Anatomy and Physiology of Hearing (added 09/06)

1. Briefly review the anatomy of the cochlea. What is the cochlear blood supply? SW

2. Discuss the effects of the pinna, head and ear canal on the transmission of sound. SW

3. What is impedance mismatching? How does the middle ear compensate/correct this problem? AL

The external ear funnels acoustic signals into the ear and plays an important role in sound localization, while the middle ear (including the tympanic membrane and the ossicular chain) matches the impedance between the air-filled external environment and the fluid-filled inner ear, or cochlea.

Impedance

Impedance generally can be thought of as the impediment to movement. In the study of acoustics, impedance is defined as the ratio of the acoustic pressure over the volume velocity generated by the acoustic pressure. Imagine an acoustic stimulus striking an elastic membrane (e.g., the tympanic membrane); the greater the sound pressure of the acoustic stimulus, the larger the motion of the membrane, and the higher the velocities achieved by that motion. The exact relationship between the pressure of the acoustic stimulus and the membrane volume velocity is governed by acoustic impedance.

There are three components to acoustic impedance: stiffness, resistance (damping), and mass. If the membrane were stiffer than normal, the volume velocity generated by the acoustic stimulus would be decreased. Similarly, if the mass of the membrane were increased, one would also expect the volume velocity generated by the acoustic stimulus to decrease. In addition, a small amount of sound energy is lost because of the damping effect of the system. In a simple acoustic resonator, stiffness varies inversely with frequency and dominates the acoustic impedance at low frequencies, whereas the impedance of a mass increases with frequency and dominates at high frequencies. When the acoustic impedance is at its lowest point (i.e., at the frequency where the stiffness and mass components of the acoustic impedance cancel each other out), it is said that the system is in resonance.

Middle Ear: TM vibrates → ossicular chain vibration → inner ear fluid vibration

Because the inner ear is fluid-filled, if the sound stimulus strikes the inner ear fluid directly, most of the acoustic energy is deflected, as the impedance of fluid is much greater than the impedance of air. The pathway of sound transmission to the inner ear in the absence of the ossicular system is referred to as acoustic coupling.4 It has been shown
that the difference between ossicular coupling and acoustic coupling is about 60 dB, which is the maximal amount of hearing loss expected in patients with ossicular discontinuity. The middle ear plays an important role in the process of “impedance matching” between the air-filled middle ear and the fluid-filled inner ear, allowing for efficient sound transmission. The most important factor in the middle ear’s impedance matching capability comes from the “area ratio” between the tympanic membrane and the stapes footplate.

Lever Ratio: the difference in length of the manubrium of the malleus and the long process of the incus. Because the manubrium is slightly longer than the long process of the incus, a small force applied to the long arm of the lever (manubrium) results in a larger force on the short arm of the lever (incus long process). In humans, the lever ratio
is about 1.31 : 1 (2.3 dB). The combined effects of the area ratio and the lever ratio give the middle ear output a 28-dB gain theoretically. In reality, the middle ear sound pressure gain is only about 20 dB; this is mostly due to the fact that the tympanic membrane does not move as a rigid diaphragm.

Loss of energy due to **impedance mismatching** and transduction losses is another inherent drawback of conventional aids. The mechanical **impedance** (change in pressure for a given displacement flow) of the air-filled external auditory canal differs from that of the fluid-filled cochlea. Without a middle ear mechanism, a majority of the acoustic energy striking the stapes footplate reflects back into the air. When the tympanic membrane and ossicular chain are functioning normally, they act as an impedance-matching transformer by virtue of the relative areas of the tympanic membrane and stapes footplate and by the lever action of the ossicular chain.[34] The relatively large-displacement, low-pressure movements of air against the tympanic membrane are transduced to the relatively small-displacement, high-pressure movements of the footplate. Except for bone-conducting aids, all traditional hearing aids use a speaker to output an (amplified) acoustic wave into the air of the external auditory canal. When this middle ear apparatus is malfunctioning, as occurs in otosclerosis, tympanic membrane perforation, or in a canal-wall-down mastoidectomy, traditional hearing aids must overcome the **impedance mismatch**. The result is either reduced effective gain, increased distortion, or both.

Even when the ossicular chain is functioning normally, the transduction of acoustic energy from air at the input of a traditional hearing aid to stapes footplate motion is imperfect. Whenever a signal flows from one physical realm (e.g., electrical current in a speaker) to another (e.g., acoustic waves in air), some energy is lost (e.g., to heat) and noise or distortion can add to the desired signal. There are several transduction steps for a traditional hearing aid—from acoustic waves in ambient air, to electrical current in a microphone, to a larger electrical current in a speaker wire or piezoelectric driver, to acoustic waves in air within the external auditory canal, to movement of the tympanic membrane and ossicular chain, to acoustic waves in perilymph, to hair cell stereociliary deflection and depolarization, and so forth. Most are unavoidable (although cochlear implants bypass these steps through direct cochlear nerve stimulation). However, directly coupling a hearing aid actuator movement of the ossicular chain can delete some of these transduction steps, boosting gain and reducing distortion. Nearly all implantable hearing aids make use of this approach.

4. Describe the role of the middle ear muscles in sound conduction. (for extra points....what is the innervation for each?)

AL

Two striated muscles, the tensor tympani and the stapedius, are located in the middle ear. The former attaches to the malleus and is innervated by the trigeminal nerve. The stapedius muscle
attaches to the stapes and is innervated by the stapedial branch of the facial nerve. Noticeably the stapedius and tensor tympani muscles are the smallest striated muscles in the body and also have a high innervation ratio, that is, nerve fibers per muscle fiber. Although no question remains that contraction of these muscles affects sound transmission through the middle ear, the details of the effect and the extent of the influence of the middle ear muscles are still not fully understood. A number of disparate functions have been attributed to the middle ear muscles.

One function of the middle ear muscles is to protect the cochlea from loud sounds (2). When sounds louder than approximately 80 dB SPL are presented monaurally or binaurally, consensual (bilateral) reflex contraction of the stapedius muscle occurs. This contraction increases the stiffness of the ossicular chain and tympanic membrane, attenuating sounds less than approximately 2 kHz. Although the tensor tympani contracts as part of a startle response, acoustic reflex data from human subjects with neurologic involvement of cranial nerves V and VII suggest that the tensor tympani does not normally respond to intense acoustic stimulation. Laboratory and field studies of noise-induced hearing loss have shown convincingly that the stapedial reflex protects the cochlea, particularly from low-frequency (<2 kHz) sounds in excess of 90 dB. Inasmuch as the latency of the acoustic reflex is greater than 10 ms, the cochlea may be unprotected from short-duration, unanticipated impulsive sounds.

The following functions have been attributed to the middle-ear muscles. Some of these functions include providing strength and rigidity to the ossicular chain; contributing to the blood supply of the ossicular chain; reducing physiologic noise caused by chewing and vocalization; improving the signal-to-noise ratio for high-frequency signals, especially high-frequency speech sounds such as voiceless fricatives, by means of attenuating high-level, low-frequency background noise; functioning as an automatic gain control and increasing the dynamic range of the ear; and smoothing out irregularities in the middle-ear transfer function.

5. Discuss the effects of TM perforation and middle ear effusions on sound conduction. CB
6. Discuss the inner ear fluids. CB

7. Give us an in-depth review on the function of the inner and outer hair cells. TT

8. Review the basilar membrane and traveling wave. TT

9. Describe the final pathway of neural stimulation from the cochlea to the brain. HH