. All perforations such that 0.1 ≤ d ≤ 4 mm are placed into the appropriate category. Next, within each size category, means are computed separately for |P_{RW}/P_{OW}|, \( \angle(P_{RW}/P_{OW}) \), and |H_{WPD}| from perforations in the anterior-inferior quadrant and posterior-inferior quadrant. These means are then tested to determine if their differences are significant. The resulting p values for the perforation-location dependence of |P_{RW}/P_{OW}|, \( \angle(P_{RW}/P_{OW}) \), and |H_{WPD}| are listed in Tables 3.5, 3.6, and 3.7, respectively.

In general, there is no evidence of a perforation-location dependence for any of the three quantities |P_{RW}/P_{OW}|, \( \angle(P_{RW}/P_{OW}) \), and |H_{WPD}|. In all but three comparisons, p > 0.05. The remaining three comparisons where p < 0.05 are not suggestive of any trends. For example, for the diameter range 1 < d ≤ 2 mm, there is a possible location dependence for \( \angle(P_{RW}/P_{OW}) \) between anterior and posterior perforations for the frequencies 500 and 1000 Hz. However, this dependence is not seen for smaller or larger perforations at these frequencies for \( \angle(P_{RW}/P_{OW}) \). In general, we conclude that our results do not support any perforation-location dependence on any of the three quantities |P_{RW}/P_{OW}|, \( \angle(P_{RW}/P_{OW}) \), and |H_{WPD}|.
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>(0.1 \leq d \leq 1)</th>
<th>(1 &lt; d \leq 2)</th>
<th>(2 &lt; d \leq 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 Posterior</td>
<td>7 Posterior</td>
<td>6 Posterior</td>
</tr>
<tr>
<td></td>
<td>8 Anterior</td>
<td>6 Anterior</td>
<td>2 Anterior</td>
</tr>
<tr>
<td>125</td>
<td>0.5315</td>
<td>0.7820</td>
<td>0.927(^*)</td>
</tr>
<tr>
<td>250</td>
<td>0.8245</td>
<td>0.1839</td>
<td>0.9799</td>
</tr>
<tr>
<td>500</td>
<td>0.6867</td>
<td><strong>0.0438</strong></td>
<td>0.5743</td>
</tr>
<tr>
<td>1000</td>
<td>0.7308</td>
<td><strong>0.0443</strong></td>
<td>0.6103</td>
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<tr>
<td>2000</td>
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<td>0.3211</td>
<td>0.7094</td>
</tr>
<tr>
<td>4000</td>
<td>0.5848</td>
<td>0.0630</td>
<td>0.6396</td>
</tr>
</tbody>
</table>

Table 3.6: Computed probabilities \((p)\) that test the null hypothesis that the means of \(\zeta(P_{RW}/P_{0W})\) for the two perforation locations anterior-inferior and posterior-inferior are from the same population; values where \(p \leq 0.05\) are underlined and bold. Diameter \(d\) in mm.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>(0.1 \leq d \leq 1)</th>
<th>(1 &lt; d \leq 2)</th>
<th>(2 &lt; d \leq 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 Posterior</td>
<td>7 Posterior</td>
<td>6 Posterior</td>
</tr>
<tr>
<td></td>
<td>8 Anterior</td>
<td>6 Anterior</td>
<td>2 Anterior</td>
</tr>
<tr>
<td>125</td>
<td>0.6348</td>
<td>0.3286</td>
<td>0.1571</td>
</tr>
<tr>
<td>250</td>
<td>0.9905</td>
<td>0.6286</td>
<td>0.4297</td>
</tr>
<tr>
<td>500</td>
<td>0.0876</td>
<td>0.3333</td>
<td>0.8981</td>
</tr>
<tr>
<td>1000</td>
<td>0.5428</td>
<td>0.0599</td>
<td>0.7902</td>
</tr>
<tr>
<td>2000</td>
<td>0.0748</td>
<td>0.1371</td>
<td>0.4679</td>
</tr>
<tr>
<td>4000</td>
<td>0.5764</td>
<td>0.8845</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 3.7: Computed probabilities \((p)\) that test the null hypothesis that the means of \(\log |H_{WPD}|\) for the two perforation locations anterior-inferior and posterior-inferior are from the same population; there are no values where \(p \leq 0.05\). Diameter \(d\) in mm.
3.3.4 Effects of tympanic-membrane perforations on the window pressure-difference per pressure at the tympanic membrane: \( |\Delta P_{\text{win}}/P_{TM}| \)

3.3.4.1 Measurements of \( |\Delta P_{\text{win}}/P_{TM}| \)

Measurements of the window pressure-difference per pressure at the tympanic membrane \( |\Delta P_{\text{win}}/P_{TM}| \), which is the acoustic-route stimulus to the cochlea, are plotted in the left column of Fig. 3-8 for the example bone 24 Left and in the figures of Appendix J (page 261) for all eight bones. In all cases, the measured \( |\Delta P_{\text{win}}/P_{TM}| \) with a normal tympanic membrane is smaller than \( |\Delta P_{\text{win}}/P_{TM}| \) with a tympanic-membrane perforation of any size: perforations appear to increase \( |\Delta P_{\text{win}}/P_{TM}| \).

However, we note that our estimates of error in \( |\Delta P_{\text{win}}/P_{TM}| \) affect the interpretation of the \( |\Delta P_{\text{win}}/P_{TM}| \) measurements. The right column of Fig. 3-8 shows that, below 1000 Hz, our measurements of \( |\Delta P_{\text{win}}/P_{TM}| \) and our lower limit for measuring \( |\Delta P_{\text{win}}/P_{TM}| \), which results from relative errors in the measurement of \( P_{OW} \) and \( P_{RW} \), are about equal. Thus, we are unable to measure the true pressure difference at these lower frequencies. Instead, we are only able to assign an upper limit to the pressure difference \( |\Delta P_{\text{win}}/P_{TM}| \). It seems that we can measure \( |\Delta P_{\text{win}}/P_{TM}| \) above 1000 Hz, where the measured \( |\Delta P_{\text{win}}/P_{TM}| \) is greater than our limit for measurement.

The consistent finding that, for frequencies below 1000 Hz, \( |\Delta P_{\text{win}}/P_{TM}| \) increases when the tympanic membrane is perforated is consistent with our error estimates and does not mean that we have measured the actual pressure difference as opposed to an upper limit on the pressure difference. As discussed in chapter 3.2.2.5, \( |\Delta P_{\text{win}}/P_{TM}| \) is limited by \( 0.4|H_{P_{CAV}}| \). With the tympanic-membrane normal, \( |H_{P_{CAV}}^{\text{norm}}| \) is three to ten times smaller than the perforated case of \( |H_{P_{CAV}}^{\text{perf}}| \). As a result, it is possible to measure a \( |\Delta P_{\text{win}}^{\text{norm}}/P_{TM}| \) that is three to ten times smaller than the perforated case \( |\Delta P_{\text{win}}^{\text{perf}}/P_{TM}| \). Thus, even though \( |\Delta P_{\text{win}}^{\text{norm}}/P_{TM}| < |\Delta P_{\text{win}}^{\text{perf}}/P_{TM}| \), for frequencies below 1000 Hz, we are still only able to assign upper limits to the measurements.

3.3.4.2 Effect of perforation size on \( |\Delta P_{\text{win}}/P_{TM}| \)

In Fig. 3-9, plots of the means of all \( |\Delta P_{\text{win}}/P_{TM}| \) measurements, grouped by perforation size, show the trends that occur with perforation size as a parameter. First, the \( |\Delta P_{\text{win}}/P_{TM}| \) for the normal tympanic membrane is always less than the \( |\Delta P_{\text{win}}/P_{TM}| \) associated with a perforated tympanic membrane. Again, we stress that for frequencies below 1000 Hz, these measurements constitute an upper bound for \( |\Delta P_{\text{win}}/P_{TM}| \), and not necessarily true values of \( |\Delta P_{\text{win}}/P_{TM}| \). Second, as frequency increases above about 1000 Hz, the perforation size does seem to influence \( |\Delta P_{\text{win}}/P_{TM}| \) in that at these higher frequencies the larger perforations lead to larger \( |\Delta P_{\text{win}}/P_{TM}| \). Thus, \( |\Delta P_{\text{win}}/P_{TM}| \) appears to depend on perforation size, at least for frequencies above 1000 Hz.
Figure 3-8: LEFT: Measurement of $|\Delta P_{win}/P_{TM}|$ on bone 24 Left. The parameter is perforation size, and symbols indicate every 20th data point. RIGHT: Measurement of $|\Delta P_{win}/P_{TM}|$ for each tympanic-membrane condition compared to our estimate for our measurement limit, which is shaded in gray. For each case, the estimate for the measurement limit is 0.04$|H_{PCAV}|$ (Table 3.1) where the $|H_{PCAV}|$ is from Fig. 3-4 and corresponds to the appropriate tympanic-membrane condition. Note that, due to differences in $|H_{PCAV}|$, the y-axis range differs between the normal and the other cases.
Figure 3-9: Mean window-pressure difference magnitudes $|\Delta P_{win}/P_{TM}|$ computed in the logarithmic domain for the indicated tympanic-membrane condition. The standard errors for the normal tympanic membrane and perforation diameters $2 < d \leq 3$ mm are indicated by the shaded regions. The standard errors for all other groups are about the same or smaller than those for $2 < d \leq 3$ mm. Symbols indicate every 20th data point. The six black circles indicate measurements from Békésy (1947) of the window pressure difference from one temporal bone with the tympanic membrane removed. We note that below 1000 Hz, all values are limited by relative errors in the measurement of the oval- and round-window pressures; at these lower frequencies the means should be considered an upper bound on $|\Delta P_{win}/P_{TM}|$. 
We performed a probabilistic analysis to determine when the differences between the means of the seven different groups plotted in Fig. 3.9 are significant. Using the “resampling-permutation” methodology described in chapter 3.2.3, we compute probabilities \( p \) for each \(|\Delta P_{\text{win}}/P_{TM}|\) mean measurement relative to all other mean measurements. The resulting probabilities that test for differences in the means of \(|\Delta P_{\text{win}}/P_{TM}|\) are reported in Table 3.8. The statistical test is consistent with the qualitative impression given by Fig. 3.9. In particular, the differences between \(|\Delta P_{\text{win}}/P_{TM}|\) with a normal tympanic membrane and \(|\Delta P_{\text{win}}/P_{TM}|\) with a tympanic-membrane perforation of any size are highly significant \((p \ll 0.05)\) for nearly all perforation sizes at nearly all tested frequencies. At frequencies below 1000 Hz, there are no significant differences \((p < 0.05)\) between perforations of different sizes; either there are no true differences or our analysis is limited by our inability to measure the true pressure difference at these lower frequencies. Finally, above 1000 Hz, there is some evidence of significant differences in \(|\Delta P_{\text{win}}/P_{TM}|\) between the larger and smaller perforations, especially at 2000. However, a clear systematic trend is not obvious at these higher frequencies.

3.3.4.3 Effect of perforation location on \(|\Delta P_{\text{win}}/P_{TM}|\)

We compare the effects of perforation location on the \(|\Delta P_{\text{win}}/P_{TM}|\) in a similar manner to our comparison of perforation size performed above in chapter 3.3.3.3. Again, we compare perforations in the anterior-inferior quadrant to those in the posterior-inferior quadrant. First, we form three perforation-size categories - (1) \(0.1 \leq d \leq 1\) mm; (2) \(1 < d \leq 2\) mm; and (3) \(2 < d \leq 4\) mm. All perforations such that \(0.1 \leq d \leq 4\) mm are placed into the appropriate category. Next, within each size category, means are computed separately for \(|\Delta P_{\text{win}}/P_{TM}|\) from perforations in the anterior-inferior quadrant and posterior-inferior quadrant. These means are then tested to determine if their differences are significant. The resulting \( p \) values for the perforation-location dependence of \(|\Delta P_{\text{win}}/P_{TM}|\) are listed in Table 3.9. There is no evidence of any perforation-location dependence for \(|\Delta P_{\text{win}}/P_{TM}|\), as for all tests \( p > 0.05 \).
<table>
<thead>
<tr>
<th>Number in Category</th>
<th>Normal</th>
<th>$0.1 \leq d \leq 1$</th>
<th>$1 &lt; d \leq 2$</th>
<th>$2 &lt; d \leq 3$</th>
<th>$3 &lt; d \leq 4$</th>
<th>$4 &lt; d \leq 7$</th>
<th>No TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 Hz</td>
<td>Normal</td>
<td>1.0</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
<td>$0.1 \leq d \leq 1$</td>
<td>1.0</td>
<td>0.7490</td>
<td>0.4226</td>
<td>0.8095</td>
<td>0.6632</td>
<td>0.6468</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; d \leq 2$</td>
<td>1.0</td>
<td>0.2143</td>
<td>0.5868</td>
<td>0.4327</td>
<td>0.4139</td>
<td>0.5777</td>
<td></td>
</tr>
<tr>
<td>$2 &lt; d \leq 3$</td>
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<td>0.5278</td>
<td>0.6573</td>
<td>0.8222</td>
<td>0.8543</td>
<td>0.9302</td>
<td></td>
</tr>
<tr>
<td>$3 &lt; d \leq 4$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8611</td>
<td>0.7354</td>
<td>0.5759</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4 &lt; d \leq 7$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8611</td>
<td>0.7354</td>
<td>0.5759</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>No TM</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>250 Hz</td>
<td>Normal</td>
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<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.6115</td>
<td></td>
<td></td>
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<tr>
<td>$3 &lt; d \leq 4$</td>
<td>1.0</td>
<td>0.8353</td>
<td>0.8611</td>
<td>0.7354</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4 &lt; d \leq 7$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.8611</td>
<td>0.7354</td>
<td>0.5759</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No TM</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
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<td>Normal</td>
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<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
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</tr>
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<td>$1 &lt; d \leq 2$</td>
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<td>0.2338</td>
<td>0.4273</td>
<td>0.9630</td>
<td>0.2087</td>
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<td>0.6963</td>
<td>0.2346</td>
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<tr>
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<td></td>
<td></td>
<td></td>
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</tr>
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<td>1.0</td>
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</tr>
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<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
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</tr>
<tr>
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<td>0.0110</td>
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<td>0.0021</td>
<td>0.0008</td>
<td></td>
</tr>
<tr>
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<td>0.0663</td>
<td>0.0212</td>
<td>0.1134</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2 &lt; d \leq 3$</td>
<td>1.0</td>
<td>0.1611</td>
<td>0.5217</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$3 &lt; d \leq 4$</td>
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<td>0.0701</td>
<td>0.2820</td>
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</tr>
<tr>
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<td>0.4187</td>
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<td>0.0001</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
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<tr>
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<td>0.0000</td>
<td>0.0000</td>
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</tr>
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<td>0.0942</td>
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<td></td>
<td></td>
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<tr>
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<td>0.4732</td>
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</tbody>
</table>

Table 3.8: Computed probabilities ($p$) that test the null hypothesis that any two means of $|\Delta P_{win}/P_{TM}|$, plotted in Fig. 3.9, for different perforation diameters are from the same population. Values where $p \leq 0.05$ are underlined and bold. Perforation diameter d in mm.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>$0.1 \leq d \leq 1$</th>
<th>$1 &lt; d \leq 2$</th>
<th>$2 &lt; d \leq 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Posterior</td>
<td>0.6140</td>
<td>0.3261</td>
<td>0.2122</td>
</tr>
<tr>
<td>8 Anterior</td>
<td>0.7064</td>
<td>0.2701</td>
<td>0.3904</td>
</tr>
<tr>
<td>7 Posterior</td>
<td>0.2199</td>
<td>0.2254</td>
<td>0.9656</td>
</tr>
<tr>
<td>6 Posterior</td>
<td>0.7806</td>
<td>0.3581</td>
<td>0.8285</td>
</tr>
<tr>
<td>2 Anterior</td>
<td>0.2670</td>
<td>0.2547</td>
<td>0.6746</td>
</tr>
<tr>
<td>2000</td>
<td>0.9919</td>
<td>0.3805</td>
<td>0.6370</td>
</tr>
</tbody>
</table>

Table 3.9: Computed probabilities ($p$) that test the null hypothesis that the means of $\log|\Delta P_{win}/P_{TM}|$ for the two perforation locations anterior-inferior and posterior-inferior are from the same population; there are no values where $p \leq 0.05$. Diameter d in mm.
3.4 Discussion

3.4.1 Interpretation of results in terms of sound transmission via the acoustic route

Our measurements of the acoustic-route stimulus to the cochlea, namely $\Delta P_{\text{win}}/P_{TM}$, are limited by measurement errors below about 1000 Hz (chapter 3.3.4). Thus, below 1000 Hz, we have provided an upper limit for the acoustic-route stimulus. In fact, the stimulus could be below our estimate for both the perforated and the normal tympanic membrane conditions. Thus, we are unable to make definitive conclusions on the effects of perforation location or perforation size on the acoustic-route stimulus for frequencies below 1000 Hz. In this section, we use our calculations of $H_{PCAV}$ and $P_{RW}/POW$ to predict how $\Delta P_{\text{win}}/P_{TM}$ might be affected by perforations of different sizes and locations for frequencies above 1000 Hz, where our measurements are accurate and it appears that $\Delta P_{\text{win}}/P_{TM}$ may depend on perforation size but does not depend on perforation location.

As introduced above in chapter 3.1, the total drive to the acoustic route ($\Delta P_{\text{win}}/P_{TM}$) can be described in terms of the middle-ear cavity pressure ($H_{PCAV}$) and the ratio between the oval- and round-window pressures ($P_{RW}/POW$) (Equation 3.2). Thus, the behavior of $H_{PCAV}$ and $P_{RW}/POW$ should describe the behavior of $|\Delta P_{\text{win}}/P_{TM}|$. We note that here we choose to discuss $\Delta P_{\text{win}}/P_{TM}$ in terms of $P_{RW}/POW$ instead of $H_{WPD} = 1 - P_{RW}/POW$, due to the limits on calculation of $H_{WPD}$ that result from pressure-measurement errors.

Our measurements show that, within our measurement limits, $P_{RW}/POW$ is independent of (1) whether the tympanic membrane is normal or perforated, (2) the perforation size and, (3) the perforation location (chapter 3.3.3). In particular, our measurement-limits allow us to detect differences in this ratio that vary by factors of more than 0.06 in magnitude and 0.01 cycles in angle; thus, if $P_{RW}/POW$ does depend on any of these three factors, the effects are small. Thus, we conclude that the ratio between the pressures at the oval and round windows are not affected by tympanic-membrane perforations. As a result, perforation-induced changes in $|\Delta P_{\text{win}}/P_{TM}|$ must be independent of $H_{WPD}$ and must result solely from perforation-induced changes in $H_{PCAV}$.

If perforation-induced changes in $|\Delta P_{\text{win}}/P_{TM}|$ are a direct result from perforation-induced changes in $H_{PCAV}$, then we can examine the behavior of $H_{PCAV}$ to predict how perforations affect $|\Delta P_{\text{win}}/P_{TM}|$. Note, we emphasize that the changes with perforations should be similar between $|\Delta P_{\text{win}}/P_{TM}|$ and $H_{PCAV}$, but not the absolute behavior; $|H_{PCAV}|$ is always multiplied by the frequency-dependent constant $|H_{WPD}|$ to obtain $|\Delta P_{\text{win}}/P_{TM}|$. Thus, we conclude that perforations result in the following changes in $|\Delta P_{\text{win}}/P_{TM}|$: (1) at the lowest frequencies, a perforation of any size should increase $|\Delta P_{\text{win}}/P_{TM}|$ (just as $|H_{PCAV}|$ is increased) by a constant amount of about 10 to 20 dB; (2) as the perforation...
size increases, the low-frequency region over which $|\Delta P_{win}/P_{TM}|$ shows a constant increase should extend to higher and higher frequencies; and (3) both the frequency and the sharpness of the first local maxima should increase with increasing perforation size. Thus, even though we can't measure the absolute level of $|\Delta P_{win}/P_{TM}|$ with a tympanic-membrane perforation, we do have evidence that $|\Delta P_{win}/P_{TM}|$ increases with perforations.

For frequencies below 1000 Hz, we do not know the frequency dependence of $|\Delta P_{win}/P_{TM}|$ because we are only able to place an upper bound on the transfer function $|H_{WPD}|$. However, for some of our $|\Delta P_{win}/P_{TM}|$ measurements, the changes described in the preceding paragraph that are based on changes in $|H_{PCAV}|$ are apparent. For example, the measurements of $|\Delta P_{win}/P_{TM}|$ on bone 13 (Fig. J-1) indicate that with a perforated tympanic membrane, $|\Delta P_{win}/P_{TM}|$ reaches a local maximum that increases in frequency as perforation diameter increases. In general, such behavior is more difficult to detect in the $|\Delta P_{win}/P_{TM}|$ measurements than in the $|H_{PCAV}|$ measurements, but the trend is apparent in several of the individual $|\Delta P_{win}/P_{TM}|$ measurements of Appendix J. It seems possible that the preparations where this trend is most apparent correspond to preparations where the measurement errors in $P_{OW}$ and $P_{RW}$ were the smallest.

In summary, we conclude that sound transmission via the acoustic route is independent of perforation location because $P_{RW}/P_{OW}$ and $H_{PCAV}$ appear independent of perforation location, and sound transmission via the acoustic route is dependent on perforation size because $H_{PCAV}$ depends on perforation size. Additionally, these characteristics of sound transmission via the acoustic route are a direct result of changes in the middle-ear cavity pressure per pressure at the tympanic membrane, measured here as $H_{PCAV}$, and are unrelated changes in the relative magnitude and phase angle of the oval- and round-window sound pressures. In fact, $P_{RW}/P_{OW}$ appears independent of (1) whether the tympanic membrane is normal or perforated, (2) the perforation size and, (3) the perforation location. In other words, the relative magnitudes and angles of the pressures just outside the oval and round windows are unaffected by any tympanic-membrane perforation. This result (1) refutes the classic view described above in chapter 3.1 where the perforation location is said to affect the relative phase of the oval and round windows, and (2) provides the first description of the window pressure ratio $P_{RW}/P_{OW}$ that is based on experimental data.

### 3.4.2 When is the acoustic route important for hearing with tympanic-membrane perforations?

As discussed above in chapter 3.1, when the ear is normal, the ossicular route is the dominant mechanism for sound transmission to the cochlea, and transmission via the acoustic route is negligible. The measurements presented in this chapter suggest that sound transmission via the acoustic route increases when the tympanic membrane is perforated. Here, we use these measurements to determine whether or not the acoustic route becomes a significant
route of sound transmission with perforations.

In chapter 2 we presented measurements of the middle-ear transfer function $\frac{V_s}{P_{TM}}$ (stapes velocity per pressure at the tympanic membrane) made with both normal and perforated tympanic membranes. $\frac{V_s}{P_{TM}}$ measures the total transmission to the stapes; thus, $\frac{V_s}{P_{TM}} = \frac{V_{\text{total}}}{P_{TM}}$, where $\frac{V_{\text{total}}}{P_{TM}}$ includes transmission via both the ossicular and acoustic routes.

$$\frac{V_s}{P_{TM}} = \frac{V_{\text{acoustic}}}{P_{TM}} + \frac{V_{\text{ossicular}}}{P_{TM}}$$  (3.7)

In this section, we use our measurements of the window-pressure difference per pressure at the tympanic membrane, $|\Delta P_{\text{win}}/P_{TM}|$, to establish an upper bound for the acoustic-route transmission $|\frac{V_{\text{acoustic}}}{P_{TM}}|$. We then compare this upper bound for $|\frac{V_{\text{acoustic}}}{P_{TM}}|$ with our measurements of $|\frac{V_{\text{total}}}{P_{TM}}|$ (chapter 2) in order to determine the importance of $|\frac{V_{\text{acoustic}}}{P_{TM}}|$ on the total transmission.

3.4.2.1 Prediction of $\frac{V_{\text{acoustic}}}{P_{TM}}$ from the window-pressure difference

The stapes velocity per pressure at the tympanic membrane that results from the pressure difference at the oval and round windows, $\frac{V_{\text{acoustic}}}{P_{TM}}$, can be approximated from three quantities: the pressure measurements at the oval and round windows, the stapes-cochlear acoustic impedance ($Z_{SC}$), and the area of the stapes footplate, ($A_s$).

$$\frac{V_{\text{acoustic}}}{P_{TM}} = \frac{P_{OW} - P_{RW}}{P_{TM}Z_{SC}A_s}$$  (3.8)

Here we use the average $Z_{SC}$ reported by Merchant et al. (1996) and the average $A_s = 3.2 \text{mm}^2$ reported by Weyer and Lawrence (1954).

Note, Equation 3.8 assumes that the stapes-cochlear acoustic impedance is the only impedance that the pressure difference $P_{OW} - P_{RW}$ acts upon in order to stimulate the cochlea. In an ear without an intact ossicular system, Equation 3.8 would be correct. However, here the ossicular system is attached at the stapes to the oval window. Thus, the window-pressure difference drives both $Z_{SC}$ and the ossicular system working in reverse from the stapes, through the incus, malleus and tympanic membrane; we refer to this latter impedance as $Z_{ME}^{reverse}$. Thus, this reverse impedance $Z_{ME}^{reverse}$ may also affect the sound transmission via the acoustic route. In particular, to correct Equation 3.8 to include the attached ossicular chain, the $Z_{SC}$ should be replaced by $Z_{SC} + Z_{ME}^{reverse}$. Analysis of unpublished calculations of $Z_{ME}^{reverse}$ from Rosowski, Merchant, and Davis (1990b) (Fig. 3-10) shows that $|Z_{ME}^{reverse}|$, is about 10 dB lower than the $|Z_{SC}|$ of Merchant et al. (1996), at least up to about 1000 Hz. Between 1000 and 2000 Hz, $|Z_{ME}^{reverse}|$ approaches $|Z_{SC}|$ and then appears to return to about 10 dB below $|Z_{SC}|$. Thus, our approximation of $\frac{V_{\text{acoustic}}}{P_{TM}}$ (Equation 3.8) may be inaccurate just above 1000 Hz, and possibly above 2000 Hz, where we do not have a way to compare $Z_{SC}$ to $Z_{ME}^{reverse}$. However, since we have few data for
\(Z_{\text{ME}}^{\text{reverse}}\), we ignore \(Z_{\text{ME}}^{\text{reverse}}\) in our calculation of \(\frac{V_{\text{acoustic}}}{P_{TM}}\), and we observe that since the angles of \(Z_{\text{ME}}^{\text{reverse}}\) and \(Z_{SC}\) do not appear to be of opposite signs, the effect of ignoring \(Z_{\text{ME}}^{\text{reverse}}\) probably only increases our estimate of \(\frac{V_{\text{acoustic}}}{P_{TM}}\), which is consistent with our goal of setting an upper-limit on \(\frac{V_{\text{acoustic}}}{P_{TM}}\).

3.4.2.2 Comparison of \(\frac{V_{\text{acoustic}}}{P_{TM}}\) to \(\frac{V_{\text{total}}}{P_{TM}}\)

Fig. 3-11 plots our upper bounds for middle-ear sound transmission via the acoustic route, \(\frac{V_{\text{acoustic}}}{P_{TM}}\) (Equation 3.8) with both a normal tympanic membrane and the tympanic membrane removed. Also plotted on Fig. 3-11 is the mean total middle-ear sound transmission \(\frac{V_{\text{total}}}{P_{TM}}\) from chapter 2. Comparison between the total transmission and the transmission via the acoustic route allows us to determine the relative importance of the acoustic route in sound transmission to the cochlea under different conditions.

According to Fig. 3-11, with a normal tympanic membrane, the total stapes velocity is 50 to 70 dB greater than the upper bound on the acoustic-route stapes velocity for frequencies up to 2000 Hz, and above 2000 Hz, the difference is at least 40 dB. Thus, when the tympanic membrane and ossicular chain are normal, transmission via the acoustic route is negligible.

When the tympanic membrane is removed\(^3\), the upper-bound on transmission via the acoustic route \(\frac{V_{\text{acoustic}}}{P_{TM}}\) increases (Fig. 3-11), and at the same time the total transmission \(\frac{V_{\text{total}}}{P_{TM}}\) decreases. If the decrease in \(\frac{V_{\text{total}}}{P_{TM}}\) is substantial, the acoustic-route transmission could make significant contributions to the total transmission and thus provide an upper limit for total loss. This upper limit is equivalent to the ratio between total sound transmission in the normal condition (\(\frac{V_{\text{total}}}{P_{TM}}\) with a normal tympanic membrane) and the upper-bound on the acoustic-route sound transmission in the tympanic-membrane removed condition (\(\frac{V_{\text{acoustic}}}{P_{TM}}\) with the tympanic membrane removed). Our estimate for this upper limit for loss with tympanic-membrane perforations is plotted in the lower part of Fig. 3-11: the limit is between 40 and 60 dB at frequencies up to 2000 Hz, and from 2000 to 4000 Hz, the acoustic-route limit is between 30 and 40 dB.

Fig. 3-12 compares the total transmission loss that we measured with different sized tympanic-membrane perforations (chapter 2) to our estimated upper limit for transmission loss that is determined by the acoustic route. Here we see that our measured losses are well above the limit set by the acoustic route, indicating that the ossicular route dominates our stapes-velocity measurements, even with perforations. However, this upper-limit does suggest that the acoustic route may limit the total loss at the lowest frequencies, especially for the larger perforations.

---

\(^3\)This tympanic-membrane-removed condition is similar to the condition of tympanic-membrane perforations in that the pressure difference between the oval and round windows is similar for both the tympanic-membrane-removed condition and most perforation sizes (Fig. 3-9).
Figure 3-10: Comparison between the impedances of the stapes and cochlea ($Z_{SC}$) and the ossicular chain in reverse, $Z_{ME}^{reverse}$. $Z_{SC}$ comes from measurements of Merchant et al. (1996) (Figure 5), and $Z_{ME}^{reverse}$ comes from unpublished data of Rosowski, Merchant, and Davis (1990b). $Z_{ME}^{reverse}$ was computed from ear-canal impedance measurements made on human temporal bones. In particular, impedance measurements with the middle-ear in different states were made (i.e., normal, stapes fixed, incudo-stapedial joint severed). From these impedance measurements, a two-port network was defined, and $Z_{ME}^{reverse}$ was computed from the two-port network characteristics, where the two-port network was terminated by the $Z_{SC}$ measured by Merchant et al. (1996). TOP: Magnitude. BOTTOM: Angle.
Figure 3-11: TOP: Comparison of the total stapes velocity $|V_S^{total}/P_{TM}|$ to the upper-bound for the acoustic-route stapes velocity $|V_S^{acoustic}/P_{TM}|$. $|V_S^{total}/P_{TM}|$ was measured with the laser-doppler system on bones with a normal tympanic membrane. The mean ± standard error, associated with 21 bones, comes from Fig. 1-10. The mean of N=6 normal bones is the mean from the 6 bones used to measure the acoustic-route stapes velocity with the tympanic membrane removed. $|V_S^{acoustic}/P_{TM}|$ is calculated from Equation 3.8 for the normal and the tympanic-membrane removed conditions. The standard error accounts for variation in both (1) the $\Delta P_{win}/P_{TM}$ measurements made here and (2) the $Z_{SC}$ measurements made by Merchant et al. (1996). BOTTOM: The ratio between $|V_S^{total}/P_{TM}|$ with a normal tympanic membrane and the upper limits for (1) $|V_S^{acoustic}/P_{TM}|$ with a normal tympanic membrane and (2) $|V_S^{acoustic}/P_{TM}|$ with the tympanic membrane removed.
Fig. 3-12 also plots the mean audiogram measured by Békésy (1936) on five ears missing the tympanic membrane, malleus, incus, and stapes. In these ears, it seems that the acoustic route could be responsible for hearing. Thus, the similarity between this audiogram and our upper limit on hearing loss imposed by the acoustic route are consistent with one another.

Figure 3-12: Comparison between our measured loss in total transmission (chapter 2) to our estimated upper-limit for transmission loss that results from the acoustic route. Also plotted is the mean audiogram collected by Békésy (1936; 1960 p. 105) on five ears missing the tympanic membrane, malleus, incus or stapes. The presumed path for sound transmission in these ears is the acoustic route.
Chapter 4

Acoustic models for the middle-ear with a tympanic-membrane perforation

4.1 Model configuration

In this chapter, we develop a lumped-element model to describe sound transmission in ears with tympanic-membrane perforations. A model of the middle-ear with a tympanic-membrane perforation is useful for several reasons. For example, such a model can help us understand the hearing loss associated with different sized tympanic-membrane perforations, and such an understanding may aid in the diagnosis of other middle-ear pathologies without requiring exploratory surgery. Additionally, a model tests current normal middle-ear models and leads to an improved understanding of sound transmission through the middle ear in general.

Our model is motivated by the experimental results of chapters 2 and 3, the model-element values are based on experimental data whenever possible, and the model predictions are compared with data presented in chapter 2. The model makes predictions of sound transmission loss with tympanic-membrane perforations, with perforation diameter as a parameter. Thus, it is possible to use our model to predict the expected hearing loss with a given tympanic-membrane perforation.

As described in the Introduction to this thesis (page 13 and Fig.I-2), sound can reach the cochlea via two distinct routes that we call the “acoustic route” and the “ossicular route” (Békésy 1947; Schmitt 1958; Peake et al. 1992; Merchant et al. 1997a). Briefly, the acoustic route refers to the cochlea's response to the pressure difference outside the oval and round windows, and the ossicular route refers to the transmission of sound via the ossicular chain. The ossicular route includes two mechanisms, as described in detail in chapter 2: (1) the
drive to the tympanic membrane, expressed quantitatively as the normalized pressure difference across the tympanic membrane $H_{\Delta PM}$ and (2) the coupling of the tympanic membrane to the cochlea through the ossicular system, described quantitatively as the stapes velocity per pressure difference across the tympanic membrane $H_{TOC}$. The results of chapter 3 show that the acoustic route of sound transmission is negligible for many tympanic-membrane perforations; the acoustic route becomes important only when losses approach 40 to 60 dB, but for most perforations the losses are much less than 50 dB (Fig. 3-12). Thus, in order to simplify the description of sound transmission with tympanic-membrane perforations, our model of sound transmission with tympanic-membrane perforations focuses on the ossicular route of sound transmission. However, hearing loss predicted with this simplified model is always limited by the acoustic route, which has an upper bound of 40 to 60 dB re normal; see Fig. 3-12 for our estimate of an upper-bound for sound transmission via the acoustic-route with tympanic-membrane perforations.

### 4.1.1 3-block model

Our model is based on the lumped-element model of the middle ear shown in Fig. 4-1. This “series” middle-ear model is similar to the models of Onchi (1961), Zwislocki (1962) and Kringlebotn (1988) in that the middle-ear cavity impedance $\hat{Z}_{CAV}$ is in series with $\hat{Z}_{TOC}$, which represents the impedance of the tympanic membrane, ossicles, and cochlea. For the normal ear, (Fig. 4-1A), the middle-ear cavity impedance $\hat{Z}_{CAV}$ terminates $\hat{Z}_{norm}^{TOC}$. For the perforated tympanic membrane situation, the impedance $\hat{Z}_{PERF}$ is in parallel with the impedance $\hat{Z}_{TOC}^{perf}$ (Fig. 4-1B). In this perforated case, some of the total volume velocity that flows through $\hat{Z}_{TOC}$ with a normal tympanic membrane now flows through $\hat{Z}_{PERF}$ directly to $\hat{Z}_{CAV}$. As a result, the stapes volume velocity ($\hat{\nu}_S$), and thus stapes velocity ($\hat{V}_S$) changes with a tympanic-membrane perforation.

Many of our model parameters can be determined from measurements. In order to distinguish between model parameters and measurements, we assign a “hat” to the model variables. For example, we refer to the measured pressure at the tympanic membrane as $P_{TM}$ and the model’s pressure at the tympanic membrane as $\hat{P}_{TM}$. Our model includes analogies for both stages of ossicular-route sound transmission that were discussed in chapter 2: the drive to the tympanic membrane $H_{\Delta TM}$ and the coupling of sound from the tympanic membrane to the cochlea $H_{TOC}$. First, in the model of Fig. 4-1, the drive to the tympanic membrane can be represented in terms of the model impedances.

\[
\hat{H}_{\Delta TM} = \frac{\hat{P}_{TM} - \hat{P}_{CAV}}{\hat{P}_{TM}} = \frac{\hat{Z}_{TOC} \| \hat{Z}_{PERF}}{\hat{Z}_{TOC} \| \hat{Z}_{PERF} + \hat{Z}_{CAV}} = \frac{1}{1 + \frac{\hat{Z}_{CAV}(\hat{Z}_{TOC} + \hat{Z}_{PERF})}{\hat{Z}_{TOC}\hat{Z}_{PERF}}} \tag{4.1}
\]
Figure 4-1: A: Lumped element model of the middle ear with a normal tympanic membrane. B: Lumped element model of the middle ear with a perforated tympanic membrane. In both A and B, $\hat{Z}_{TOC}$ represents the impedance of the tympanic membrane - ossicular chain - cochlear system, and $\hat{Z}_{CAV}$ represents the impedance of the middle-ear cavity. In B, $\hat{Z}_{PERF}$ represents the impedance of the perforation in the tympanic membrane.
Second, the coupling of sound from the tympanic membrane to the cochlea, where $\hat{H}_{TOC}$, is the stapes velocity per pressure difference across the tympanic membrane and is represented in Fig. 4-1 by the lumped element $\hat{Z}_{TOC}$.

$$\hat{H}_{TOC} = \frac{\dot{V}_s}{P_{TM} - \dot{P}_{CAV}} = \frac{1}{\hat{Z}_{TOC}} \quad (4.2)$$

We note that the model topology of Fig. 4-1 is a simplification of the model topology suggested in chapter 2.4.2 Fig. 2-26. Here, we simplify the two-port network of Fig. 2-26 to the one-port lumped element $\hat{Z}_{TOC}$. Our “simple” three block model of Fig. 4-1 is equivalent to the assumption that $\hat{\alpha}$ is unaffected by perforations.

4.1.2 Strategy

Our modeling approach has several steps. First, we determine impedance values for the boxes of Fig. 4-1A and Fig. 4-1B. We use measurements made on our temporal-bone preparation whenever possible (chapter 2); specifically we have measurements that correspond to $\hat{Z}^{\text{norm}}_{TM}$, $\hat{Z}^{\text{perf}}_{TM}$, and $\hat{Z}_{CAV}$, and we estimate $\hat{Z}^{\text{norm}}_{TOC}$ from our measurements. We do not have measurements that can be used to estimate $\hat{Z}^{\text{perf}}_{PERF}$ or $\hat{Z}^{\text{perf}}_{TOC}$; we develop an acoustic model to represent $\hat{Z}_{PERF}$, and we argue that $\hat{Z}^{\text{perf}}_{TOC}$ can be approximated by the $\hat{Z}^{\text{norm}}_{TOC}$ derived from our measurements. Second, we compare the model’s predictions to data collected on our temporal-bone preparation. Specifically, we compare three quantities: input impedance at the tympanic membrane, pressure difference across the tympanic membrane, and transmission loss. To examine how the parameter middle-ear cavity volume affects sound transmission, we develop a middle-ear cavity model that allows us to predict $\hat{Z}_{CAV}$ with a variable mastoid-cavity volume, and we use this middle-ear cavity model to predict how the mastoid-cavity volume affects sound transmission. Finally, we simplify our perforated middle-ear model and provide a simple algebraic equation that predicts transmission loss with tympanic-membrane perforations as a function of perforation diameter, frequency, and middle-ear cavity volume; the simplified equation is valid for frequencies below 1000 Hz.

4.2 Choice of model components

4.2.1 Components from measurements

In chapter 2.3.5, we discussed measurements of the impedance $Z_{TM}$ made at the tympanic membrane on 10 human temporal-bone preparations with both normal ($Z^{\text{norm}}_{TM}$) and perforated ($Z^{\text{perf}}_{TM}$) tympanic membranes (Appendix F, page 235). Here, we use these measurements to determine some of the parameters for the model of Fig. 4-1.
4.2.1.1 Impedances with a normal tympanic membrane: \( \tilde{Z}_{\text{TM}}^{\text{norm}}, \tilde{Z}_{\text{TOC}}^{\text{norm}}, \) and \( \tilde{Z}_{\text{CAV}} \)

We use measurements made on our preparation for the model parameters \( \tilde{Z}_{\text{TM}}^{\text{norm}} \) and \( \tilde{Z}_{\text{CAV}} \), and we calculate \( \tilde{Z}_{\text{TOC}}^{\text{norm}} \) from these measurements. According to our model with a normal tympanic membrane (Fig. 4-1A),

\[
\tilde{Z}_{\text{TM}}^{\text{norm}} = \tilde{Z}_{\text{TOC}}^{\text{norm}} + \tilde{Z}_{\text{CAV}}.
\]  

(4.3)

At the end of each experiment presented in chapter 2.3.5, we removed the entire tympanic membrane and repeated the impedance measurement at the tympanic-membrane location. (The ossicles were left intact). This measurement with the tympanic membrane removed serves as our measurement of \( Z_{\text{CAV}} \) and our model value \( \tilde{Z}_{\text{CAV}} \). Since we have measurements for both \( \tilde{Z}_{\text{TM}}^{\text{norm}} \) and \( \tilde{Z}_{\text{CAV}} \), we are able to compute \( \tilde{Z}_{\text{TOC}}^{\text{norm}} \) from Equation 4.3 as

\[
\tilde{Z}_{\text{TOC}}^{\text{norm}} = \tilde{Z}_{\text{TM}}^{\text{norm}} - \tilde{Z}_{\text{CAV}}.
\]  

(4.4)

Fig. 4-2 shows our \( \tilde{Z}_{\text{TM}}^{\text{norm}} \) and \( \tilde{Z}_{\text{CAV}} \) (from measurements) and calculations of \( \tilde{Z}_{\text{TOC}}^{\text{norm}} \) made on each of the ten temporal-bone preparations. At frequencies below 2000 Hz, it is clear that with a normal tympanic membrane, \( |\tilde{Z}_{\text{TM}}^{\text{norm}}| \gg |\tilde{Z}_{\text{CAV}}| \), and thus \( |\tilde{Z}_{\text{TOC}}^{\text{norm}}| \approx |\tilde{Z}_{\text{TOC}}^{\text{norm}}| \). Even above 2000 Hz, \( |\tilde{Z}_{\text{TM}}^{\text{norm}}| \) and \( |\tilde{Z}_{\text{TOC}}^{\text{norm}}| \) are very similar, because the same inequality holds for most frequencies. Thus, in general, \( |\tilde{Z}_{\text{TOC}}^{\text{norm}}| \gg |\tilde{Z}_{\text{CAV}}| \).

4.2.1.2 Impedances with a perforated tympanic membrane: \( \tilde{Z}_{\text{TM}}^{\text{perf}}, \tilde{Z}_{\text{PERF}}, \tilde{Z}_{\text{TOC}}^{\text{perf}}, \) and \( \tilde{Z}_{\text{CAV}} \)

We use measurements made on our human temporal-bone preparation for the model parameters \( \tilde{Z}_{\text{TM}}^{\text{perf}} \) and \( \tilde{Z}_{\text{CAV}} \). In this section we develop our description for the impedances \( \tilde{Z}_{\text{PERF}} \) and \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \), as we do not have measurements of these two quantities. First, we present an acoustic model of \( \tilde{Z}_{\text{PERF}} \) from theory (chapter 4.2.2). With a model for \( \tilde{Z}_{\text{PERF}} \) from theory, we can compute \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \) from the model of Fig. 4-1B and the components \( \tilde{Z}_{\text{TM}}^{\text{perf}}, \tilde{Z}_{\text{CAV}}, \) and \( \tilde{Z}_{\text{PERF}} \) as:

\[
\tilde{Z}_{\text{TOC}}^{\text{perf}} = \frac{\tilde{Z}_{\text{PERF}}(\tilde{Z}_{\text{TM}}^{\text{perf}} - \tilde{Z}_{\text{CAV}})}{\tilde{Z}_{\text{PERF}} + \tilde{Z}_{\text{CAV}} - \tilde{Z}_{\text{TM}}^{\text{perf}}}. 
\]  

(4.5)

However, the calculation of \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \) depends on the difference \( \tilde{Z}_{\text{TM}}^{\text{perf}} - \tilde{Z}_{\text{CAV}} \), and our measurements show that in most cases, \( \tilde{Z}_{\text{TM}}^{\text{perf}} \approx \tilde{Z}_{\text{CAV}} \). Thus, small errors in the measurements of \( Z_{\text{TM}}^{\text{perf}} \) and \( Z_{\text{CAV}} \) have large effects on the calculation of \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \) from Equation 4.5, and these errors make it difficult for us to compute \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \), especially at the lower frequencies where \( Z_{\text{TM}}^{\text{perf}} \) and \( Z_{\text{CAV}} \) are nearly indistinguishable. Thus, instead of computing \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \) from Equation 4.5, we approximate \( \tilde{Z}_{\text{TOC}}^{\text{perf}} \) by (our measurement) \( Z_{\text{TOC}}^{\text{norm}} \). In chapter 2.3.4, we showed experimentally that, in most of our measurements, the transfer function between stapes
Figure 4-2: Impedances from ten temporal-bone preparations. Symbols indicate every 20th data point. LEFT: Impedance measured at the normal tympanic membrane, $Z_{TM}^{\text{norm}}$. MIDDLE: Impedance measured with the tympanic membrane removed $Z_{CAV}$. RIGHT: Impedance $Z_{TOC}^{\text{norm}}$ calculated from measurements as $Z_{TOC}^{\text{norm}} = Z_{TM}^{\text{norm}} - Z_{CAV}$. TOP: Magnitude BOTTOM: Angle.
velocity and pressure difference across the tympanic membrane \( H_{TOC} = \frac{V_s}{P_{TM} - P_{CAV}} \) does not change dramatically with tympanic-membrane perforations. Specifically, Fig.2-21 shows the mean changes across eight of our temporal-bone preparations for different tympanic-membrane perforation diameters. The mean changes in \( |H_{TOC}| = \left| \frac{V_s}{P_{TM} - P_{CAV}} \right| = \left| \frac{1}{Z_{TOC}} \right| \) are less than 5 dB at all frequencies for perforations smaller than 3mm in diameter, and changes for larger perforations are rarely greater than 5 dB, although we lack data below about 800 to 1000 Hz for perforations greater than 3 mm in diameter.

4.2.2 Acoustic model of tympanic-membrane perforations

4.2.2.1 Development of a one-port model for a perforation

Our lumped-element model of the middle ear with a tympanic-membrane perforation (Fig. 4-1) requires a model for the impedance of the perforation. Here we propose a mathematical formulation for this one-port lumped-element component. We view the perforation as a short, narrow tube where the length of the tube is the thickness of the tympanic membrane and the radius of the tube is the radius of the tympanic-membrane perforation. We note that this model differs from the physical situation of a tympanic-membrane perforation. Ideally, our model would represent a hole in a thin membrane. However, we were unable to determine the theoretical impedance of such a hole in a membrane for the combination of perforation sizes and frequencies of interest. Thus, as a simplifying assumption, we assume the perforation can be represented as a short tube with length equivalent to tympanic-membrane thickness.

An acoustic mass is the classic model for uniform-plane-wave flow of air through a tube open at both ends where the tube dimensions are much smaller than the wavelengths of interest (Kinsler et al. 1982; Beranek 1986). However, the situation of a tympanic-membrane perforation does not fit this classic model. Most importantly, the diameters of tympanic-membrane perforations are small enough that the viscous losses at the edges of the perforation are not negligible (see Beranek 1986; pp. 131-138). Thus, our lumped-element model of the tympanic-membrane perforation must be a mixed resistance-mass element. Egolf (1977, p. 201) refers to acoustic tubes with such narrow diameters as “capillary tubes”, and he points out that “unfortunately, exact equations for sound transmission through capillary tubes over the entire audio frequency range are not included in many of the more conventional textbooks on acoustics” (e.g., Kinsler, Frey, Coppens, and Sanders (1982) and Morse and Ingard (1968)). In formulating our model of the tympanic-membrane perforation we have had a similar experience in having difficulty finding descriptions of the equations that describe sound flow through a capillary tube.

Fortunately, Egolf (1977) provides equations that describe sound flow through a capillary tube. He ascribes their original derivation to Iberall (1950), who developed equations that
describe transient fluid flow in pipes. Egolf (1977) adapts the equations from Iberall (1950) for sound flow. The equations of Egolf (1977) are in the form of the following two-port description.

\[
\begin{bmatrix}
P_{PERF} \\
U_{PERF}
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
P_{CAV} \\
U_{CAV}
\end{bmatrix}
\]

(4.6)

where

\[
A = \cosh \Gamma l_{PERF},
\]

\[
B = Z \sinh \Gamma l_{PERF},
\]

\[
C = Z^{-1} \sinh \Gamma l_{PERF},
\]

\[
D = \cosh \Gamma l_{PERF}.
\]

(4.7)

For our case, \(P_{PERF}\) (equivalent to \(P_{BC}\)) and \(U_{PERF}\) are the pressure and volume velocity at the tympanic-membrane perforation, \(P_{CAV}\) and \(U_{CAV}\) are the pressure and volume velocity in the middle-ear cavity, and \(l_{PERF}\) is the length of the perforation (i.e., thickness of the tympanic membrane). Additionally,

\[
\Gamma = \frac{j \omega}{c} \left( \frac{1 + 2(\gamma - 1) \frac{J_1(\alpha r_{PERF})}{\alpha r_{PERF} J_0(\alpha r_{PERF})}}{1 - \frac{2J_1(\beta r_{PERF})}{\beta r_{PERF} J_0(\beta r_{PERF})}} \right)^{1/2}
\]

(4.8)

and

\[
Z = \frac{\rho c}{\pi r_{PERF}^2} \left\{ \left[ 1 - \frac{2J_1(\beta r_{PERF})}{\beta r_{PERF} J_0(\beta r_{PERF})} \right] \left[ 1 + 2(\gamma - 1) \frac{J_1(\alpha r_{PERF})}{\alpha r_{PERF} J_0(\alpha r_{PERF})} \right] \right\}^{-1/2}
\]

(4.9)

where

\[
f = \text{frequency (Hz)}
\]

\[
\omega = 2\pi f
\]

\[
\alpha = (-j\omega\rho\sigma/\mu)^{1/2}
\]

\[
\beta = (-j\omega\rho/\mu)^{1/2}
\]

\[
c = \text{sound propagation velocity in air} = 345 \text{ (m/s)}
\]

\[
\gamma = \text{ratio of specific heats of air} = 1.41 \text{ (dimensionless)}
\]

\[
r_{PERF} = \text{radius of perforation (m) = diameter/2}
\]

\[
\rho = \text{density of air} = 1.18 \text{ (kg/m}^3)\]

\[
\sigma = \text{prandtl number of air} = 0.706 \text{ (dimensionless)}
\]

\[
\mu = \text{absolute viscosity of air} = 1.82 \times 10^{-5} \text{ kg/(sec m)}
\]

\[
J_0 = \text{Bessel function of the first kind of order zero}
\]
with a complex argument (dimensionless)

\[ J_1 = \text{Bessel function of the first kind of order one} \]

with a complex argument (dimensionless)

The model formulated by Equations 4.6, 4.7, 4.8, and 4.9 is a two-port network model of a tympanic-membrane perforation. We simplify the model to a one-port lumped element by computing the input impedance \( P_{\text{PERF}}/U_{\text{PERF}} \) with the two-port network terminated by an impedance of zero. The terminating impedance of zero is not exactly correct because the perforation is really terminated by a radiation impedance. However, the radiation impedance is small and acts to increase the effective length (i.e., thickness) of the perforation (Beranek 1986; p.131); the use of an end correction (discussed below with Equation 4.12) will account for the radiation impedance.

In summary, our acoustic model of the perforation is

\[ \hat{Z}_{\text{PERF}} = \frac{P_{\text{PERF}}}{U_{\text{PERF}}} = \frac{B}{D} = Z \tanh \Gamma l_{\text{PERF}} \]  \hspace{1cm} (4.10)

where \( P_{\text{PERF}}, U_{\text{PERF}}, \) and several other relevant quantities are defined by Equations 4.6, 4.7, 4.8, 4.9, and 4.12. Fig. 4-3 shows the model prediction for the perforation impedance, with perforation diameter as the parameter. At the lower frequencies, the impedance for the smaller perforations has both a resistive and a massive component. As the perforation size increases, the low-frequency impedance also becomes more and more mass dominated. At higher frequencies, the perforation impedance becomes mass dominated. In the next paragraph, we provide a simpler set of equations to describe the mass and resistance of \( \hat{Z}_{\text{PERF}} \), but our simplification is accurate for limited frequencies and perforation sizes.

**4.2.2.1.1 \( \hat{Z}_{\text{PERF}} \) can be represented by a mass element for some perforation sizes at some frequencies.**

The equations that describe \( \hat{Z}_{\text{PERF}} \) are complicated and \( \hat{Z}_{\text{PERF}} \) is most easily determined numerically. However, \( \hat{Z}_{\text{PERF}} \) can be approximated by a mass over some of the frequency and perforation-diameter range of interest by

\[ \hat{Z}_{\text{PERF}}^{\text{mass}} = j\omega \frac{\rho l_{\text{PERF}}}{2 \pi \gamma_{\text{PERF}}} \]  \hspace{1cm} (4.11)

where the variables are defined above and \( l_{\text{PERF}} \) is defined below in Equation 4.12.

Fig. 4-4 compares the model from Egolf (1977) to the pure-mass perforation model from on Equation 4.11. Fig. 4-4 provides a visual impression of when \( \hat{Z}_{\text{PERF}} \) is mass-dominated and also when the resistive component of \( \hat{Z}_{\text{PERF}} \) provided by Equation 4.10 is important. In general, the full model of Egolf (Equation 4.10) is needed for smaller perforations at the lowest frequencies, while the mass-dominated model of Equation 4.11 seems adequate when the perforation diameter exceeds about 1 mm.

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Figure 4-3: Model predictions of $\tilde{Z}_{PERF}$ from Equation 4.10 for the impedance of a tympanic-membrane perforation. The parameter $d$ is perforation diameter.
Figure 4.4: Comparison between the perturbation impedance of our model $Z_{per}$ (Equation 4.10) to a perturbation model that is a mass-only element.
4.2.2.1.2 Model assumptions

The derivations of Equations 4.8 and 4.9 require many assumptions (see Egolf, 1977; p. 202). Our model formulation does not meet one of Egolf's (1977) assumptions. In particular, the length of our tube (tympanic-membrane thickness) is not large compared to the perforation diameter, and as a result we are unable to ignore the effect of the radiation impedance that terminates the "tube". (The tympanic-membrane thickness is less than 0.1 mm (Lim 1970), and the perforation diameters of interest are 0.1 mm to 5.0 mm). However, it is possible to use an "end correction" to account for the radiation impedance that terminates the perforations. The end correction adds an effective length to the physical length of the tube. In our case the appropriate end correction is $l'_{\text{PERF}}$:

$$l'_{\text{PERF}} = 2(0.85) r_{\text{PERF}}$$  \hspace{0.5cm} (4.12)

where $r_{\text{PERF}}$ is the radius of the tympanic-membrane perforation (Beranek 1986; p.132). Since the actual tympanic-membrane thickness is much less than the end correction for all perforations we consider, the length we use for our model of the perforation is simply the end correction $l'_{\text{PERF}}$.

A second assumption inherent in our model for $Z_{\text{PERF}}$ involves the relative particle velocities of the tympanic membrane and the air through the perforation. Our model is a model of a "capillary tube" through a stationary baffle, when in fact the tympanic membrane is a membrane that vibrates. Here, we estimate two relevant velocities: (1) the tympanic-membrane velocity $V_{TM}$ and (2) the particle velocity of air flowing through the perforation $V_{\text{PERF}}$. We argue that in regions where $|V_{\text{PERF}}| \gg |V_{TM}|$, the perforation model with a stationary baffle approximates the situation where the baffle is a membrane that vibrates.

We estimate the tympanic-membrane velocity from the ear-canal pressure measurement and the impedance measurement as

$$V_{TM} = \frac{P_{TM}}{Z_{TM} A_{TM}}$$  \hspace{0.5cm} (4.13)

where $A_{TM}$ is the tympanic-membrane area; our calculations assume $A_{TM} = 70 \text{ mm}^2$. We calculate $V_{\text{PERF}}$ from our measurements of ear-canal pressure, middle-ear cavity pressure, and our estimate of the perforation impedance,

$$V_{\text{PERF}} = \frac{P_{TM} - P_{\text{CAV}}}{Z_{\text{PERF}} A_{\text{PERF}}}$$  \hspace{0.5cm} (4.14)

where $A_{\text{PERF}}$ is the measured cross-sectional area of the perforation.

Estimates of the velocities $|V_{TM}|$ and $|V_{\text{PERF}}|$ from one of our experimental bones (bone 24L) are plotted in Fig.4-5. For the four perforations that range in diameter from 0.5 mm to 2.0 mm, the relation $|V_{\text{PERF}}| > 10|V_{TM}|$ holds at almost every frequency. As the perforation size increases, the two particle velocities converge so that for the largest perforation of 5 mm, the two particle velocities are comparable at many frequencies, especially above 1000 Hz.
Figure 4-5: Estimates of the particle-velocity magnitudes of (1) the tympanic-membrane and (2) the air through the perforation. These particle velocities were obtained from the actual pressure measurements made in the ear canal; thus the absolute velocities depend on the ear-canal pressure. At low frequencies, the ear canal pressure was about 70 to 80 dB SPL, although it was frequency dependent. For each perforation size, the estimates of both $V_{TM}$ and $V_{PERF}$ use the same ear-canal pressure $P_{EC}$. 
However, for most of our perforation sizes, it appears that the particle velocity of the air flowing through the perforation is much greater than the particle velocity of the tympanic membrane; thus, our approximation seems reasonable.

4.3 Comparison of 3-block model predictions to experimental data

4.3.1 Organization

We compare predictions from our model to the experimental data presented in chapter 2.3. Here, we determine how well our model (Fig. 4-1) can predict some of the quantities we measured on our temporal-bone preparation. We made measurements of four specific quantities with both normal and perforated tympanic membranes: (1) Total sound transmission measured as stapes velocity per pressure at the tympanic membrane (chapter 2.3.2), (2) Pressure difference across the tympanic membrane (chapter 2.3.3), (3) Stapes velocity per pressure difference across the tympanic membrane (chapter 2.3.4), and (4) Input impedance at the tympanic membrane (chapter 2.3.5). Here, we specifically compare the model to three of these four measurement quantities [(1), (2) and (4) listed above]. Our model assumes that quantity (3), stapes velocity per pressure difference across the tympanic membrane, is not affected by perforations. This assumption is described further in chapter 4.2.1, and is equivalent to the model assumption \( \hat{Z}_{\text{norm}}^{\text{TOC}} = \hat{Z}_{\text{perf}}^{\text{TOC}} \).

In the following model predictions we use the model of Fig.4-1B, where: \( \hat{Z}_{\text{CAV}} \) is a direct measurement made on each of the ten temporal bones; \( \hat{Z}_{\text{perf}}^{\text{TOC}} = \hat{Z}_{\text{norm}}^{\text{TOC}} = \hat{Z}_{\text{TOC}} \) and \( \hat{Z}_{\text{norm}}^{\text{TOC}} \) is computed from direct measurements on each of the ten temporal bones using Equation 4.4; and finally, \( \hat{Z}_{\text{PERF}} \) is calculated for each perforation diameter from Equation 4.10.

The next four sections compare model predictions with experimental data. We start by comparing our measurements of impedance at the tympanic membrane with perforations to the model predictions of impedance at the tympanic membrane. For this case, the model is based on bone-specific measurements except for the impedance of the perforation. Thus, similarity between the measurements and the model indicate that our acoustic model for the perforation is consistent with the actual perforation impedance. Next, we compare model predictions to data collected with tympanic-membrane perforations where the model element values are independent of the measurements. Specifically, we compare (1) loss in sound transmission to the cochlea and (2) pressure difference across the tympanic membrane. Since none of the experimental data in these latter two sections influence the model, similarities between the experimental data and the model predictions indicate that the model topology provides a reasonable estimation of how the perforation affects sound transmission. Finally, in the fourth section, we examine model predictions of specific
features of the data such as magnitude extrema and low-frequency slopes. In general, the figures in this section compare the model prediction to the data on bone 24L as a typical example, and model comparisons for all bones are at the end of the thesis in appendices.

4.3.2 Impedance at the tympanic membrane

We compare the impedance measured at the tympanic membrane, $Z_{TM}$, to the model prediction of the impedance at the tympanic membrane, $\hat{Z}_{TM}$. For each bone, $\hat{Z}_{TM}$ is calculated from Equation 4.3 using the bone-dependent $\hat{Z}_{TOC}$ and $\hat{Z}_{CAV}$ determined from measurements and the calculated $\hat{Z}_{PERF}$ from the measured perforation diameter and Equation 4.10.

![Figure 4-6](image)

Figure 4-6: Impedance at the tympanic membrane on bone 24L for six perforation diameters. Symbols indicate every 20th calculated point and data point. LEFT: Model predictions RIGHT: Measurements TOP: Magnitude BOTTOM: Angle.
Figure 4-7: Direct comparison between the measured and model impedances at the tympanic membrane of bone 24L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20$ dB re $10^6$Nsm$^{-5}$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Fig. 4-6 compares the model predictions to the measurements for the impedance at the tympanic membrane for the bone 24L. All of the salient features of the measurements are seen in the model predictions: (1) both model and data have similar magnitudes and decrease at 20 dB/decade at the lower frequencies with an angle that is nearly -0.25 cycles (2) both model and data change from compliance-dominated to resistive-mass dominated at a perforation-size dependent frequency that is between 700 and 2000 Hz; in both cases the compliance to resistive-mass transition frequency increases with increasing perforation size, (3) both model and data have a magnitude minima whose frequency increases with increasing perforation size, and (4) near 4000 Hz, both model and data show a similar local maxima.

Fig. 4-7 enables visual comparison between model and data impedances. Here, for each perforation, the measured data are superposed on the model prediction. The largest deviations between the model and the data occur with the smallest perforations between 500 and 2000 Hz. These deviations could result from a number of factors, including (1) inaccuracy in our assumption that \( \hat{Z}_{\text{perf}} = \hat{Z}_{\text{norm}} \) or (2) inaccuracy in our model of the perforation \( \hat{Z}_{\text{PERF}} \). However, other than this frequency band around 1000 Hz, the model and the experimental data appear to have few differences, and for perforations greater than about 1 mm in diameter, the problems around 1000 Hz are not apparent. It seems possible that errors in the assumption \( \hat{Z}_{\text{TOC}} = \hat{Z}_{\text{TOC}} \) could affect the smaller diameters more than the larger diameters. Even though changes between the perforated and normal \( Z_{\text{TOC}} \) are small for small perforations, the parallel impedance \( \hat{Z}_{\text{PERF}} \parallel \hat{Z}_{\text{TOC}} \) is affected by \( \hat{Z}_{\text{TOC}} \) most for the smaller perforations; as perforation diameter increases, \( \hat{Z}_{\text{PERF}} \) decreases and \( \hat{Z}_{\text{TOC}} \) becomes less and less important. Plots that compare the model impedance to the measured impedance for each of the ten bones are in Appendix K (page 267) In general, across all bones, the match between model and data is comparable to the match seen in Fig. 4-7. Thus, we conclude that our perforation model for \( \hat{Z}_{\text{PERF}} \) is a reasonable description of the actual acoustic impedance of the tympanic-membrane perforation.

### 4.3.3 Transmission Loss

With values for \( \hat{Z}_{\text{TOC}}, \hat{Z}_{\text{PERF}}, \) and \( \hat{Z}_{\text{CAV}} \), we use the model of Fig. 4-1 to predict loss in \( V_S/P_{TM} \) with tympanic-membrane perforations. We predict our model loss, \( \hat{L} \), from Fig. 4-1B as the loss in volume velocity (relative to normal) through the element \( \hat{Z}_{\text{TOC}} \), which includes the stapes.

\[
\hat{L} = 1 + \frac{\hat{Z}_{\text{CAV}} \parallel \hat{Z}_{\text{TOC}}}{\hat{Z}_{\text{PERF}}} \tag{4.15}
\]

The magnitudes of the model loss (\( \hat{L} \), Equation 4.15) and the experimentally-measured loss (\( \hat{L} \), Equation 2.2) are plotted side by side in the top plots of Fig. 4-8 for our example, bone 24L. From these plots it is clear that all the characteristics of the experimental data are present in the model: (1) at the low frequencies, the losses are
greatest and they decrease at about 40 dB/decade, (2) the low-frequency loss increases with increasing perforation diameter, (3) small increases (negative losses) in transmission occur around 1000 Hz, and (4) small losses in the 3000 to 4000 Hz region increase with perforation size. The lower plots of Fig. 4-8 show the angles of the model and measured losses. Again, all key features of the measurements are seen in the model predictions: (1) for low frequencies, the angle difference is negative (between -0.25 and -.50 cycles) and relatively flat; thus, the perforations introduces a lag in the transmission. (2) the low-frequency angle difference increases (relative to zero) as the perforation size increases, and (3) the angle difference increases toward zero near 1000 Hz and decreases again around 4000 Hz.

![Figure 4-8: Model predictions and measurements of transmission loss and angle change, where transmission is measured as the stapes velocity per ear canal pressure. Results are for different perforation sizes, and symbols indicate every tenth calculated or measured data point. LEFT: Model Predictions. RIGHT: Experimental measurements on bone 24L. TOP: Magnitude Loss. BOTTOM: Angle Change.](image)

Fig. 4-9 provides superposed plots of the measured and predicted (model) transmission loss for the example bone 24 L. Here, for each perforation, the measured data are plotted
Figure 4-9: Direct comparison between the measured and model sound transmission losses of bone 24L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The preparation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
on top of the model prediction. [Such plots for all ten bones are provided in Appendix L (page 279).] The similarities listed above are evident, but also differences between data and model are apparent. Just as with the results discussed above for impedance at the tympanic membrane, deviations between the model and the data occur for the smaller perforations within a narrow frequency band centered at 1000 Hz. Again, these deviations could result from either (1) inaccuracy in our assumption that \( \hat{Z}_{\text{PERF}} = \hat{Z}_{\text{normal}} = \hat{Z}_{\text{TOC}} \) or (2) inaccuracy in our model of the perforation \( \hat{Z}_{\text{PERF}} \). Another difference between the transmission data and the transmission model is seen at the lower frequencies. Here, considering the larger perforations on all ten bones (e.g., greater than 2 to 3 mm in diameter), the transmission loss appears to be systematically underestimated by up to about 5 to 10 dB. It seems likely that this underestimation may result from our assumption \( \hat{Z}_{\text{PERF}} = \hat{Z}_{\text{normal}} = \hat{Z}_{\text{TOC}} \); our measurements shown in Fig. 2-21 indicate that changes on the order of 5 to 10 dB probably do occur in \( \hat{Z}_{\text{normal}} \) when the perforation size exceeds 2 to 3 mm in diameter; with these larger perforations, deviations between the model and the data are similar for all perforation diameters and do not appear to depend on the diameter. Occasionally (bones 23, 22L), the transmission measurements and model show differences at the low frequencies with the smaller perforations (less than 2 mm in diameter); in these cases the loss is overestimated by the model by about 5 to 10 dB. However, for most bones, the model and experimental data are within 5 dB at the lower frequencies. In summary, the loss pattern predicted by the model matches the experimental data to within less than 10 dB in most situations, and the model-loss pattern appears to capture the salient features of the experimental data. In general, across all bones, the match between model and data is comparable to the match seen in Fig. 4-9. Thus, we conclude that the lumped-element model predicts most of the salient features of the experimental data for transmission loss.

4.3.4 Pressure difference across the tympanic membrane

With values for \( \hat{Z}_{\text{TOC}} \), \( \hat{Z}_{\text{PERF}} \), and \( \hat{Z}_{\text{CAV}} \), we use the model of Fig. 4-1 to predict the pressure difference across the tympanic membrane per pressure at the tympanic membrane, \( \hat{H}_{\Delta T M} \). Predictions of \( \hat{H}_{\Delta T M} \) are made for each bone with the bone-dependent \( \hat{Z}_{\text{TOC}} \) and \( \hat{Z}_{\text{CAV}} \), along with the \( \hat{Z}_{\text{PERF}} \) calculated for each perforation size. Here, the model predictions for \( \hat{H}_{\Delta T M} = \Delta \hat{P}_{\text{TM}} / \hat{P}_{\text{TM}} \) (Equation 4.1) are compared to the measurements of pressure difference across the tympanic membrane per ear-canal pressure \( H_{\Delta T M} = \Delta P_{\text{TM}} / P_{\text{TM}} \) (Equation 2.3). Appendix M (page 291) contains the comparison between experimental data and model predictions from all ten bones.

The model predictions of \( \hat{H}_{\Delta T M} \) and the experimentally measured \( H_{\Delta T M} \) are plotted side by side in the top plots of Fig. 4-10 for our example, bone 24L. From these plots it is clear that all characteristics of the experimental data are present in the model: (1) at the lower frequencies, the pressure difference across the tympanic membrane increases with frequency \( f \) as nearly \( f^2 \) (i.e., 40 dB per decade), (2) at low frequencies, the pressure
difference across the tympanic membrane decreases with increasing perforation diameter, (3) magnitude maxima (peaks) occur around 1000 Hz, with a corresponding angle decrease of 0.25 to 0.5 cycles, (4) the maxima frequency increases with increasing perforation size, and (5) around 3000 Hz there is a local magnitude minimum with a corresponding 0.25 to 0.5 increase in angle.

![Image](image.png)

Figure 4-10: Model predictions and measurements of the pressure difference across the tympanic membrane, normalized by the ear-canal pressure: $H_{ATM}$. Results are for measurements on bone 24L, with different perforation diameters as a parameter. Symbols indicate every 20th calculated point and data point. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: Model Predictions. RIGHT: Experimental measurements. TOP: Magnitude BOTTOM: Angle.

Fig. 4-11 provides superposed plots that compare the pressure differences observed via the data and predicted by the model. Here, for each perforation, the measured data are plotted on top of the model prediction. For the most part, the similarities listed above hold. In general, across all 10 bones, the biggest deviations between the model and the
Figure 4-11: Direct comparison between the measured $H_{ATM}$ and model $\hat{H}_{ATM}$ for bone 24L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 0.1$dB$ are removed because of inaccuracies in microphone calibrations (see Chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the angle plot is 0.25 cycles.
data occur at the lower frequencies in the magnitude comparison. Here, in many cases, the measured magnitudes are greater than the model magnitudes, and primarily with the larger perforations, the measured magnitudes sometimes plateau at low frequencies instead of exhibiting a 40 dB/decade slope (e.g., bones 8, 20, 22 Left, 23). In these cases, we suspect that our measurements of the pressure difference across the tympanic membrane are corrupted by pressure-calibration problems (see chapter 2.2.4).

4.3.5 Prediction of data features from model structure

Here we consider how some of the data features discussed above are inherent in the model of Fig. 4-1. In particular, we consider the low-frequency slope of $|H_{\Delta TM}|$, the increase in $|H_{\Delta TM}|$ near 1000 Hz with perforations, and the low-frequency behavior of the loss in sound transmission.

4.3.5.1 Low-frequency slope for $\hat{H}_{\Delta TM}$

Fig. 4-10 and Fig. 4-11 show that the low-frequency slope of both the model $|\hat{H}_{\Delta TM}|$ and the measured $|H_{\Delta TM}|$ approaches 40 dB/decade with a corresponding angle $\Delta H_{\Delta TM}$ that is between 0.25 and 0.50 cycles. The model predicts this low-frequency behavior as a result of the interaction between the perforation impedance and the cavity impedance: consider Equation 4.1, repeated here.

$$\hat{H}_{\Delta TM} = \frac{1}{1 + \frac{Z_{CAV}(2Z_{TOC} + 2Z_{PERF})}{Z_{TOC}Z_{PERF}}} \tag{4.16}$$

At low frequencies, $|\hat{Z}_{TOC}| \gg |\hat{Z}_{PERF}|$ (compare Fig. 4-2 and Fig. 4-3). Thus, at low frequencies, Equation 4.16 is approximated by:

$$\hat{H}_{\Delta TM} \approx \frac{1}{1 + \frac{Z_{CAV}}{Z_{PERF}}} \tag{4.17}$$

Additionally, at low frequencies, $\hat{Z}_{CAV}$ is compliance dominated (Fig.4-2) and for the larger perforation sizes $\hat{Z}_{PERF}$ is mass dominated (Fig. 4-3). Thus, for low frequencies and large perforations, Equation 4.17 becomes

$$\hat{H}_{\Delta TM} \approx \frac{1}{1 - \frac{1}{\omega^2 C_{CAV} M_{PERF}}} \tag{4.18}$$

For $\omega$ small, the second term in the denominator is much greater than the first term; thus, $\hat{H}_{\Delta TM} \approx \omega^2 \hat{C}_{CAV} \hat{M}_{PERF}$, and $|\hat{H}_{\Delta TM}|$ increases at 40 dB/decade with a corresponding angle of 0.5 cycles at frequencies $f$ where $f \ll \frac{1}{2\pi \sqrt{C_{CAV} M_{PERF}}}$. For our smaller perforations, $\hat{Z}_{PERF}$ also includes some resistance which reduces both the slope and the angle in a manner related to the size of the resistance. Thus, at low frequencies, our model
is consistent with the measured $H_{\Delta TM}$ where (1) for the largest perforations $|H_{\Delta TM}|$ increases at 40 dB/decade with an angle $\angle H_{\Delta TM}$ that approaches 0.5 cycles, and (2) for the smaller perforations $|H_{\Delta TM}|$ increases more slowly than 40 dB/decade with an angle $\angle H_{\Delta TM}$ that increases from above 0.25 toward 0.50 cycles as the perforation size increases and the resistive component of $\hat{Z}_{PERF}$ becomes less important.

4.3.5.2 Increased pressure difference across the tympanic-membrane with perforations

In addition to the low-frequency slope of $H_{\Delta TM}$ described above, other features of the measured $H_{\Delta TM}$ can be described by the model of Fig. 4-1. In particular, with tympanic-membrane perforations, both the measured $|H_{\Delta TM}|$ and the model $|\hat{H}_{\Delta TM}|$ reach a local maximum at which $|P_{CAV}| > |P_{TM}|$. The local maximum occurs at a frequency $f_{max}$ where $f_{max}$ increases with increasing perforation size. Typically, $f_{max}$ occurs between about 700 Hz for the smallest perforations and about 2000 Hz for the largest perforations. Additionally, both the measured $\angle (H_{\Delta TM})$ and the model $\angle (\hat{H}_{\Delta TM})$ decrease by 0.25 to 0.50 cycles over a frequency range centered at $f_{max}$. This local maximum in magnitude and angle shift can also be explained via Equation 4.18 in that $f_{max}$ is near the resonance between the middle-ear cavity and the perforation.

$$f_{max} \approx \frac{1}{2\pi \sqrt{C_{CAV} \hat{M}_{PERF}}} \quad (4.19)$$

We note that this is an approximation for $f_{max}$ because Equation 4.18 ignores the resistive component of $\hat{Z}_{PERF}$. Additionally, with this formulation, the model predicts that $f_{max}$ should increase with increasing perforation size since $M_{PERF}$ decreases with increasing perforation size (Equation 4.11 shows $M_{PERF} \propto \frac{1}{r_{PERF}}$), and according to our measurements, $f_{max}$ does indeed increase with perforation size.

4.3.5.3 Low frequency behavior of sound-transmission loss

The low-frequency behavior of sound-transmission loss is similar to that described above for $H_{\Delta TM}$: at low frequencies the loss decreases by up to 40 dB/decade and the angle change is between $-0.25$ and $-0.5$ cycles. At low frequencies, where $|\hat{Z}_{CAV}| \ll |\hat{Z}_{TOC}|$, our model prediction for sound-transmission loss, ($\hat{L}OSS$, Equation 4.15), can be simplified to

$$\hat{L}OSS \approx 1 + \frac{\hat{Z}_{CAV}}{\hat{Z}_{PERF}} \quad (4.20)$$

Thus, once again the low-frequency expression includes a “Helmholtz resonator” where the cavity impedance and the perforation impedance act as a second-order system. Such an expression is consistent with our results in that (1) the smaller perforations with the larger resistances have a slope in transmission loss that is some what less than -40 dB/decade.
and the larger mass-dominated perforations have a loss slope closer to -40 dB/decade and (2) the smaller perforations have angle changes that are closer to -0.25 cycles while the larger mass-dominated perforations have angle changes close to -0.5 cycles. Additionally, the increased transmission (decreased loss) that occurs near 1000 Hz at $f_{\text{loss}}^{\text{min}}$ for many of the perforations is consistent with a resonance between $\hat{Z}_{CAV}$ and $\hat{Z}_{TOC}$, where LOSS is minimized when $\hat{Z}_{CAV} \approx -\hat{Z}_{TOC}$ at

$$f_{\text{loss}}^{\text{min}} = \frac{1}{2\pi} \frac{1}{\sqrt{\hat{C}_{CAV} \hat{M}_{PERF}}}.$$  \hfill (4.21)

4.4 Modification of model to represent ears with normal middle-ear cavities

4.4.1 Description of the middle-ear cavity in normal bones and in our temporal bones

In a normal ear, the middle-ear space consists of the tympanic cavity, the aditus ad antrum, and the mastoid cavity. The tympanic cavity houses the ossicles and has a volume of about 0.5 cm$^3$ to 1 cm$^3$ (Gyo et al. 1986; Whittemore et al. 1993). The posterior-superior portion of the tympanic cavity opens into the larger mastoid cavity. The mastoid cavity is composed of a network of air cells; a large single air cell called the antrum sits on the mastoid side of the aditus ad antrum. Attached to the antrum are numerous air cells that, along with the antrum, form the mastoid air space. Measurements of the volume of the entire air space (tympanic cavity, aditus ad antrum, and mastoid cavity) show large variations. Molvaer (1978) measured an average volume from 55 specimens of 6.5 cm$^3$, with a range from 2 cm$^3$ to 22 cm$^3$.

There is a major difference between the middle-ear cavities of our temporal bones and those of a normal live ear. The tympanic cavity and the aditus ad antrum in our temporal-bone preparation do not differ from a normal ear, but the mastoid cavity does differ. In particular, when the temporal bone is harvested, only part of the mastoid air space is retained. Thus, the mastoid space is smaller in our preparation than in the normal condition. Additionally, we must drill the mastoid air cells in order to gain access to the stapes. As a result, we open the antrum into a larger space and we reduce the network of smaller air cells.

In this section, we examine how the differences in mastoid volume between our bones and normal ears may influence our sound transmission measurements. We do not address how the altered air-cell network may be affected; i.e., the effect of drilling the air-cell network of the malleus to form one large cavity. Instead we focus on the differences in total volume. In particular, we develop a model for the middle-ear cavity system, and we use this model
to examine how changes in the volume of the mastoid cavity affect sound transmission.

4.4.2 Middle-ear cavity model

4.4.2.1 Model topology

A simple model of the middle-ear cavity is shown in Fig. 4-12. The model topology is identical to that used by Kringlebotn (1988), but we use our measurements to select model elements. The tympanic-cavity air space is represented by the compliance $C_t$, and the mastoid-cavity air space is represented by the compliance $C_a$, where the $a$ represents the antrum since in our bones the entire mastoid space is similar to an enlarged antrum. The tympanic cavity and the mastoid cavity are connected by the "tube-like" aditus ad antrum, which we model as a series resistance $R_{aaa}$ and mass $M_{aaa}$. Thus, the resulting topology is the tympanic-air-space compliance in parallel with the series R-L-C of the aditus ad antrum terminated by the mastoid cavity. Below, we use our measurements to determine element values for this model.

![Diagram of middle-ear cavity model]

Figure 4-12: Lumped-element model for the middle-ear cavities. $C_t$ represents the tympanic cavity, and $C_a$ represents the mastoid cavity (antrum). The tympanic cavity and the mastoid cavity are connected by the "tube-like" aditus ad antrum, the series resistance $R_{aaa}$ and mass $M_{aaa}$.

4.4.2.2 Model-element values

We use our measurements of cavity impedance to determine element values for our middle-ear cavity model. All of our middle-ear cavity impedance measurements, $Z_{CAV}$, were similar to each other, across our population of 10 bones Fig. 4-2. Thus, we develop our model from the measurements on a single bone, bone 24 Left.

To determine the model-element values (i.e., $C_t$, $C_a$, $R_{aaa}$ and $M_{aaa}$), we follow the method outlined by Huang et al. (1997). Huang et al. (1997) model the middle-ear...
cavity system of both a lion and a domestic cat with the same model topology as Fig. 4-12. Additionally, they provide a quantitative method, based on impedance measurements, to determine appropriate model element values. The following procedure that involves Equations 4.22 to 4.26 is from Huang et al. (1997).

First, we assume that at low frequencies, the cavity impedance $Z_{CAV}$ can be approximated as a pure compliance $C_{CAV}$ that we can calculate from our measurements and then use to constrain the compliances $C_t$ and $C_a$ such that

$$C_{CAV} = C_t + C_a.$$  \hspace{1cm} (4.22)

We solve for $C_{CAV}$ from our measurements of $Z_{CAV}$ at 244 Hz.

$$C_{CAV}(f = 244 \text{ Hz}) = \left| \frac{1}{2\pi f Z_{CAV}} \right|$$  \hspace{1cm} (4.23)

Next, we consider two resonances within the model topology. For both resonances, we assume a high Q, so that the effects of the resistance $R_{aaa}$ are small. First, there is a parallel resonance between the mass $M_{aaa}$ and the compliances $C_t$ and $C_a$. This resonance leads to a maximum in $Z_{CAV}$ at the frequency $f_{\text{max}}$ where

$$f_{\text{max}} = \frac{1}{2\pi} \sqrt{\frac{C_t + C_a}{M_{aaa} C_t C_a}}.$$  \hspace{1cm} (4.24)

The second resonance, at a lower frequency than the first, is a series resonance between $M_{aaa}$ and $C_a$ which leads to a minimum in $Z_{CAV}$ at the frequency $f_{\text{min}}$ where

$$f_{\text{min}} = \frac{1}{2\pi} \sqrt{\frac{1}{M_{aaa} C_a}}.$$  \hspace{1cm} (4.25)

Finally, division of Equation 4.24 by Equation 4.25 leads to the relation

$$\frac{f_{\text{max}}}{f_{\text{min}}} = \sqrt{1 + (C_a/C_t)}.$$  \hspace{1cm} (4.26)

We can then compute values for $C_a$ and $C_t$ from Equations 4.22 and 4.26, with $C_{CAV}$, $f_{\text{max}}$, and $f_{\text{min}}$ determined from the experimental data. With values for $C_a$ and $C_t$, we use the frequency of the local minimum in $Z_{CAV}$ and Equation 4.25 to solve for $M_{aaa}$. Finally, we use a frequency-dependent resistance that matches the magnitude of the measured $Z_{CAV}$ (Beranek 1986, pp.137-138). The element values that result for the experimental $Z_{CAV}$ from bone 24L are included in Table 4.1.

Fig. 4-13 compares our middle-ear cavity model $\hat{Z}_{CAV}$ to our measurement of $Z_{CAV}$ on bone 24 Left. In general, below 3000 Hz, the model captures most salient features of the data. At the lowest frequencies, the model angle is nearly $-0.25$ cycles while the data angle is slight greater at about $-0.20$ cycles; this discrepancy could result from either a
real difference between the model and the data or a measurement error if there was a slight acoustic leak when the $Z_{CAV}$ measurement was made; across our population of 10 bones, some of the low-frequency $Z_{CAV}$ angles are at $-0.25$ cycles while others approach $-0.20$ cycles. Above 3000 Hz, our model and the data diverge. The local maxima in the data, near 3000 Hz, is overestimated by the model. Thus, up to 3000 Hz, the model is a reasonable description of the measured $Z_{CAV}$.

Figure 4-13: Model predictions of the middle-ear cavity impedance $\hat{Z}_{CAV}$ and the measured $Z_{CAV}$ on bone 24L. TOP: Magnitude. BOTTOM: Angle.

4.4.2.3 Comparison to other middle-ear cavity models

In many ways, our model topology is similar to other middle-ear cavity models in the literature. In particular, the two most common middle-ear model topologies come from Kringlebotn (1988) and Zwislocki (1962). These model topologies and their predictions for $\hat{Z}_{CAV}$ are shown in Fig. 4-14, and the corresponding element values are listed in Table 4.1. The Kringlebotn topology is the same as our model whereas the Zwislocki topology differs with the parallel resistor $R_M$. According to Zwislocki (1962, p. 1517), "The resistance $R_M$ represents the sound absorption in the walls of the tympanic cavity and the Eustachian
### Table 4.1: Middle-ear cavity model parameters. Volumes are estimated from the model-compliance values using Equation 4.27.

<table>
<thead>
<tr>
<th>Model (mks units)</th>
<th>$R_{aaa}$</th>
<th>$M_{aaa}$</th>
<th>$C_a$</th>
<th>$C_t$</th>
<th>$R_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zwislocki (1962)</td>
<td>$10^6$</td>
<td>1400</td>
<td>$5.1 \times 10^{-11}$</td>
<td>$3.5 \times 10^{-12}$</td>
<td>$39 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$V = 7.2 \text{cm}^3$</td>
<td>$V = 0.5 \text{cm}^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$6 \times 10^5$</td>
<td>100</td>
<td>$3.9 \times 10^{-11}$</td>
<td>$4.0 \times 10^{-12}$</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$V = 5.6 \text{cm}^3$</td>
<td>$V = 0.57 \text{cm}^3$</td>
<td></td>
</tr>
<tr>
<td>Kringlebotn (1988)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.05 \times 10^6 \sqrt{f}$</td>
<td>722</td>
<td>$7.4 \times 10^{-12}$</td>
<td>$4.2 \times 10^{-12}$</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$V = 1 \text{cm}^3$</td>
<td>$V = 0.6 \text{cm}^3$</td>
<td></td>
</tr>
<tr>
<td>bone 24L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Zwislocki model prediction seems reasonable as its prediction for $\hat{Z}_{CAV}$ has similar features to both our data and our model. On the other hand, the Kringlebotn prediction for $\hat{Z}_{CAV}$ does not include the dramatic local minimum and local maximum that our data, our model, and the Zwislocki model all contain; these differences in $\hat{Z}_{CAV}$ occur as a result of the particular element values chosen for the models.

There are some dramatic differences between our element values and those of both Kringlebotn and Zwislocki (Table 4.1). First, we expect the tympanic cavity volumes to be similar for all three situations because none of the tympanic cavities has been modified; indeed, the predicted tympanic-cavity volumes are 0.5 cm$^3$, 0.57 cm$^3$, and 0.6 cm$^3$ for the Zwislocki, Kringlebotn, and bone 24L models respectively. Similarly, the respective volumes for the mastoid cavity volumes are 7.2 cm$^3$, 0.56 cm$^3$, and 1 cm$^3$ for the Zwislocki, Kringlebotn, and bone 24L models. The difference between our volume and the volumes of the other two models is not surprising since only part of the mastoid cavity is retained on our temporal bones. Both Kringlebotn (1988) and Zwislocki (1962) used estimates of the mastoid cavity made on populations of complete mastoid cavities, but we use acoustic measurements to estimate the volume of the remaining mastoid cavity in our specimen.

The values for $M_{aaa}$ also show dramatic differences between the three models. Since we made no modifications to the aditus ad antrum, the values for both $R_{aaa}$ and $M_{aaa}$ should be consistent for all three models. However, our calculation of a value for $M_{aaa} = 722$ is nearly the mean of the values suggested by Kringlebotn and Zwislocki. The Kringlebotn $M_{aaa} = 100$ is seven times lower than our value, which is consistent with Kringlebotn’s predicted cavity impedance in which there is no mass domination. At the other extreme, the Zwislocki $M_{aaa} = 1400$ is nearly twice the size of our value. Independent anatomical observations can be used to support our model value for $M_{aaa}$. The acoustic mass can be related to the diameter and the length of the aditus ad antrum as $M_{aaa} = \rho l_{aaa}/A_{aaa}$ where $\rho$ is the density of air, $l_{aaa}$ is the length of the aditus ad antrum, and $A_{aaa}$ is the cross-sectional area of the aditus ad antrum. It is difficult to associate an
Figure 4-14: Middle-ear cavity model topologies from Kringlebotn (1988) and Zwislocki (1962) and the model predictions for cavity impedance. Element values are provided in Table 4.1. LEFT: Kringlebotn model. RIGHT: Zwislocki model. The thick solid line is Zwislocki's model prediction, and the dashed line is Zwislocki's model prediction with $R_m$ set to an open circuit.
exact length and area to the aditus ad antrum because the geometry is irregular and the boundaries are not well defined. However, the diameter appears to be on the order of 2 to 4 mm and a length might be about 3 to 5 mm, depending on how the boundaries are defined (Merchant 1998). Thus, if we assume a diameter of 3 mm (radius 1.5 mm), we can solve for a length based on the various estimates of acoustic mass as \( l_{aaa} = M_{aaa} A_{aaa}/\rho \). These length estimates are provided in Table 4.1. We see that the Zwischlocki length of 8.4 mm is larger than anatomically reasonable and the Kringlebotn length of 0.6 mm is smaller than expected anatomically. Our length of 4.6 mm seems to fit with the anatomical expectation.

Finally, the values for \( R_{aaa} \) also show differences for the three models. We use a frequency dependent \( R_{aaa} \) while the other two models assign constant values to \( R_{aaa} \). Also, the \( R_M \) of the Zwischlocki model acts to dampen the parallel resonance between \( M_{aaa} \) and \( C_t \) and \( C_a \). In general, some resistance is needed in order to dampen the resonances, but it seems that there is no obvious anatomical argument for the resistance value. In fact, our resistance is fit to match the measurement. Thus, further work is needed to determine an anatomical argument for the selection of \( R_{aaa} \).

4.4.2.4 Modification of the mastoid cavity volume

The motivation for our middle-ear cavity model comes from our need to determine how the mastoid-cavity volume affects the measurements of sound transmission we have presented (e.g., \( V_S/P_{TM} \) and \( H_{ATM} \)). Here, we modify our middle-ear cavity to include mastoid-cavity volume as a parameter. In particular, we simply modify the element \( C_a \) which represent the volume of the antrum. Instead of a constant \( C_a = 7.4 \times 10^{-12} \), we set the model \( C_a \) as a function of mastoid volume such that

\[
C_a = \frac{V_a}{\rho c^2}
\]  

(4.27)

where \( V_a \) is the volume of the mastoid cavity, \( \rho \) is the density of air, and \( c \) is the speed of sound in air. Thus, with Equation 4.27, we are able to predict \( \hat{Z}_{CAV} \) with mastoid-cavity volume as a parameter. We hold all other model elements constant.

Fig. 4-15 shows our model predictions for \( \hat{Z}_{CAV} \) with mastoid-cavity volume as a parameter. As the mastoid-cavity volume increases, several trends become apparent: (1) the compliance \( C_a \) increases, and as a result the low-frequency impedance magnitude decreases; (2) the frequency of the magnitude minima \( f_{\text{min}} \) decreases (Equation 4.25); (3) the frequency of the magnitude maxima \( f_{\text{max}} \) decreases, but not at much as \( f_{\text{min}} \); and (4) the ratio \( f_{\text{max}}/f_{\text{min}} \) increases (Equation 4.26).

4.4.2.5 Estimates of sound transmission with a larger mastoid-cavity volume

Here, we use the middle-ear cavity model developed above to predict how the mastoid-cavity volume affects our measurements of sound transmission. In particular, we compare model
Figure 4-15: Model predictions for the middle-ear cavity impedance with mastoid volume as a parameter.
predications for both $LOSS$ (Equation 4.15) and the model pressure difference across the tympanic membrane per ear-canal pressure $\hat{H}_{\Delta TM}$ (Equation 4.1) with the mastoid-cavity volume set at 1 cm$^3$ and 6 cm$^3$. For all model predictions, we use the model of Fig. 4-1 with $\hat{Z}_{TOC}$ from Equation 4.4 and the measurements on bone 24 Left, $\hat{Z}_{CAV}$ from the middle-ear cavity model of Fig. 4-12 and Table 4.1, and $\hat{Z}_{PERF}$ from Equation 4.10. We modify only the mastoid-cavity volume, which we set at either 1 cm$^3$ or 6 cm$^3$.

Fig. 4-16 plots model predictions for $LOSS$ for different sized perforations with a mastoid volume of both 1 cm$^3$ and 6 cm$^3$. These model predictions suggest that the transmission loss is decreased when the mastoid cavity is larger. In general, the features of the model with the larger mastoid cavity are consistent with our measurements on the temporal bones and our model with the smaller mastoid cavity. For both cavity volumes, the low-frequency losses increase with perforation size and also with frequency. However, the volume affects the magnitude of the loss and the frequencies where the loss reaches extrema. These results can be interpreted in terms of physical mechanisms. First, if the volume of the mastoid cavity increases, then the compliance of the middle-ear cavity impedance increases and $\hat{Z}_{CAV}$ decreases. With a decreased $\hat{Z}_{CAV}$, the low-frequency loss will decrease (Equation 4.20) and the frequency of the first minimum will decrease (Equation 4.21).

Fig. 4-17 plots model predictions of $\hat{H}_{\Delta TM}$ for different sized perforations with a mastoid volume of both 1 cm$^3$ and 6 cm$^3$. The model predicts that a larger mastoid-cavity volume acts to increase $|\hat{H}_{\Delta TM}|$ relative to the smaller mastoid-cavity volume. Additionally, the local maximum is shifted to a lower frequency, with a corresponding shift in the behavior of the angle. The local minimum is affected less than the maximum, because the local minimum occurs at frequencies above which the cavity impedance $\hat{Z}_{CAV}$ is compliance dominated and thus affected by changes in the mastoid-cavity volume.

In summary, the mastoid-cavity volume has primarily low-frequency effects on our measurements of sound transmission. Increased mastoid-cavity volumes (1) lead to increased transmission and (2) affect the local extrema such as to reduce their frequency.
Figure 4-16: Model predictions for loss in shape velocity per ear canal pressure. Loss predictions shown for a mastoid cavity volume of both 1 cm³ and 6 cm³ for different diameter permutations.

FREQUENCY (Hz)

![Graph showing frequency and loss predictions for different diameters.]

LOSS (dB)
Figure 4-17: Model predictions for the pressure difference across the tympanic membrane per ear-canal pressure, HATM. Predictions shown for a mastoid-cavity volume of both 1 cm$^3$ and 6 cm$^3$ for different diameter perforations.
4.5 Low-frequency approximation of model

In this section, we simplify our model with the goal of providing a simple method to predict the hearing loss associated with a tympanic-membrane perforation of a given diameter \( d \) at a frequency \( f \). Our simplification focuses on low frequencies \( (f < 1000 \text{ Hz}) \) and is best suited for perforations with \( d > 1 \text{ mm} \).

Examination of Fig. 4-2 and Fig. 4-18 (and Fig. F-1 to Fig. F-6) shows that our measurements indicate that for \( f < 2000 \text{ Hz} \), \( |Z_{\text{CAV}}| \ll |Z_{\text{TOC}}| \). Using this relation, we can simplify our model prediction for \( LÖSS \), Equation 4.15, to

\[
LÖSS_{f<2000\text{Hz}} \approx 1 + \frac{\hat{Z}_{\text{CAV}}}{\hat{Z}_{\text{PERF}}}. \tag{4.28}
\]

Furthermore, when \( f < 1000 \text{ Hz} \), \( \hat{Z}_{\text{CAV}} \) can be approximated by a compliance such that

\[
\hat{Z}_{\text{CAV}}^{\text{comp}} \approx \frac{1}{j\omega \hat{C}_{\text{CAV}}} \tag{4.29}
\]

where

\[
\hat{C}_{\text{CAV}} = \frac{\dot{V}}{\rho c^2}, \tag{4.30}
\]

and \( \dot{V} \) is the total volume of the middle-ear cavity. In Fig. 4-18, for the example bone 24L, we see that \( Z_{\text{CAV}} \) is well approximated by \( \hat{Z}_{\text{CAV}}^{\text{comp}} \) at frequencies below 1000 Hz.

We can also simplify \( \hat{Z}_{\text{PERF}} \) to \( \hat{Z}_{\text{PERF}}^{\text{mass}} \) under certain conditions. According to Chapter 4.2.2.1.1 and Fig. 4-4, for perforations greater than about 1 mm in diameter, \( \hat{Z}_{\text{PERF}} \) can be approximated by a pure mass (Equation 4.11) such that

\[
\hat{Z}_{\text{PERF}}^{\text{mass}} = j\omega \frac{\mu^\prime_{\text{PERF}}}{\pi \rho_{\text{PERF}}^\prime M_{\text{PERF}}^{\text{mass}}}. \tag{4.31}
\]

Thus, for perforation diameter \( d > 1 \text{ mm} \) and frequency \( f < 1000 \text{ Hz} \), we propose that the loss in transmission can be approximated by substitution of Equations 4.29 and 4.31 into Equation 4.28.

\[
LÖSS_{f<1000\text{Hz}} \approx 1 - \frac{1}{\omega^2 \hat{C}_{\text{CAV}} M_{\text{PERF}}}. \tag{4.32}
\]

Further substitution for \( \hat{C}_{\text{CAV}} \) and \( M_{\text{PERF}} \) from Equations 4.30 and 4.31 leads to the equation

\[
LÖSS_{f<1000\text{Hz}} \approx 1 - \frac{\kappa d}{f^2 \dot{V}}, \tag{4.33}
\]

where \( \kappa = 2.867 \times 10^6 \text{ cm}^3/\text{mm}^2 \), diameter \( d \) has units mm, frequency \( f \) has units Hz, and middle-ear cavity volume \( V \) has units cm\(^3\). Loss approximations calculated from Equation 4.33 are plotted in Fig. 4-19 for tympanic-membrane perforations equal to the size perforations made
Figure 4-18: Comparison between the measured impedances $Z_{TOC}$ and $Z_{CAV}$ from bone 24L, and also the estimate of $Z_{CAV}$ modeled as a single compliance with $C_{CAV} = \frac{V}{\rho \omega^2}$, where $V$ is the volume of the middle-ear cavity. Here, $V = 1.6 \text{ cc}$ was calculated from the cavity impedance measurement at 244 Hz with Equation 4.23 and 4.30. TOP: Magnitude. BOTTOM: Angle.
on bone 24L. The measured data and the exact model are also shown for comparison in Fig. 4-19. The simple model is within a few dB of both the data and the exact model for perforations greater than 1 mm in diameter and for frequencies up to at least 1000 Hz.

![Graph showing comparison between measurements and models for different perforation diameters.](image)

**Figure 4-19:** Comparison between measurements of transmission loss and model predictions of transmission loss for both the exact and the simplified models. The measurements correspond to bone 24L, the exact transmission loss model predictions use impedance data from bone 24L and Equation 4.15, and the simplified model uses Equation 4.33 with the appropriate perforation diameters and a total cavity volume of 1.6 cm$^3$ with the tympanic-cavity volume of 0.6 cm$^3$ and a mastoid-cavity volume of 1 cm$^3$.

Our simplified model assumes that the cavity impedance $\tilde{Z}_{CAV}$ can be approximated by a compliance at low frequencies. As shown earlier in chapter 4.4, the frequency range where such an approximation is valid depends on the volume of the middle-ear cavity. The middle-ear volumes that correspond to our temporal bones are typically about 1.5 cm$^3$ and are listed in Table 2.1. As previously discussed, our middle-ear volumes are smaller than the average live middle-ear volume because the entire mastoid cavity is not obtained when

---

1. These volumes are computed from the measurement of $Z_{CAV}$ at 250 Hz as $V_{CAV} = \frac{\pi^2}{2\omega |\tilde{Z}_{CAV}|}$
the bones are harvested. Thus, in live humans, where normal middle-ear cavities average about 6.5 cm$^3$ (Molvaer et al. 1978), it is possible that the frequency range where our simple model (Equation 4.33) applies is limited to frequencies with an upper frequency that is less than the 1000 Hz determined here.

We use our middle-ear cavity model with volume as a parameter to determine when the simple model of Equation 4.33 is valid with cavity volumes that correspond to the normal live ear. Fig. 4-15 shows the predicted cavity impedance, $\tilde{Z}_{CAV}$ for middle-ear volumes that range from 1.1 cm$^3$ to 8.6 cm$^3$. The predicted cavity impedances indicate where our simplified model for hearing loss with a tympanic-membrane perforation is valid; specifically, it is valid only where the cavity impedance is approximated by a pure compliance. Thus, from the results in Fig. 4-15, we conclude that as cavity volume increases, the upper frequency for our simplified model decreases. However, it appears that our simplified model is valid up to about 500 Hz for middle-ear volumes up to about 8.6 cm$^3$. Thus, using Equation 4.33 we can predict how the middle-ear volume affects hearing loss with tympanic-membrane perforations. This prediction, with cavity volume ($V$) as a parameter is shown as a function of perforation size at 125, 250, 500, and 1000 Hz, and also as a function of frequency for perforation diameters of 1, 2, 3, and 4 mm in Fig. 4-20.

We note that ears affected by middle-ear disease and thus tympanic-membrane perforations, often have reduced cavity volumes. Furthermore, children have smaller middle-ear cavity volumes than adults. Thus, variations in middle-ear volume should result in differences in hearing levels measured audiologically between ears with different middle-ear volumes. As a result, middle-ear volume is another factor that makes it difficult to study sound-transmission with tympanic-membrane perforations in a clinical population. In fact, Fig. 4-20 makes it clear that variations of at least 20 dB that depend on middle-ear cavity volume may occur in hearing loss with tympanic-membrane perforations; the cavity-volume ranges plotted in this figure are found in patient populations.
and 4 mm.

model is not appropriate for such a large volume at 1 kHz. BOTTOM: Loss plotted as a function of frequency for the perforation diameters 1, 2, 3.

Figure 4.20: Predictions of hearing loss from our simplified model (Eqn. 4.3) for a middle ear cavity volume parameter T0. Loss plotted as a function of perforation diameter for the frequencies 125, 250, 500, and 1000 Hz. Note, the volume 8 cm$^3$ is not plotted at 1 kHz because the simplified model is not appropriate for such a large volume at 1 kHz.
Summary

Introduction

1. Description of sound transmission in ears with tympanic membrane perforations does not exist.

2. Sound reaches the cochlea through 2 routes: Ossicular and acoustic coupling. (Fig.1-2; p. 13 to 14)

3. This work uses measurements made on a temporal-bone preparation to develop a description of sound transmission with perforations.

Chapter 1: Temporal-bone preparation

1. Description of method to measure stapes velocity on human temporal bones.

2. Control experiments not reported in literature:
   
   (a) Effect of cutting stapedius muscle (Fig. 1-3; p. 30).
   
   (b) Effect of reflector on stapes (Fig. 1-4; p. 33).
   
   (c) Mechanical artifact and noise floor (Fig. 1-5; p. 35).

3. Stapes moves in a 1-dimensional, translational motion below 2000 Hz. (Fig. 1-11, Fig. 1-12, and Fig. 1-13; pp. 45, 46, and 47).

4. Measurements of stapes velocity consistent with those in the literature (Fig. 1-14; p. 51).

Chapter 2: Measurements of sound transmission with tympanic-membrane perforations

\[
\frac{V_S}{P_{EC}} = \frac{\Delta P_{TM}}{P_{EC}} \frac{V_S}{\Delta P_{TM}}
\]
1. Measurements of \( \frac{V_s}{P_{EC}} \) show perforations result in frequency-dependent, size-dependent changes in sound transmission (Fig. 2-12; p. 79). Additionally, perforation-induced changes do not appear to depend on perforation location (Fig. 2-13, Fig. 2-14, and Fig. 2-15; pp. 81, 82, and 83).

2. Perforation-induced changes in \( H_{\Delta TM} \) are similar to those in \( \frac{V_s}{P_{EC}} \). (Fig. 2-19; p. 88). Thus, perforation induced changes in transmission (\( \frac{V_s}{P_{EC}} \)) result primarily from changes in the pressure difference across the tympanic membrane.

3. Perforations have small effects on \( H_{TOC} \) relative to \( H_{\Delta TM} \) (Fig. 2-21; p. 91). Thus, changes in the mechanical coupling from the tympanic membrane to the stapes with perforations plays only a small role in the total changes with perforations. Additionally, perforations composed of 1 to 2 mm slits along the manubrium have little effect on sound transmission; this result demonstrates that the coupling between the tympanic membrane and the malleus - including the collective effects of possible tension on the tympanic membrane, the specifics of the radial and circular fiber anatomy, and the tympanic-membrane area - play a relatively small role in coupling the sound pressure at the tympanic membrane to the stapes (chapter 2.3.6; p. 93).

4. Perforations affect the input impedance. At low frequencies, the perforation reduces the impedance to the impedance of the middle-ear cavity (Fig. 2-22; p. 94).

**Chapter 3: Acoustic route of sound transmission**

\[
\frac{\Delta P_{win}}{P_{EC}} = \frac{P_{OW} - P_{RW}}{P_{EC}} = \frac{P_{CAV} \cdot \frac{P_{OW} - P_{RW}}{P_{EC}}}{H_{P_{CAV}} \cdot \frac{H_{WPD}}{H_{P_{CAV}}}} = \frac{P_{OW}}{P_{EC}} \left( 1 - \frac{P_{RW}}{P_{OW}} \right) \]

1. \( |H_{P_{CAV}}| \) increases with perforations (i.e., the middle-ear cavity pressure increases relative to the ear-canal pressure) in a frequency- and size-dependent manner (Fig. 3-4; p. 119). \( H_{P_{CAV}} \) is not a function of perforation location (Fig. 3-5; p. 121).

2. \( H_{WPD} \) and \( \frac{P_{RW}}{P_{OW}} \) are not affected by perforations above 1000 Hz (Fig. 3-7; p. 125). Below 1000 Hz, if \( \frac{P_{RW}}{P_{OW}} \) is affected by perforations, the effects are small (Fig. 3-7; p. 125 and chapter 3.3.3.2 and 3.4.1).

3. The acoustic-route stimulus \( \frac{\Delta P_{win}}{P_{EC}} \) depends on the perforation size and is independent of perforation location for frequencies greater than 1000 Hz (Fig. 3-9; p. 133). Below 1000 Hz, we place an upper bound on \( \frac{\Delta P_{win}}{P_{EC}} \), and we argue that for these lower
frequencies, the acoustic-route stimulus depends on perforation size and not perforation location (chapter 3.4.1). Thus, we conclude that sound transmission via the acoustic route is independent of perforation location and dependent on perforation size (chapter 3.4.1).

4. The acoustic route limits the total loss with perforations to at least 40 to 60 dB (Fig. 3-11; p. 141). Thus, when losses are smaller than 40 to 60 dB, the ossicular route is the dominant route of sound transmission with perforations (Fig. 3-12; p. 142).

Chapter 4: Model of the middle-ear with a tympanic-membrane perforation

1. Fig. 4-1 (p. 145) shows a middle-ear model with a perforation represented as a shunt path $Z_{PERF}$ across the tympanic membrane-ossicular system to the middle-ear cavity. $Z_{PERF}$ is modeled as a short narrow tube (Fig. 4-3; p. 4-3).

2. The model captures many of the measured features of the data. In particular, $Z_{TM}$ (Fig. 4-6 and Fig. 4-7; p. 157 and 158); Transmission Loss (Fig. 4-8 and Fig. 4-9; pp. 160 and 161); Pressure difference across the tympanic membrane $H_{ATM}$ (Fig. 4-10 and Fig. 4-11; pp. 163 and 164).

3. Development of a middle-ear cavity model to use for model predictions with larger cavities than the cavities on our temporal bones (chapter 4.4). Use of this model makes model predictions with cavity volume as a parameter. As the cavity volume increases, loss with tympanic membrane perforations decreases (Fig. 4-16; p. 4-16).

4. Low-frequency approximation of the model allows for calculation of transmission loss from a simple algebraic equation (Equation 4.33 at frequencies below 1000 Hz and for perforation diameters greater than 1 mm. The equation parameters are perforation diameter, middle-ear cavity volume, and frequency (Fig. 4-20; p. 4-20).
Appendix A

Information on all temporal bones acquired
## All temporal bones used: October 1995 to January 1998

<table>
<thead>
<tr>
<th>ID</th>
<th>General</th>
<th>Medical</th>
<th>Experiment notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>tb1</strong></td>
<td>Autopsy: MGH A95-276</td>
<td>Pulmonary hemorrhage&lt;br&gt;Hepatocellular cancer&lt;br&gt;Intra-abdominal bleed</td>
<td>$V_s/P_{EC}$ measurements; foil on footplate; Measurements fresh (951017, 951018) and frozen (951027, 960429)</td>
</tr>
<tr>
<td><strong>tb2</strong></td>
<td>Autopsy: MGH A95-299</td>
<td>Schizophrenia&lt;br&gt;Lipid pneumonia&lt;br&gt;Fibrosis of left lung</td>
<td>$V_s/P_{EC}$ measurements; foil on footplate; Measurements fresh (951102, 951103)</td>
</tr>
<tr>
<td><strong>tb3</strong></td>
<td>Autopsy: MGH A96-39</td>
<td>Tongue cancer</td>
<td>TM has scarring near umbo. $V_s/P_{EC}$ measurements with foil on footplate. Measurements made with static pressures in middle ear air space. Measurements fresh (960219, 960227).</td>
</tr>
<tr>
<td><strong>tb4</strong></td>
<td>Autopsy: MGH A96-55</td>
<td>Urinary tract infection&lt;br&gt;Alzheimer's</td>
<td>$V_s/P_{EC}$ measurements. Foil on footplate. Measurements made with static pressures in middle ear air space. Measurements fresh (960307, 960308).</td>
</tr>
<tr>
<td><strong>tb5</strong></td>
<td>Autopsy: MGH A96-87</td>
<td>Aspiration pneumonia&lt;br&gt;Achalasia&lt;br&gt;Malnutrition</td>
<td>$V_s/P_{EC}$ measurements. Foil on footplate. Measurements made with TM perforations made with needles. Not clear that the middle-ear air space was sealed acoustically. Measurements fresh (960330, 960401). (Calibration at 250 Hz had problems - used the measurement from bone 2.)</td>
</tr>
<tr>
<td><strong>tb6</strong></td>
<td>Autopsy: MGH A96-136</td>
<td>Myocardial infarction&lt;br&gt;Metastatic abdominal malignancy</td>
<td>$V_s/P_{EC}$ measurements with TM perforations. Mostly low frequency source. Foil on footplate. Measurements with perforations are noisy. Chirps, not tones, used to stimulate. Stimulus levels not high enough. Measurements fresh (960250, 960521, 960523, 960530).</td>
</tr>
<tr>
<td><strong>tb7</strong></td>
<td>Autopsy: MGH A96-192</td>
<td>Lung cancer&lt;br&gt;Pulmonary infarction</td>
<td>Measurements made of $V_s/P_{EC}$, $P_{TM}$, $P_{OW}$, and $P_{RW}$. After 2 perforations noticed a cracked footplate. It seems likely that footplate cracked early on as there are large differences between normal measurements tb 14 and tb 24. Measurements fresh (960722).</td>
</tr>
<tr>
<td><strong>tb8</strong></td>
<td>Autopsy: MGH A96-208</td>
<td>Myocardial infarction</td>
<td>Foil on posterior crus. Measurements of $V_s/P_{EC}$, $P_{TM}$, $P_{OW}$, and $P_{RW}$ made with TM perforations. Measurements fresh (960805).</td>
</tr>
<tr>
<td><strong>tb9</strong></td>
<td>Autopsy: MGH A96-273</td>
<td>Metastasized cancer&lt;br&gt;Seizure disorder&lt;br&gt;Alzheimer's</td>
<td>Foil on posterior crus. Measurements of $V_s/P_{EC}$, $P_{TM}$, $P_{OW}$, and $P_{RW}$ made with 4 TM perforations, but a high artifact level made $V_s$ measurements questionable. Acoustic measurements with perfs ok. Bone prepared about 2 weeks prior to perforation measurements - perforation measurements on 10-31-96.</td>
</tr>
<tr>
<td><strong>tb10</strong></td>
<td>Autopsy: MGH A96-294</td>
<td>GI bleed&lt;br&gt;Hepatic failure</td>
<td>Foil on posterior crus. Normal measurements made - high level and second day of measurements had much higher sensitivity and not repeatable. On day 2 of measurements the oval window microphone probe went through the I-S joint. Measurements 96-11-16, 96-11-17.</td>
</tr>
<tr>
<td><strong>tb11</strong></td>
<td>Autopsy: MGH A96-302</td>
<td>Hypoxia&lt;br&gt;Pulmonary hypertension&lt;br&gt;Chronic bronchitis&lt;br&gt;Lung collapse&lt;br&gt;Fetal alcohol syndrome</td>
<td>Foil on posterior crus. Measurements were not stable. TM scarred, facial nerve attached to stapes. Measured responses both increased and decreased over time. A hole was accidently made in the footplate while poking at the facial nerve. Perforations were not made. Measurements 96-11-22, 96-11-26, 96-11-28.</td>
</tr>
</tbody>
</table>
### All temporal bones used (continued): October 1995 to January 1998

<table>
<thead>
<tr>
<th>ID</th>
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<th>Medical</th>
<th>Experiment notes</th>
</tr>
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<tbody>
<tr>
<td>tb12</td>
<td>Autopsy: MGH A96-312 Sex: F Age: 62 Death: 11-24-96; 10:23am In Saline: 11-26-96; 1:15pm</td>
<td>Myocardial infarction</td>
<td>Foil on posterior crus. Measurements made with 4 perforations, but artifact was high. Measurements seemed unstable as there were changes over short time periods. Measurements 96-12-05</td>
</tr>
<tr>
<td>tb13L</td>
<td>Autopsy: MGH A96-326 Sex: F Age: 103 Death: 12-13-96; 6:50am In Saline: 12-13-96; 3:15pm</td>
<td>Stroke</td>
<td>Foil on posterior crus. Measurements made with perforations on left bone. Right bone frozen and later used to learn how to open the vestibule, but no measurements made on right. Measurements 96-12-16, 96-12-17, 96-12-19.</td>
</tr>
<tr>
<td>tb13R</td>
<td>Autopsy: MGH A97-7 Sex: M Age: 73 Death: 1-5-97; 4:45pm In Saline: 1-6-97, 4pm</td>
<td>Chronic pulmonary edema Diabetic Pneumonia Renal failure</td>
<td>Bones ruined while drilling. No measurements made.</td>
</tr>
<tr>
<td>tb15</td>
<td>Autopsy: MGH A97-74 Sex: M Age: 68 Death: 2-12-97; 2:20pm In Saline: 2-12-97; 2:10pm</td>
<td>Pulmonary edema Congestive heart failure Myocardial infarction Coronary artery disease</td>
<td>Bones previously frozen. Prepared with cavities wide open to make vestibule pressure measurements. Measurements 97-03-07, 97-03-11, 97-03-14.</td>
</tr>
<tr>
<td>tb16</td>
<td>Autopsy: MGH A97-113 Sex: M Age: 74 Death: 3-11-97; 2:10pm In Saline: 3-12-97; 12:30pm</td>
<td>Adult respiratory arrest syndrome Pulmonary infection Congestive heart failure</td>
<td>Bones prepared with cavities wide open to make vestibule pressure measurements. Measurements 97-03-17, 97-03-18. Stapes velocity also measured.</td>
</tr>
<tr>
<td>tb19L</td>
<td>Autopsy:MGH A97-156 Sex: M Age: 63 Death: 04-22-97; 12:30am In Saline: 04-22-97; 4:00pm</td>
<td>Metastatic adenocarcinoma Metabolic acidosis Multiple chemo cycles</td>
<td>Black &quot;ash-like&quot; sandy crust covered much of the osseous surface and cavity. Easily aspirated away and then cavity had normal appearance. Perforations made in posterior inferior quadrant because PI quadrant is largest. Measurements made on 970501. First perforation made near margin of TM and patched. Second perforation made near umbo. Differences between locations were small. Further perforations were extensions of the first perforation. Measurements 97-05-01</td>
</tr>
<tr>
<td>tb20</td>
<td>Autopsy:MGH A97-157 Sex: M Age: 68 Death: 04-23-97; 2:56pm In Saline: 04-24-97; 2:45pm</td>
<td>Myocardial infarction Coronary artery disease Heart block Pacemaker Carotid endarterectomy</td>
<td>Measurements made 2 to 3 weeks post mortem. Measurements on normal bone were not repeatable in either ear. After moistening, the response systemically decreased. Perforations not made. LEFT: Measurements on 970507 to 970511. On 970507 things seemed stable. Measurements with cavity open. On later days, stapes velocity decreased rapidly with time (over a course of 5 to 10 minutes), but could be reversed through moistening the annular ligament. RIGHT: Measurements on 970512 and 970513. Measurements with cavity open. Evidence of decreased response with time on 970513. Did not perforate.</td>
</tr>
<tr>
<td>tb21L</td>
<td>Autopsy:MGH A97-158 Sex: M Age: 78 Death: 04-23-97; 2:56pm In Saline: 04-24-97; 2:45pm</td>
<td>Myocardial infarction Coronary artery disease Heart block Pacemaker Carotid endarterectomy</td>
<td>Measurements made 2 to 3 weeks post mortem. Measurements on normal bone were not repeatable in either ear. After moistening, the response systemically decreased. Perforations not made. LEFT: Measurements on 970507 to 970511. On 970507 things seemed stable. Measurements with cavity open. On later days, stapes velocity decreased rapidly with time (over a course of 5 to 10 minutes), but could be reversed through moistening the annular ligament. RIGHT: Measurements on 970512 and 970513. Measurements with cavity open. Evidence of decreased response with time on 970513. Did not perforate.</td>
</tr>
<tr>
<td>tb22L</td>
<td>Autopsy:MGH A97-179 Sex: F Age: 78 Death: 05-13-97; 5:30pm In Saline: 05-14-97; 3:00pm</td>
<td>Aspiration pneumonia Spinal cerebellar degeneration Post breast carcinoma</td>
<td>Measurements made on both temporal bones. In both ears the posterior-inferior quadrant was much larger than the anterior-inferior one. LEFT: Measurements on 970516, 970518. Cavity sealed. Perforations made in anterior-inferior quadrant on 970518. Right: Measurements on 970522. Cavity sealed. Perforations made in posterior-inferior quadrant starting at margin of TM.</td>
</tr>
<tr>
<td>ID</td>
<td>General</td>
<td>Medical</td>
<td>Experiment notes</td>
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<tr>
<td>tb23</td>
<td>Autopsy: MGH A97-215</td>
<td>Congestive heart failure</td>
<td>Measurements made on 970626. Perforations made in anterior-inferior quadrant starting at margin of TM.</td>
</tr>
<tr>
<td></td>
<td>Sex: F</td>
<td>Aortic stenosis</td>
<td></td>
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<tr>
<td></td>
<td>Age: 77</td>
<td>Coronary heart disease</td>
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<td></td>
<td></td>
<td>Bladder cancer</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>In Saline: 06-20-97; 2:30pm</td>
<td></td>
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<tr>
<td>tb24R</td>
<td>Sex: F</td>
<td>Ischemic foot</td>
<td></td>
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<tr>
<td></td>
<td>Age: 77</td>
<td>Aspiration pneumonia</td>
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<tr>
<td></td>
<td></td>
<td>Atrial fibrillation</td>
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<td>In Saline: 06-25-97; 1:15pm</td>
<td></td>
</tr>
<tr>
<td>tb25</td>
<td>Autopsy: MGH A97-250</td>
<td>Coronary thrombosis</td>
<td>Measurements to show clear examples of effects of open vs. closed cavity, drying out and stability of preparation over time, foil on four staples locations for modes of motion, and effect of damage to round and oval windows.</td>
</tr>
<tr>
<td></td>
<td>Sex: F</td>
<td>Coronary artery disease</td>
<td></td>
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<tr>
<td></td>
<td>Age: 84</td>
<td>Acute renal failure</td>
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<tr>
<td></td>
<td></td>
<td>In Saline: 08-07-97; 2pm</td>
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</tr>
<tr>
<td>tb26</td>
<td>Autopsy: MGH A97-291</td>
<td>Ruptured abdominal aneurism</td>
<td>Measurements on 970925. Foil on two staples footplate locations for modes of motion, linearity measurements, affects of 1 vs. 2 vs. 3 pieces of foil on the staples.</td>
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<tr>
<td></td>
<td>Sex: F</td>
<td>Atrial fibrillation</td>
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<td></td>
<td>Age: 60</td>
<td>Barrettes esophagus</td>
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<tr>
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<td>In Saline: 09-16-97; 4:15pm</td>
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<tr>
<td>tb27</td>
<td>Autopsy: MGH A97-K321</td>
<td>Metastatic melanoma pericardiocentisia</td>
<td>Measurements on 971023. Foil on two staples footplate locations and posterior crus for modes of motion, linearity measurements, alts in the TM to demonstrate that &quot;H2&quot; has little effect on total transmission.</td>
</tr>
<tr>
<td></td>
<td>Sex: M</td>
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<tr>
<td></td>
<td>Age: 43</td>
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<td>Death: 10-16-97; 7:30am</td>
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<td>In Saline: 10-17-97; 1:35pm</td>
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<tr>
<td>tb28</td>
<td>Autopsy: MGH A97-395</td>
<td>Multiple cerebral infarcts</td>
<td>Measurements on 980106. Foil at two staples locations: anterior footplate and posterior crus. Not possible to view posterior part of footplate, due to anatomy. Measurements of modes of motion with normal TM and anterior-inferior perforations. Cavities were open.</td>
</tr>
<tr>
<td></td>
<td>Sex: M</td>
<td>CNS vasculitus</td>
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<td>Age: 42</td>
<td>Klebsiella pneumonia</td>
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<td>CAD</td>
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<td>In Saline: 12-31-97; 3:15pm</td>
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<tr>
<td>tb29</td>
<td>Autopsy: MGH A98-23</td>
<td>Myocardial Infarction</td>
<td>Measurements on 980123. Foil at two staples locations: anterior footplate and posterior crus. Not possible to view posterior part of footplate, due to anatomy. Measurements of modes of motion with normal TM and anterior-inferior perforations. Cavities were closed.</td>
</tr>
<tr>
<td></td>
<td>Sex: M</td>
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<tr>
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<td>Age: 55</td>
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<td>Death: 1-19-98; 7pm</td>
<td></td>
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<tr>
<td></td>
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<td>In Saline: 1-20-98; 3:30pm</td>
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Appendix B

Measurements of the middle-ear transfer function from all bones

Appendix B contains measurements of the middle-ear transfer function between stapes velocity and ear-canal pressure ($V_S/P_{EC}$) for each bone. In several cases, measurements were made with the bone in normal condition over a period of a few days. In other cases, measurements on the bone in the normal condition were made only on a single day. For each bone, a number of individual measurements are shown such that the plotted measurements cover the span of measurements made on each bone. Typically, consecutive measurements on a single bone were indistinguishable and thus only one measurement in a series of several may be plotted; exceptions are noted. Situations that seem to create variations between measurements on a single bone include when (1) the bone is repositioned in the experimental chamber and the laser is then realigned (e.g. changes in the angle between the stapes motion and the laser beam) (2) the bone is open to the air for a long time without being moistened (the time is bone dependent and can range from a couple of minutes to several hours, and the situation can usually be reversed by moistening the ear with saline) and (3) the bone sits overnight and bone dust from previous drilling collects in the middle ear system (rinsing the bone with saline can reverse this situation). The captions for each figure detail any circumstances that may have led to variability for a particular preparation.

In the figures that follow, a single measurement is plotted in a black line that is thicker than the other measurements. It is this measurement represented by the thick line that was chosen as a representative measurement from the particular bone and is included in Fig.1-10. The representative measurement was selected as either the measurement with the largest low-frequency magnitude or the measurement that seemed most stable (i.e. repeatable), and when measurements on a given bone were made with both open and closed cavities, the representative measurement was always a measurement made with a closed cavity. The rule of the largest low-frequency magnitude comes from the observation that as the bone begins to dry out, the low-frequency magnitude decreases. In most cases, such a decrease
in magnitude was reversible and remained at the increased magnitude when the bone was moistened with saline (e.g. bone 8). However, in some cases, particularly bones 11, 21 Left and 21 Right, the drying-out effects occurred within minutes of each measurement. As a result of such instability, perforations were not made on these bones.

The different measurements for a given bone may have been made with different numbers of samples for each computed average and under different cavity conditions (i.e. open or sealed). Each caption gives details on these variables for the case of the representative measurement only. All measurements shown are in response to a chirp stimulus (24 Hz to 25 kHz), with the exception of the measurements on bone 20, which were in response to tones swept from 24 to 10000 Hz. The measurements below 100 Hz are not plotted because they are often corrupted by the mechanical artifact.
Figure B-1: Measurements on temporal bones 1 and 2. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. Here, the middle-ear cavities were open for both bones 1 and bone 2. The bone 1 response is the average of 200 samples, and the bone 2 response is the average of 1000 samples.
Figure B-2: Measurements on temporal bones 3 and 4. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. Here, the middle-ear cavities were open for bone 3 and sealed for bone 4. The bone 3 response is the average of 200 samples, and the bone 4 response is the average of 1000 samples.
Figure B-3: Measurements on temporal bones 5 and 6. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The grey shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. Here, the middle-ear cavities were sealed for bones 5 and 6. The bone 5 response is the average of 1000 samples, and the bone 6 response is the average of 2000 samples.
Figure B-4: Measurements on temporal bones 7 and 8. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed and the responses are the average of 2000 samples. During the experiment on bone 7 the footplate was noticed to be cracked. Differences in the measurements on this bone are probably due to the footplate condition. The earliest measurement is the thick black line that does not have a large dip at 2000-3000 Hz. The variability in the bone 8 measurements seemed to result from drying-out effects; the lowest magnitude measurements occurred when the bone was open to the air and not moistened for the longest periods of time. After moistening the bone, the response returned to the maximal value and was stable over repeated measurements.
Figure B-5: Measurements on temporal bones 9 and 10. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed and the responses are the average of 2000 samples. The bone 9 measurements were made on 4 different days over a time span of 10 days. The difference between day 1 and day 2 measurements on bone 10 is due to disarticulation of the incudo-stapedial joint some time between the displayed measurements.
Figure B-6: Measurements on temporal bones 11 and 12. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed and the responses are the average of 2000 samples. The measurements for bone 11 show a decrease in response between two consecutive measurements. Such a drop in response indicated an unstable preparation and perforations were not made.
Figure B-7: Measurements on temporal bone 13. No measurements were made on bone 14 because it was ruined during drilling. The top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. The middle-ear cavity was sealed and the response is the average of 2000 samples. Note, the largest magnitude response was made with the middle-ear cavity open.
Figure B-8: Measurements on temporal bones 15 and 16. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{BC}|$, and the bottom plot is the corresponding angle of $V_s/P_{BC}$. The gray shaded region on the $|V_s/P_{BC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were open and the responses are the average of 2000 samples. Additionally, bone 16 was frozen prior to measurement.
Figure B-9: Measurements on temporal bones 17 and 18. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed and the responses are the averages of 1000 samples. The measurement on bone 18 that has a low magnitude was reversed by flushing some bone dust away from the oval-window region.
Figure B-10: Measurements on temporal bones 19 and 20. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed. The bone 19 response is the average of 1000 samples. The measurements on bone 20 were made in response to tones instead of the chirp stimulus used for all other measurements in this appendix. In this case, the response at each frequency is the average of 20 samples.
Figure B-11: Measurements on temporal bones 21 left and 21 right. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were open and the responses are the average of 1000 samples. For bone 21 left, the representative, thicker-lined measurement was repeatable on the first day of measurements. However, the next day the response was not stable. Shown are two measurements made within 5 minutes of each other that illustrate how the response systematically decreased time after moistening the middle ear. The measurements on bone 21 right showed a similar decline with time. The tympanic membranes on these bones were not perforated due to this instability.
Figure B-12: Measurements on temporal bones 22 left and 22 right. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed and the responses are the average of 1000 samples.
Figure B-13: Measurements on temporal bone 23. The top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. The middle-ear cavities were sealed and the response is the average of 1000 samples.
Figure B-14: Measurements on temporal bones 24 left and 24 right. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were sealed. The bone 24 left response is the average of 2000 samples, and the bone 24 right response is the average of 1000 samples. The lower magnitude response from bone 24 right were reversible by moistening the preparation.
Figure B-15: Measurements on temporal bones 25 and 26. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. For both bones, the middle-ear cavities were open and the responses are the average of 1000 samples.
Figure B-16: Measurements on temporal bones 27 and 28. For each bone, the top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_S/P_{EC}|$, and the bottom plot is the corresponding angle of $V_S/P_{EC}$. The gray shaded region on the $|V_S/P_{EC}|$ plot is the artifact magnitude. For bone 27, the middle-ear cavities were open for the three measurements in the thin lines, and the thicker-lined representative-data plot had a sealed middle-ear cavity. For bone 28, all measurements were with the cavities open. For both bones, the responses are the average of 1000 samples.
Figure B-17: Measurements on temporal bone 29. The top plot is the input ear-canal pressure magnitude, the middle plot is the magnitude $|V_s/P_{EC}|$, and the bottom plot is the corresponding angle of $V_s/P_{EC}$. The gray shaded region on the $|V_s/P_{EC}|$ plot is the artifact magnitude. The middle-ear cavities were sealed, and the responses are the averages of 1000 samples.
Appendix C

Measurements of the middle-ear transfer function with perforations: $V_S / P_{TM}$
Figure C-1: Stapes velocity per pressure at the tympanic membrane ($V_S/P_{TM}$) measured on bones 8 and 9 with increasing-sized tympanic-membrane perforations. Symbols indicate every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: |LOSS|. 
Figure C-2: Stapes velocity per pressure at the tympanic membrane ($V_S/P_{TM}$) measured on bones 13 and 18 with increasing-sized tympanic-membrane perforations. Symbols indicate every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: $|\text{LOSS}|$. Note, ear-canal pressure measurements on bone 18 are not corrected to transform $P_{EC}$ to $P_{TM}$ (chapter 2.2.3.2).
Figure C-3: Stapes velocity per pressure at the tympanic membrane ($V_S/P_{TM}$) measured on bones 19 and 20 with increasing-sized tympanic-membrane perforations. Symbols indicate every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: |LOSS|.
Figure C-4: Stapes velocity per pressure at the tympanic membrane \( \frac{V_S}{P_{TM}} \) measured on bones 22 Left and 22 Right with increasing-sized tympanic-membrane perforations. Symbols indicate every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: [LOSS].
Figure C-5: Stapes velocity per pressure at the tympanic membrane ($V_s/P_TM$) measured on bone 23 with increasing-sized tympanic-membrane perforations. Symbols indicate every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: [LOSS].
Figure C-6: Stapes velocity per pressure at the tympanic membrane \( (V_s/P_{TM}) \) measured on bones 24 Left and 24 Right with increasing-sized tympanic-membrane perforations. Symbols indicate every fifth data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: LOSS.
Appendix D

Measurements of the pressure difference across the tympanic membrane with perforations:

$H_{\Delta TM}$
Figure D-1: Pressure difference across the tympanic membrane per pressure at the tympanic membrane ($H_{\Delta TM} = (P_{TM} - P_{CAV})/P_{TM}$) measured on bones 8 and 9 with increasing-sized tympanic-membrane perforations. Symbols indicate every 25th data point. TCP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal.
Figure D-2: Pressure difference across the tympanic membrane per pressure at the tympanic membrane ($H_{\Delta TM} = (P_{TM} - P_{CAV})/P_{TM}$) measured on bones 13 and 18 with increasing-sized tympanic-membrane perforations. Symbols indicate every 25th data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal. Note, ear-canal pressure measurements on bone 18 are not corrected to transform $P_{EC}$ to $P_{TM}$ (chapter 2.2.3.2).
Figure D-3: Pressure difference across the tympanic membrane per pressure at the tympanic membrane ($H_{\Delta TM} = (P_{TM} - P_{CAV})/P_{TM}$) measured on bones 19 and 20 with increasing-sized tympanic-membrane perforations. Symbols indicate every 25th data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal.
Figure D-4: Pressure difference across the tympanic membrane per pressure at the tympanic membrane ($H_{\Delta TM} = (P_{TM} - P_{CAV})/P_{TM}$) measured on bones 22 Left and 22 Right with increasing-sized tympanic-membrane perforations. Symbols indicate every 25th data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal.
Figure D-5: Pressure difference across the tympanic membrane per pressure at the tympanic membrane $(H_{\Delta TM} = (P_{TM} - P_{CAV})/P_{TM})$ measured on bone 23 with increasing-sized tympanic-membrane perforations. Symbols indicate every 25th data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal.
Figure D-6: Pressure difference across the tympanic membrane per pressure at the tympanic membrane ($H_{\Delta TM} = (P_{TM} - P_{CAV})/P_{TM}$) measured on bones 24 Left and 24 Right with increasing-sized tympanic-membrane perforations. Symbols indicate every 25th data point. TOP: Magnitude. MIDDLE: Angle. BOTTOM: Magnitude change from normal.
Appendix E

Measurements of stapes velocity per pressure difference across the tympanic membrane with perforations: $H_{TOC}$
Figure E-1: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bones 8 and 9. Perforation size is the parameter. Perforation diameters $d$ and perforation locations are noted. Individual frequency points where either $|V_S|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{TM}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. TOP: Magnitude and Angle of $H_{TOC}$. BOTTOM: Magnitude and angle changes in $H_{TOC}$ from normal.
Figure E-2: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bones 13 and 18. Perforation size is the parameter. Perforation diameters d and perforation locations are noted. Individual frequency points where either $|V_S|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{TM}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. TOP: Magnitude and Angle of $H_{TOC}$. BOTTOM: Magnitude and angle changes in $H_{TOC}$ from normal. Note, ear-canal pressure measurements on bone 18 are not corrected to transform $P_{EC}$ to $P_{TM}$ (chapter 2.2.3.2).
Figure E-3: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bones 19 and 20. Perforation size is the parameter. Perforation diameters $d$ and perforation locations are noted. Individual frequency points where either $|V_S|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{TM}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. TOP: Magnitude and Angle of $H_{TOC}$. BOTTOM: Magnitude and angle changes in $H_{TOC}$ from normal.
Figure E-4: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bones 22 Left and 22 Right. Perforation size is the parameter. Perforation diameters d and perforation locations are noted. Individual frequency points where either $|V_S|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{TM}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. TOP: Magnitude and Angle of $H_{TOC}$. BOTTOM: Magnitude and angle changes in $H_{TOC}$ from normal.
Figure E-5: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bone 23. Perforation size is the parameter. Perforation diameters $d$ and perforation locations are noted. Individual frequency points where either $|V_S|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{TM}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. **TOP:** Magnitude and Angle of $H_{TOC}$. **BOTTOM:** Magnitude and angle changes in $H_{TOC}$ from normal.
Figure E-6: The stapes velocity per pressure difference across the tympanic membrane, $H_{TOC}$ (Equation 2.7), measured on bones 24 Left and 24 Right. Perforation size is the parameter. Perforation diameters $d$ and perforation locations are noted. Individual frequency points where either $|V_s|$ is within 20 dB of the measured artifact or $|\Delta P_{TM}/P_{TM}|$ is less than 0.1 are not included in calculation of the mean. Symbols indicate every fifth data point. TOP: Magnitude and Angle of $H_{TOC}$. BOTTOM: Magnitude and angle changes in $H_{TOC}$ from normal.
Appendix F

Measurements of middle-ear input impedance with tympanic-membrane perforations: $Z_{TM}$
Figure F-1: Impedences at the tympanic membrane measured on bones 8 and 9. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.
Figure F-2: Impedances at the tympanic membrane measured on bone 13. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.

BONE 18:
Valid Impedance measurements do not exist.
Figure F-3: Impedances at the tympanic membrane measured on bones 19 and 20. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.
Figure F-4: Impedances at the tympanic membrane measured on bones 22 Left and 22 Right. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.
Figure F-5: Impedances at the tympanic membrane measured on bones 23. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.
Figure F-6: Impedances at the tympanic membrane measured on bones 24 Left and 24 Right. Symbols indicate every 20th data point. TOP: Magnitude MIDDLE: Angle BOTTOM: Change from normal.
Appendix G

Measurements of $H_{P_{CAV}}$ from all bones
Figure G-1: Measurements of the transfer function $H_{PCAV} = \frac{P_{OW}}{P_{EC}}$ on bones 8 and 9, with a normal tympanic membrane and with increasingly larger perforations. Symbols indicate every 20th data point. TOP: Magnitude. BOTTOM: Angle.
Figure G-2: Measurements of the transfer function $H_{P_{CAV}} = P_{OW}/P_{EC}$ on bones 13 and 18, with a normal tympanic membrane and with increasingly larger perforations. Symbols indicate every 20th data point. TOP: Magnitude. BOTTOM: Angle.
Figure G-3: Measurements of the transfer function $H_{P\text{CAV}} = \frac{P_{OW}}{P_{EC}}$ on bones 19 and 20, with a normal tympanic membrane and with increasingly larger perforations. Symbols indicate every 20th data point. TOP: Magnitude. BOTTOM: Angle.
Figure G-4: Measurements of the transfer function $H_{P_{CAV}} = P_{OW}/P_{EC}$ on bones 22 Left and 22 Right, with a normal tympanic membrane and with increasingly larger perforations. Symbols indicate every 20th data point. TOP: Magnitude. BOTTOM: Angle.
Figure G-5: Measurements of the transfer function $H_{PAV} = P_{OW}/P_{EC}$ on bone 23, with a normal tympanic membrane and with increasingly larger perforations. Symbols indicate every 20th data point. TOP: Magnitude. BOTTOM: Angle.
Figure G-6: Measurements of the transfer function $H_{PCAV} = P_{DW}/P_{EC}$ on bones 24 Left and 24 Right, with a normal tympanic membrane and with increasingly larger perforations. Symbols indicate every 20th data point. TOP: Magnitude. BOTTOM: Angle.
Appendix H

Measurements of $P_{RW}/P_{OW}$ and $H_{WP_D}$ from all bones
Figure H-1: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on b 9, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-2: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 13, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-3: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 18, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-4: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 19, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-5: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 20, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-6: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 22 Left, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-7: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WPD} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 24 Left, symbols indicate every 25th data point, and the parameter is perforation size.
Figure H-8: Measurement of the ratio between the sound pressures at the round and oval windows, $P_{RW}/P_{OW}$ (Left column) and the transfer function $H_{WP} = (1 - P_{RW}/P_{OW})$ (Right Column). The measurements are on bone 24 Right, symbols indicate every 25th data point, and the parameter is perforation size.
Appendix J

Measurements of the window-pressure difference $|\Delta P_{win}/P_{TM}|$ from all bones
Figure J-1: Measurement of $\left| \frac{\Delta P_{\text{data}}}{P_{TM}} \right| = \left| \frac{P_{OW} - P_{RW}}{P_{TM}} \right|$ on bones 9 and 13. Symbols indicate every 25th data point.
Figure J-2: Measurement of $|\Delta \frac{P_{\text{non}}}{P_{TM}}| = |\frac{P_{\text{off}} - P_{\text{on}}}{P_{TM}}|$ on bones 18 and 19. Symbols indicate every 25th data point.

Figure J-3: Measurement of $|\Delta \frac{P_{\text{non}}}{P_{TM}}| = |\frac{P_{\text{off}} - P_{\text{on}}}{P_{TM}}|$ on bones 20 and 22L. Symbols indicate every 25th data point.
Figure J-4: Measurement of \( |\frac{P_{\text{wave}} - P_{\text{broad}}}{P_T}| \) on bones 24L and 24R. Symbols indicate every 25th data point.
Appendix K

Comparison between model and data: $Z_{TM}$. 
Figure K-1: Direct comparison between the measured and model impedances at the tympanic membrane of bone 8. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20$ dB re $10^9$Ns/m$^5$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-2: Direct comparison between the measured and model impedances at the tympanic membrane of bone 9. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20 \text{ dB re } 10^9 \text{Ns/m}^2$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-3: Direct comparison between the measured and model impedances at the tympanic membrane of bone 13. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20$ dB re $10^9$Ns/m$^{-5}$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-4: Direct comparison between the measured and model impedances at the tympanic membrane of bone 19. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20 \text{ dB re } 10^9 \text{Ns/m}^2$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-5: Direct comparison between the measured and model impedances at the tympanic membrane of bone 20. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of –20 dB re 10⁹Ns/m⁻⁵ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-6: Direct comparison between the measured and model impedances at the tympanic membrane of bone 22L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20 \text{ dB re } 10^9 \text{Ns/m}^{-2}$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-7: Direct comparison between the measured and model impedances at the tympanic membrane of bone 22R. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20\text{ dB re } 10^9\text{ Ns/m}^2$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-8: Direct comparison between the measured and model impedances at the tympanic membrane of bone 23. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20$ dB re $10^9$Ns/m$^2$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-9: Direct comparison between the measured and model impedances at the tympanic membrane of bone 24L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20 \text{ dB re } 10^9 \text{N s m}^{-5}$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Figure K-10: Direct comparison between the measured and model impedances at the tympanic membrane of bone 24R. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by dashed lines with a symbol at every tenth data point, and the model predictions are indicated by the solid line. LEFT: Magnitude. For each perforation, a reference line of $-20\text{dB}$ re $10^9\text{Ns/m}^2$ is indicated; the reference line typically crosses the measurement and model plots between 100 and 200 Hz. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks is 0.25 cycles.
Appendix L

Comparison between model and data: Transmission Loss.
Figure L-1: Direct comparison between the measured and model sound transmission losses of bone 8. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-2: Direct comparison between the measured and model sound transmission losses of bone 9. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-3: Direct comparison between the measured and model sound transmission losses of bone 13. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-4: Direct comparison between the measured and model sound transmission losses of bone 19. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-5: Direct comparison between the measured and model sound transmission losses of bone 20. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-6: Direct comparison between the measured and model sound transmission losses of bone 22L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-7: Direct comparison between the measured and model sound transmission losses of bone 22R. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-8: Direct comparison between the measured and model sound transmission losses of bone 23. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-9: Direct comparison between the measured and model sound transmission losses of bone 24L. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB Loss is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Figure L-10: Direct comparison between the measured and model sound transmission losses of bone 24R. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every data point, and the model predictions are indicated by the solid line. Measurements contaminated by the mechanical artifact (see chapter 2.2.3) are not plotted. LEFT: LOSS magnitude. For each perforation, a reference line at 0 dB LOSS is indicated on the right-hand side of the graph. The separation of adjacent ticks on the loss graph is 10 dB. The bottom plot indicates the dB difference between the model prediction and the measurement. Each curve begins with the symbol that corresponds to the perforation diameter indicated on the top set of plots. RIGHT: LOSS angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the angle plot is 0.25 cycles. The bottom plot indicates the differences between the model prediction and the measurement for each perforation.
Appendix M

Comparison between model and data: $H_{\Delta TM}$. 
Figure M-1: Direct comparison between the measured $H_{ATM}$ and model $\hat{H}_{ATM}$ for bone 8. The results for each perforation are vertically shifted to avoid overlapping. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 0.1 dB are removed because of inaccuracies in microphone calibrations (see Chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. The separation of adjacent ticks on the magnitude plot is 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. The separation of adjacent ticks on the angle plot is 0.25 cycles.
Figure M-2: Direct comparison between the measured $H_{\Delta TM}$ and model $\hat{H}_{\Delta TM}$ for Bone 9. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the the angle plot is equivalent to 0.25 cycles.
Figure M-3: Direct comparison between the measured $H_{\Delta TM}$ and model $\hat{H}_{\Delta TM}$ for Bone 13. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the angle plot is equivalent to 0.25 cycles.
Figure M-4: Direct comparison between the measured $H_{\Delta TM}$ and model $\hat{H}_{\Delta TM}$ for Bone 19. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the the angle plot is equivalent to 0.25 cycles.
Figure M-5: Direct comparison between the measured $H_{\Delta TM}$ and model $\tilde{H}_{\Delta TM}$ for Bone 20. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the the angle plot is equivalent to 0.25 cycles.
Figure M-6: Direct comparison between the measured $H_{\Delta TM}$ and model $\tilde{H}_{\Delta TM}$ for Bone 22L. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the angle plot is equivalent to 0.25 cycles.
Figure M-7: Direct comparison between the measured $H_{\Delta T M}$ and model $\hat{H}_{\Delta T M}$ for Bone 22R. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the angle plot is equivalent to 0.25 cycles.
Figure M-8: Direct comparison between the measured $H_{\Delta TM}$ and model $\hat{H}_{\Delta TM}$ for Bone 23. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the angle plot is equivalent to 0.25 cycles.
Figure M-9: Direct comparison between the measured $H_{\Delta TM}$ and model $\tilde{H}_{\Delta TM}$ for Bone 24L. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the the angle plot is equivalent to 0.25 cycles.
Figure M-10: Direct comparison between the measured $H_{\Delta TM}$ and model $\hat{H}_{\Delta TM}$ for Bone 24R. The results for each perforation are shifted in order to increase visibility. The measurements are indicated by a symbol at every 10th data point connected by a dashed line, and the model predictions are indicated by the solid line. Measurements less than 20 dB are removed because of inaccuracies in microphone calibrations (see chapter 2.2.4). LEFT: MAGNITUDE. For each perforation, a reference line at 0 dB is indicated on the right-hand side of the graph. Each relative hash-mark on the graph is equivalent to 10 dB. RIGHT: Angle. For each perforation, a reference line of 0 cycles is indicated; the reference line is indicated on the right-hand side of the figure. Each relative hash-mark on the angle plot is equivalent to 0.25 cycles.
References


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