The ability to hear is critical to interacting with the environment and other people. The mechanism of hearing can be broken down into conductive, sensory and neural components, each sequentially necessary for the appreciation of sound. This paper’s goal is to discuss the conductive component of hearing. This will include a discussion of the physics of sound, the physics of conductive hearing, tympanograms and the acoustic reflex, the physiopathology of Carhart’s Notch, and Diagnostic Implications of Carhart’s Notch.

**Physics of Sound**

Sound is transmitted through air as longitudinal compression waves. Several physical aspects are important to understanding how sound is perceived.

- **Frequency**: sounds waves have a repetitive aspect that are described as
  - Frequency = cycles / unit time.
  - Commonly described as cycles per second (Hertz)

- **Wavelength**: Distance between repeating units of a propagating wave
  - Wavelength = velocity / frequency

- **Period**: The length of time till the wave repeats itself
  - Period = 1/frequency

- **Amplitude**: The “heights” the wave from zero
  - The nonnegative scalar measure of a wave’s magnitude of oscillation

- **Intensity**: Intensity is a measure of energy flux
  - Intensity is NOT synonymous with strength, amplitude, or level
  - Intensity is the net power radiated over the surface that the sound power passes through. Intensity decreases with the square of the distance from the source of the sound
Speed
- The distance a wave travels per unit time. The speed of sound is 770 mph in dry air at 70 degrees Fahrenheit.
- The speed of sound increases with the stiffness of the medium and decreases with the density of the medium.

Direction
- Direction is the vector component of the wave.
- Sound’s directional properties allow us to “know” where sound is coming from.

Resonance
- Small amounts of vibration energy at the right frequency can cause an object to vibrate at large amplitudes.
- This is commonly seen on playgrounds. Imagine a child in a swing. Each time a child is pushed, the push is not large enough by itself to have the child swing to his delight. However, with sequential small pushes the child will swing higher and higher. This is because the pusher intuitively knows to push the child at the resonance frequency allowing each small pushes to “add up.”

Pitch
- is the perceived fundamental frequency of a sound.
- not an objective physical property but a subjective psychophysical attribute.
- perceived pitch may differ because of overtones, or partials, in the sound.

Timbre
- Why two guitars sound different even when they play the same note.
- the characteristic quality of a sound, independent of pitch and loudness, from which its source or manner of production can be inferred. Timbre depends on the relative strengths of the components of different frequencies, which are determined by resonance.
- Timbre is difficult to define.
- “the psychoacoustician's multidimensional wastebasket category” McAdams, 1979.

Sound Pressure Level (SPL)
- As the human ear can detect sounds with a very wide range of amplitudes, sound pressure is often measured as a level on a logarithmic decibel scale.
\[ L_p = 10 \log_{10} \left( \frac{p^2}{p_{ref}^2} \right) = 20 \log_{10} \left( \frac{p}{p_{ref}} \right) \text{ dB} \]
- \( p \) is the sound pressure.
- \( p_{ref} \) is the reference pressure in the medium (air in most cases).
- This is a logarithmic scale, expressed in decibels because the range of human hearing is quite large.

Frequency Weighting
- The human ear is more sensitive to different frequencies than others. Sound at the sound pressure level will be perceived at different levels of loudness depending on the sound’s frequency.
- Frequency weighting curves have been developed to help define the threshold for hearing at different frequencies.
- Different frequency weighting curves have been developed in the past.
- The most common weighting curve today is called “A weighting.”
- D weighting was used in industrial applications because human thresholds for noise (not pure tones) is different than for pure tones.
- Sound level, loudness, and intensity are not the same thing
  - Sound level is a physical property
  - Loudness refers to how a sound is perceived
  - Intensity is sound power per unit area

**Physics of Conductive Hearing**

Sound in the form of air vibrations arrives at the auricle and is transmitted through the external acoustic canal. Sound then causes the tympanic membrane to vibrate. Vibration energy in the tympanic membrane is transmitted through the ossicles to the oval window into the cochlea. Pressure vibrations are transmitted into the scala vestibuli and into the cochlea. Vibrations of the scala vestibuli are greatest at the location where the resonance frequency of the cochlea corresponds to the frequency of the transmitted sound waves. In this way, a topographic representation of sound is possible. The basilar membrane vibrates which causes deflection of the steroicilia, and stimulation of the cochlear nerve.

This begs the question: what is the purpose of the middle ear? The reason lies in the problem of impedance: the resistance of transfer of energy between two media. Imagine sunny day by a pool. Sun shines on the water. Some of the light bounces off the water while the balance is transmitted through the water. This why we can both see a glare on top of the water, but it is not dark below the surface. Without the middle ear, most of the sound would bounce off of the surface of the oval window and little would be transmitted into the cochlea. This is because sound most pass from one media (air) into another (liquid) in order to stimulate the cochlea.

The middle ear reduces the problem of impedance mismatch through several mechanisms. For one, the area of the tympanic membrane is ~ 17 times larger than the area of the oval window. This can be understood through the “Garden Party Effect.” Imagine that designer Yves Saint Laurent and his date arrive at a garden party. Despite the fact that his date is famishly underweight, her high stiletto heels still sink into the ground. In this way, a small force (starved model’s weight) can depress a relatively hard medium (grassy lawn) because all of her force (80 lbs) is concentrated over her stiletto heels (4cm$^2$).

A second mechanism by which the middle ear overcomes impedance mismatch is through the ossicles. The malleus is 1.3 times longer than the incus. Taken together, 1.3 x 17 equals a combined mechanical advantage of 22. Using our previous formula for sound pressure level:

$$20 \log 22 = 26.8$$

Therefore, the contribution of the tympanic membrane and ossicles to overcoming impedance mismatch via the lever and area ratio is approximately equal to 27 decibels.

We may stimulate the ear either with sound pressure waves or via vibrations applied directly to the skull. These second mechanism is noted on audiograms as bone conduction and is used to assess the sensory neural component of hearing. There are three mechanisms in which vibratory energy placed directed onto the skull will cause stimulation of the cochlea: 1) distortional 2) inertial – ossicular 3) osseotympanic
The distortional mechanisms is due to vibration directly distorting the skull. As the cochlea is part of the skull, it would be distorted as well. Because the round window yields more than the oval window, the scala vestibuli and scala tympani have different compliances. This results in the deflection of the basilar membrane and deflection of steroicillia with stimulation of the auditory nerve.

The inertial-ossicular mechanism of conductive hearing relates to the ability of vibration energy directed to the skull to cause motion of the ossicles. Imagine a plate with an orange in the middle. Shaking the plate will cause the orange to move, but not necessarily in phase with the plate. Likewise, vibration to the cause the ossicles to move. When move, they impart their energy on window which stimulates the However, this is dependent on the direction of vibrations in the direction of vibration is parallel to the axis of the movement of inertial-ossicular mechanism of conductive hearing takes place. of skull vibration is perpendicular to the axis of the movement of the effect is negligible. As any vibrating object, the ossicles have frequency. Therefore the inertial-ossicular mechanism of hearing is more prominent about 2kHz, the resonance frequency ossicles.

The osseotympanic mechanism of bone conductive hearing is best illustrated by occlusion of the external auditory canal. Occlusion may be artificially induced by covering the external ear with a headphone or seen naturally as the result of pathologic conditions such as cerumen impaction. Vibration energy is transmitted through the skull, causing a vibration of the soft tissues of the external auditory canal. This vibratory energy is transmitted into the air of the external auditory canal. Some escapes the external auditory canal while some reaches the tympanic membrane. The tympanic membrane is this stimulated, energy is transferred to the ossicles and onward to the cochlea. This explains why when the external ear canal is occluded, the bone-conduction threshold improves. Vibration energy into the external auditory canal bounces back from the object occluding the external auditory canal. Less sound energy is lost and more is reflected onto the tympanic membrane. This is particularly pronounced in the lower frequencies.

**Tympanograms**

A tympanogram is used to assess the compliance of the middle ear system. The external auditory canal is occluded with a probe in order to maintain a pressure seal. A sound is then presented to the tympanic membrane. Meanwhile, pressure pump changes the pressure in the external auditory canal. At the same time, a microphone measures the sound reflected back off of the tympanic membrane. In this manner, the compliance of the middle ear system is ascertained.
The maximum compliance value occurs at peak of the curve on the graph. Maximum compliance of the middle ear system occurs when the pressure in the middle ear cavity is equal to the pressure in the external auditory canal. A normal tympanogram (type A tympanogram) is shaped like an A and has a peak at 0 daPa. A Type As (stiff) has a peak at 0 daPa but has a lower amplitude. This can imply a stiff middle ear which can suggest conditions such as tympanosclerosis, poor ossicular mobility, or otosclerosis. An Ad (dynamic) tympanogram represents a highly compliant middle ear. For unknown reasons, our audiologists see this more often in swimmers. A retracted tympanic membrane can produce a C type tympanogram, due to negative middle ear pressure. A B type tympanogram results from low compliance. This can be due to tympanic membrane perforation, cerumen impaction, or middle ear effusion.
Conductive Hearing Loss and Carhart's Notch

June 2008

Diagram A: 1.5 mhos
1.0 mhos
0.5 mhos

Diagram B: 1.5 mhos
1.0 mhos
0.5 mhos

Diagram C: 1.5 mhos
1.0 mhos
0.5 mhos

Diagram D: 1.5 mhos
1.0 mhos
0.5 mhos

Admittance vs. Air Pressure daPa
The Acoustic Reflex

The acoustic reflex is another method of assessing middle ear function. With a stimulus of sound, the stapedius muscle will contract, causing a change in the impedance of the middle ear system. This change in middle ear impedance occurs slightly after the presentation of the stimulus, and disappears once the stimulus is removed. If there is partial or total fixation of the stapedius footplate, the acoustic reflex is affected. With partial fixation of the anterior footplate, a diphasic reflex can occur. The diphasic reflex is typified by a decrease in impedance followed by a return to baseline. With the termination of the sound stimulus, the impedance decreases and returns to normal again. This is believed to result from the return of the partially fixed stapes to its former position. A completely fixed stapes results in no movement in response to contraction of the stapedius muscle. Thus, there is no change in impedance and no acoustic reflex is noted. Up to 40% of normal hearing subjects have mixed acoustic reflexes. The pathophysiology of this is not completely understood.

Conductive Hearing Loss and Carhart’s Notch

After reviewing the physics of sound and conductive hearing, it is possible to begin discussion of Carhart’s notch – a phenomenon of otosclerosis. Otosclerosis is typified by fixation of the foot plate of the stapes. An in-depth discussion of otosclerosis is found in the grand rounds given by Dr. Alan Cowen several years ago.

A audiogram in otosclerosis will often show decrease in air conduction at all frequencies. Carhart’s notch refers specifically to a decrease in bone conduction of 10-15 dB seen around 2kHz. As
bone conduction on the audiogram is taken to imply sensory neural hearing reserve: the best that hearing can be if there is no loss in conductive hearing. Carhart’s notch is interesting because it often disappears after successful stapes surgery. Paradoxically, improving conductive hearing appears to improve sensory neural hearing. This occurs because Carhart’s notch does not represent true sensory neural hearing. Carhart’s notch is an artifact of stapes fixation.

Let us return to our previous discussion of the inertial-ossicular mechanism of conductive hearing. In the inertial-ossicular mechanism of conductive hearing, vibration energy transmitted to the skull causes movement of the ossicular chain. This effect would be most pronounced at the resonance frequency of the ossicles – around 2 kHz. The contribution of the inertial-ossicular mechanism to conductive hearing is smaller away from the resonance frequency of the ossicles.

If the stapes footplate is fixed, this increases impedance and decreases the amount of sound energy available for transmission through air to the middle ear. If we stimulate the middle ear by applying vibrations directly to the skull, we bypass the ossicles by the directly vibrating the cochlea via distortional mechanism of conductive hearing. However, the inertial-ossicular mechanism of bone-conductive hearing is impaired. This is why bone conduction is decreased around the resonance frequency of the ossicles, 2kHz. This also explains that successful stapes surgery will remedy the fixation of the stapes footplate and return inertial-ossicular to normal.

Diagnostic Implications of Carhart’s Notch

Though Carhart’s notch is found most commonly in otosclerosis, it is neither perfectly sensitive nor specific. Carhart’s notch can found in other conditions that affect the middle ear such as primary malleus fixation and otitis media with effusion. Furthermore, early cochlear otosclerosis may not affect the entire stapes footplate. Progression of otosclerosis to cochlear otosclerosis can cause a true sensory neural loss. Models have been attempted to describe the relationship between Carhart’s notch and clinically improved hearing, but their clinical implications are limited. One study however found that a Carhart’s notch was predictive of a fixed stapedial foot plate at the time of stapidectomy.
**Distribution of Carhart’s Notch (CN) by Middle-Ear Pathology**

<table>
<thead>
<tr>
<th>Pathology</th>
<th>Mean age (years)</th>
<th>Total Ears (n)</th>
<th>CN at 1 kHz</th>
<th>CN at 2 kHz</th>
<th>Total CN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cholesteatoma</td>
<td>-</td>
<td>23</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TM perforation</td>
<td>-</td>
<td>25</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Ossicular defect</td>
<td>-</td>
<td>47</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Granulation otitis</td>
<td>-</td>
<td>52</td>
<td>8</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Chronic otitis media</td>
<td>32.7 +/- 14.4</td>
<td>147</td>
<td>10</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td><strong>Otosclerosis</strong></td>
<td><strong>43.6 +/- 12.5</strong></td>
<td><strong>26</strong></td>
<td><strong>1</strong></td>
<td><strong>17</strong></td>
<td><strong>18</strong></td>
</tr>
<tr>
<td>Middle-ear effusion</td>
<td>19.5 +/- 19.4</td>
<td>70</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Tympanosclerosis</td>
<td>23.3 +/- 7.1</td>
<td>61</td>
<td>1</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Others</td>
<td>31.5 +/- 13.7</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2936 +/- 16.5</strong></td>
<td><strong>315</strong></td>
<td><strong>14</strong></td>
<td><strong>41</strong></td>
<td><strong>55</strong></td>
</tr>
</tbody>
</table>

**DISCUSSANT’S REMARKS: Francis B. Quinn, Jr., MD**

Whenever I ask my medical student class to give me the function of the tympanic membrane and ossicles, they invariably answer that these structures “amplify” the sound so that it can be perceived by the inner ear mechanism. In a sense they are correct in that the absence of these structures, the hearing threshold is degraded by up to 30 dB on average.

Leading them into a discussion of clinical impedance audiometry, limited mainly to tympanometry, however, requires that I introduce them to the concept of acoustic impedance, a concept foreign to all but the few having come to us with a degree in engineering or with some familiarity with alternating electrical circuits or geophysical exploration.

In essence, the pinna, ear canal, tympanic membrane, and ossicles together form an impedance matching system, permitting energy represented by pressure waves in air to be transferred to pressure waves in the fluids of the inner ear with minimal entropy. These sound waves are not amplified; rather, they are translated to a form to which the transducer mechanism of the inner ear can resonate.

Physiologically, acoustic impedance is a function whose variables are stiffness, mass, and frequency of the assembled components of the outer and middle ear. An understanding of the function has enabled us to appreciate its great utility in the diagnosis of many of the disorders of the middle and inner ear, as well as cranial nerves VII and VIII.
References:

- Yves Pelletier, Physics animations
  - http://web.ncf.ca/ch865/graphics/ElectricFlux.jpeg
  - www.homeschoolmath.net/worksheets/equation_editor.php
- “The Acoustic Reflex,” Richard W. Harris, Ph.D., Brigham Young University