Auditory Transduction

How the ear converts acoustic energy into a neural response

The bottom line

Hair cells are specialized so that motion of their stereocilia changes their electrical potential, resulting in neurotransmitter release and action potentials in the nerve fibers that contact the hair cells.

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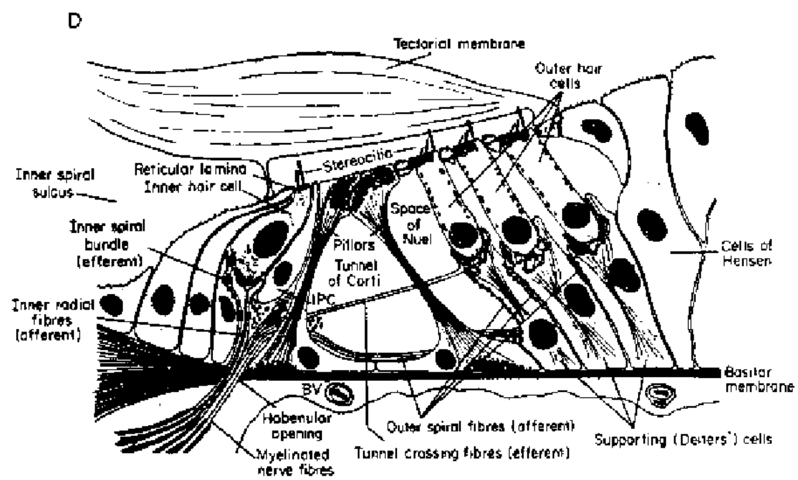
A closer look at the organ of Corti



From Pickles (1992)

Remember that the hair cell bodies are beneath a solid barrier, while their stereocilia extend above that barrier.

The solid barrier between the hair cell bodies and the stereocilia is the

(A) Reissner’s membrane

(B) basilar membrane

(C) helicotrema

(D) reticular lamina

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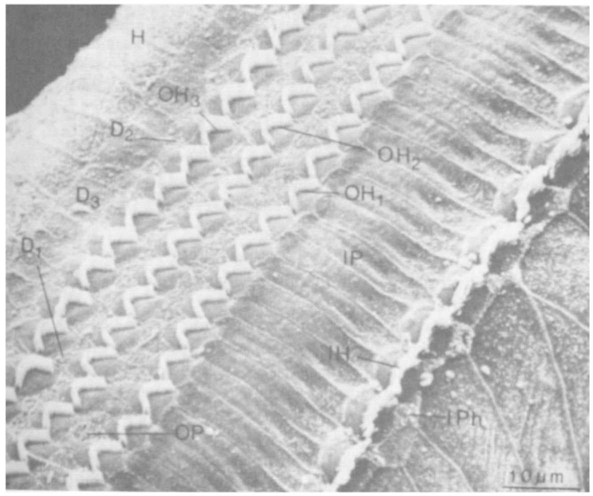
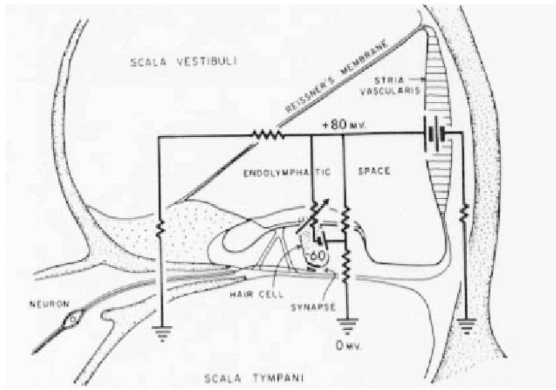
Reticular lamina



From Gelfand (1998), Lim (1986)

The reticular lamina is the solid surface at the tops of the hair cells.

Electrical situation in the organ of Corti



From Gelfand (1998)

This is important in maintaining the electrical potential differences that "drive" the transduction process. The inside of the hair cell is about 40-60 mV more negative than the perilymph. The endolymph is about 80 mV more positive than the perilymph. The positive charge is carried by potassium (K) ions; endolymph is produced by the stria vascularis. The 120-140 mV potential difference between the endolymph and the inside of the hair cells is called the endocochlear potential.

If there is a positive potential difference between the endolymph and the inside of the hair cells, electrical currents will tend to flow

(A) into the hair cells

(B) out of the hair cells

(C) into the stria vascularis

(D) across Reissner's membrane

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Another view...

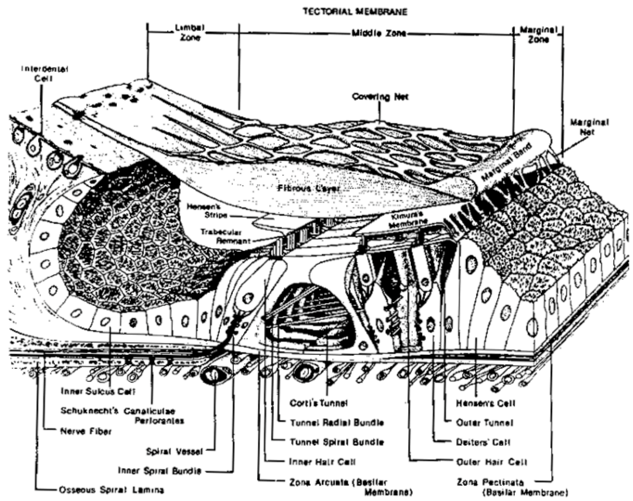

Figure 2.21 The tectorial membrane in relation to the other structures of the organ of Corti. From Lim (1980) with permission of *J. Acoust. Soc. Am.*

From Gelfand (1998)

This picture shows the mechanical arrangement of the parts of the organ of Corti. Notice that the tectorial membrane is only attached to the rest of the organ of Corti by thin strands on its outer edge. It is solidly attached on the modiolar side (cut off in this picture).

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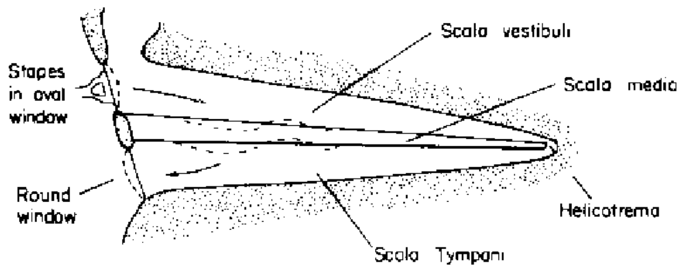
Basilar membrane motion



From Pickles (1992)

Motion of the stapes footplate in the oval window leads to a pressure change in the cochlear fluids which is offset by the “bulging” of the round window. Thus, there is a pressure differential across the basilar membrane that sets it in motion. The length of the basilar membrane is short compared to the wavelength of sounds, so it is NOT as if the sound is transmitted along the cochlear duct. The pressure change is simultaneous along the duct.
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Cochlear motion

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

Another view of how the basilar membrane moves.

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The motion of the basilar membrane is similar to the motion

(A) of a sine wave

(B) of a triangular wave

(C) of a rope that is “flicked” at one end

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If I play a tone into the ear, the motion of the basilar membrane will be most like

(A) a sine wave.

(B) a triangular wave.

(C) a rope alternately “flicked” up and down.

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“shearing action”

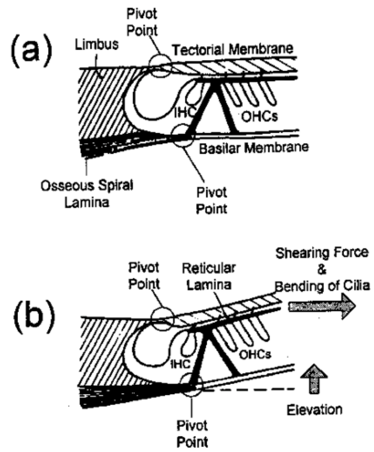

Figure 4.11 Relative positions of the basilar membrane and tectorial membrane (a) at rest, and (b) duration elevation toward the scala vestibuli. (Based on Davis, 1958.) Davis' (1958) model calls for upward deflection to result in outward bending of the stereocilia, as shown in frame (b).

From Gelfand (1998)

Because the tectorial membrane is not tightly coupled to the reticular lamina, when the basilar membrane moves, the tectorial membrane lags behind due to inertia, and the angle between the reticular lamina and the tectorial membrane changes. The tectorial membrane “shears” across the reticular lamina, and the stereocilia of the hair cells.

“shearing action” movie

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

Inner hair cell stereocilia

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

The stereocilia of the inner hair cells are not embedded in the tectorial membrane, but those of outer hair cells are. Motion of the fluid aurrounding the IHC stereocilia, however, moves them.

Shearing of the tectorial membrane across the reticular lamina displaces the

(A) stereocilia

(B) basilar membrane

(C) Deiter's cells

(D) pillar cells

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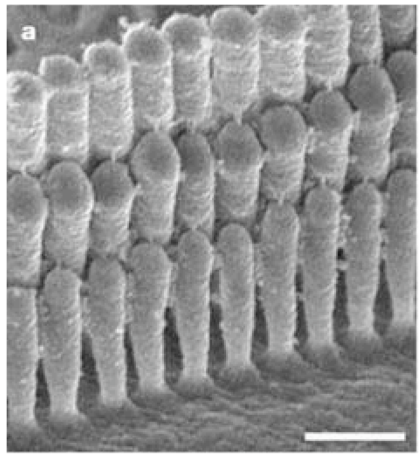
Stereocilia



From Schneider et al. (2002)

Remember that each row of stereocilia is taller than the next, and that the tip of each stereocilium is linked to the side of the stereocilium behind it by a tip link.

IHC excitation

probelft.mov

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

Moving the stereocilia toward the tallest row makes the voltage within the hair cells more positive and increases the firing of the auditory nerve fibers contacting the hair cell.

IHC inhibition

probergh.mov

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

Pushing the stereocilia toward the shortest row, makes the voltage inside the hair cell more negative and reduces the response rate of the auditory nerve fibers contacting the hair cell.

Stereocilia motion

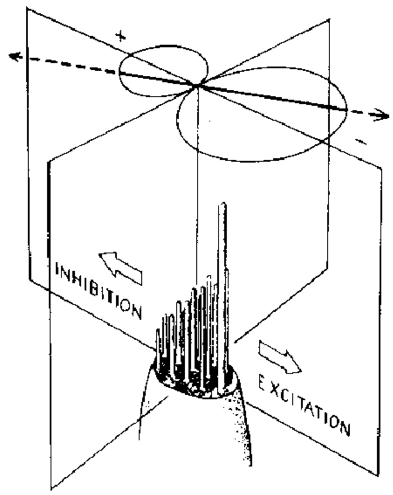


Figure 4.8 Directional sensitivity of sensory hair cells. From Flock (1971), with permission of Springer-Verlag, Inc.

From Gelfand (1998)

This figure summarizes the directional sensitivity of stereocilia.

Neural response

phaslock.mov

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

So, for example, if you play a tone, the neurons attached to this hair cell will tend to fire at the positive peaks in the pressure waveform and be inhibited when the pressure goes negative. As a result, the neurons tend to respond at the same phase of the sine wave on each cycle. This tendency is called phase-locking.

Positive pressure ________ the hair cells; negative pressure _______ the hair cells.

(A) excites; excites

(B) excites; inhibits

(C) inhibits; excites

(D) inhibits; inhibits

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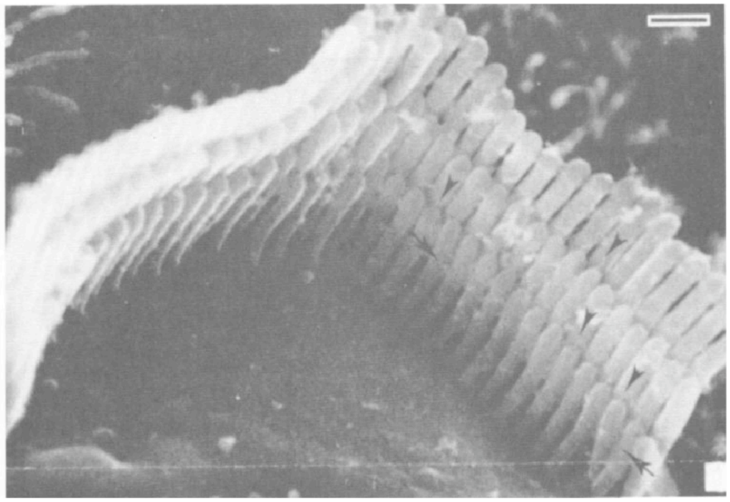
Tip links



From Gelfand (1998)

The connections between stereocilia by tip links is crucial to tranduction.

Opening transduction channels

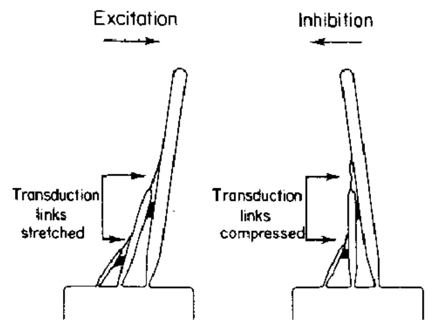


Figure 4.12 Upward-pointing (or tip-to-side) cross-links among hair cell stereocilia in relation to the sensory transduction process (see text). From *Hearing Research 15*, Pickles, Comis and Osborne (Cross-links between stereocilia in the guinea pig organ of Corti, and their possible relation to sensory transduction, 103-112, © 1984) with kind permission from Elsevier Science Publishers–NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

From Gelfand (1998)

Pushing over the stereocilia gets the current flowing (and the voltage in the HC more positive) by stretching the tip links between stereocilia (here called transduction links). Pushing in the opposite direction leads to a negative voltage change in the HC which inhibits the neural response.

Transduction channels

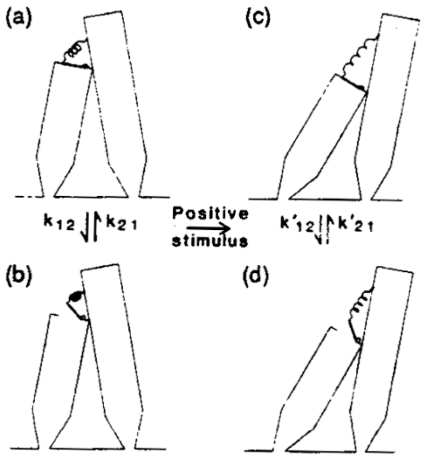


Figure 4.12 The opening and closing of the "trap door" allows ions to pass through mechanoelectric transduction channels. (From Hudspeth [15], The cellular basis of hearing, *Science*, 230, 745–752 (1985). Copyright 1985 by AAAS.)

From Gelfand (1998)

Stretching the tip links opens ion channels in the tips of the stereocilia . In this figure the ion channels are portrayed as trap doors. In the “resting” state (pictures a and b) the tip link is not stretched and the trap door is closed most of the time. When the tip links are stretched by a stimulus, the trap door is open most of the time (pictures c and d).

Positive pressure _________ the tip links; negative pressure _______ the tip links

(A) stretches; stretches

(B) stretches; compresses

(C) compresses; stretches

(D) compresses; compresses

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Receptor potential

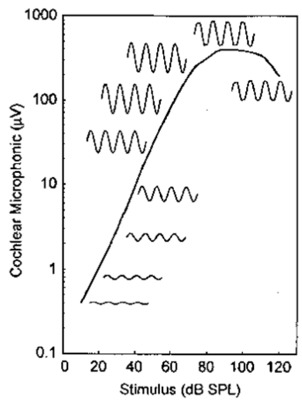

Figure 4.16 An idealized input-output function for cochlear microphonics in response to pure tone stimuli presented at increasing levels. The sine waves represent the cochlear microphonic responses at various points on the function (notice the distortion at high levels). Based on various data and figures by Wever and Lawrence (1950, 1954) and Davis and Eldridge (1959).

From Gelfand (1998)

So the ions flow into the hair cell following the motion of the basilar membrane which follows the changes in sound pressure. If we measured the ion flow, the graph of the electrical potential over time would resemble the time waveform of the sound. This electrical potential is called a receptor potential and in the inner ear we call it the cochlear microphonic. Notice that as the sound pressure level goes up, the amplitude of the cochlear microphonic goes up.
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As the sound pressure increases

(A) the amplitude of basilar membrane motion increases.

(B) the displacement of the stereocilia increases.

(C) the tip links are stretched more.

(D) more ions flow into the hair cell.

(E) all of the above.

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If more ions flow into the hair cell

(A) the neurons contacting the hair cell will respond more.

(B) the neurons contacting the hair cell wil respond less.

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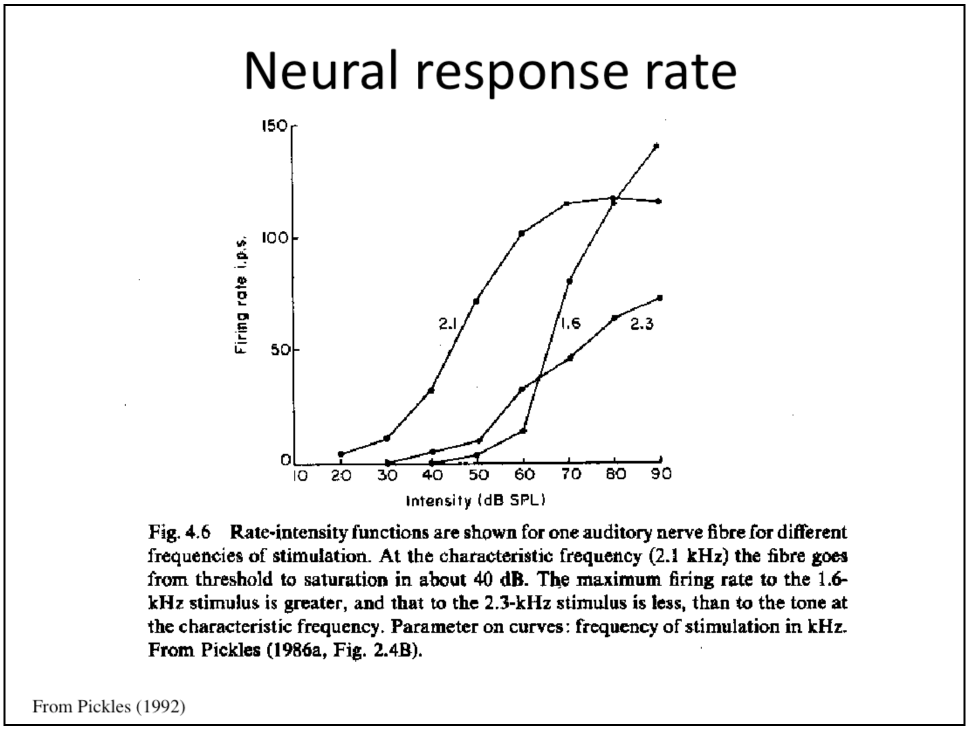

And of course, the bigger the receptor potential, the greater the number of action potentials. So the firing rate of the auditory nerve fibers is a potential “code” for sound intensity.
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If I play a tone into the ear, action potentials in the neurons contacting a hair cell

(A) will tend to occur at the negative phase of the sound wave.

(B) will tend to occur at the positive phase of the sound wave.

(C) will occur equally often at all phases of the sound wave.

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Neural response

phaslock.mov

http://www.neurophys.wisc.edu/h&b/animation/animationmain.html

The timing of the action potentials is also important, because if neurons always respond at one phase of the stimulus, then that could be a code for sound frequency. In other words, the timing of action potentials could represent the time waveform of the sound.

Conclusions

- The stria vascularis maintains a potential difference between the tops and bottoms of hair cells.
- When the basilar membrane is set into motion, the tectorial membrane shears across the hair cell stereocilia.
- When the stereocilia are pushed “out”, the tip links are stretched, opening ion channels in the stereocilia tips that allow ions to flow into the hair cell.

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Conclusions (continued)

- This electrical change results in neurotransmitter release and a response in the auditory nerve fibers contacting the hair cell.

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Text sources

- Gelfand, S.A. (1998) Hearing: An introduction to psychological and physiological acoustics. New York: Marcel Dekker.
- Pickles, J.O. (1988) An introduction to the physiology of hearing. Berkeley: Academic Press.
- Schneider, M.E., Belyantseva, I.A., Azevedo, R.B. & Kachar, B. (2002) Structural cell biology: Rapid renewal of auditory hair bundles. Nature, 418:837-838.

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