# Ear Anatomy

To talk about how the ear and brain process the physical characteristics of sound and convert these into what we actually perceive as sound, it is important to first understand how the ear itself functions in the presence of a sound wave. There are three principle parts to the auditory system. (see handout).

1) Outer Ear
   - (i) pinna
   - (ii) auditory canal/meatus
2) Middle Ear (Air-filled)
   - (i) eardrum/tympanic membrane/tympanum
   - (ii) ossicles - malleus/hammer, incus/anvil, stapes/stirrup
   - (iii) Eustachian tube
3) Inner Ear (Fluid-filled)
   - (i) Cochlea
     - a) oval window $\xrightarrow{\text{opening of}}$ scala vestibuli } connected by helicotrema,
     - b) round window → scala tympani } both filled w/ perilymph
     - c) Scala media - filled w/ endolymph, sits between scala.
       - 1) organ of Corti
       - 2) basilar membrane } connected by cilia
       - 3) tectorial membrane }
   - (ii) Auditory Nerve

When a sound wave travels through the air and into your ear, it first hits the pinna. The pinna both helps direct sound into your ear and, due to its unique shape, alters the frequency content of the incoming sound wave depending on the direction from which it came, adding some directional information to the sound so we can identify the location of its source.

Once directed into the ear, the sound wave passes through the meatus and hits the eardrum. Frequencies in the range of ~1-3.5 kHz vibrate the eardrum most easily, but it vibrates over the entire audible frequency range (~20 Hz - 20 kHz)

The eardrum and ossicles primarily serve to perform an impedance match between the air in the middle ear and the fluid in the inner ear.

Thinking back to the FHO, we defined the mechanical impedance $\tilde{Z}_m$ of the oscillator as the ratio of the force applied to the oscillator to the oscillator's resulting velocity. We can think of this impedance in terms of energy transfer as well. If a system has a very high impedance, it takes a lot of force to get the system moving even a little, so it's difficult to transfer energy to the system. However, if the system has a very low impedance, it only takes a little bit of force to get the system moving very quickly, so it's very easy to transfer energy to it.

In the case of the ear, we have something similar, but in terms of what's called an acoustic impedance, $\tilde{Z}_a$, which is the ratio of acoustic (sound) pressure applied to an object/medium to the resulting volume flow of the object/medium. (Note: by acoustic pressure, we mean the pressure created by a sound source that is in excess of the ambient pressure, e.g. atmospheric pressure).

If there is a large difference in acoustic impedance between two mediums (as is the case for inner ear fluid vs. water [about 4,000 : 1]), it is very difficult to transfer energy from the low $\tilde{Z}_a$ medium to the high $\tilde{Z}_a$ medium.

To allow for the best possible energy transfer between the two media, we'd like their impedances to be roughly equal (impedance match them).

The ear performs this matching by doing two things:

$$\left.\begin{array}{l}\text{1) Force amplification}\\ \text{2) Area reduction}\end{array}\right\} \text{ Since } \tilde{Z}_a = \frac{p}{u} = \frac{(F/A)}{u},\ F\uparrow \text{ and } A\downarrow \Rightarrow \tilde{Z}_a\uparrow \text{ for the air.}$$

For (1), the ossicles connecting the eardrum to the oval window of the cochlea act like a lever, providing a mechanical advantage that amplifies the force imparted on the eardrum by the sound wave so the resulting force at the oval window is larger.

For (2), the eardrum has a surface area about 27× larger than the oval window, so the area over which the force acts is much smaller for the oval window.

In combination, these 2 factors result in the required impedance match needed to efficiently transfer sound energy to the inner ear. Without it, we would hardly be able to hear (think about going swimming and trying to hear someone speaking outside the water while you're below it).

Also in the middle ear, the Eustachian tube serves to equalize the pressure inside the middle ear (behind the eardrum) with the atmospheric pressure outside the ear. This pressure mismatch is why our ears hurt when we go to high altitudes (e.g. an unpressurized airplane cabin). Swallowing helps because it is what causes the Eustachian tube to open, allowing pressure to equalize.

Past here is the inner ear, which begins where the stapes connects to the oval window of the cochlea, a coiled-up double tube with a fluid-filled cavity sitting between the two tubes.

The membrane-covered oval window is the opening of the upper tube of the cochlea, the scala vestibuli. The lower tube, the scala tympani, opens at the round window. The tubes are connected at their ends by the helicotrema. Between the two tubes is the scala media, the endolymph-filled cavity where the sound wave gets converted to an electrical signal to be sent to the brain.

When the ossicles vibrate the oval window, the perilymph contained in the two scala tubes sloshes back and forth, creating pressure on the scala media, causing the basilar membrane inside the scala media to vibrate.

The basilar membrane is connected to the tectorial membrane by about 30,000 hairlike receptors, the cilia. When the basilar membrane vibrates, the tectorial membrane remains mostly fixed, causing the cilia to shear between the two membranes, which creates electrical impulses that are sent along the auditory nerve to the brain up through the organ of Corti.

The reason we can pick out the individual frequencies (or more accurately, pitches) that we perceive as making up the sounds we hear is the special shape of the basilar membrane. At the end of the scala media that is near the opening of the cochlea, the membrane is narrow and stiff. As we move toward the other end, it becomes more broad and flimsy. The narrower end is more easily vibrated by higher frequencies, and the thicker end responds better to lower frequencies. Because of this, a pure tone would only cause significant vibration in a small section of the basilar membrane, so only cilia in this section would send large impulses to the brain to be interpreted as particular pitches.

This mechanism essentially maps different frequencies to different parts of the basilar membrane, and thus different parts of the brain. Because of this, our ear and brain act somewhat like a Fourier analyzer, albeit a much less straightforward one with some caveats we will discuss later (see Missing Fundamental and Frequency vs. Pitch). This mapping is called a tonotopic mapping (tono-frequency, top-place). Because of these caveats and other oddities in how we perceive sound, we cannot use a strictly physical approach to analyze our perception. Instead, we enter a field that mixes physics and psychology - psychoacoustics.