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The physical review of sound waves propagation into the human cochlea

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Highlights

- **This paper discusses the physics of human ear anatomy.**
- **The physics of sound wave interaction in the cochlea.**
- **The delay in wave propagation on the basilar membrane should be considered**
- **In developing cochlear implants, devices do improve hearing.**

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ABSTRACT

In the last three decades, medicine and technology have evolved a lot and have permitted to solve and provide many treatments considered impossible before that period. One of these hopeless cases that of interest to many people are the cochlear implants that are associated with deafness. This paper discusses the human ear anatomy and the physics of the interaction of sound waves in the cochlea.

1. Introduction:

Deafness can be classified into two categories: (i) partial deafness and (ii) complete deafness. Partial deafness is damage in the mechanical part of the external, middle and internal ear (damage of partial or complete malfunction of certain hear cells in certain but not on all of the basilar membranes). The complete deafness is associated with the inner ear section, when all of the hear cells on the basilar membrane are totally damaged, and the mechanical vibrations on the basilar membrane cannot be translated into electrical pulses to fire the sensory nerves. Given the importance of the subject of the ear and the problems to which the ear is exposed, and in particular the subject of the deaf, it was thought of great interest to study the physics of sound waves vibration into the inner ear, the cochlea.

2. The Human Ear Anatomy

The ear has three partitions: the External ear, the Middle ear, and the Inner ear, as seen in Fig.1. The external ear guides sound waves into the ear canal, causing the vibration of the eardrum. Inside the middle ear, the tympanic membrane is attached to the ossicles (Blatrix, 1999). These ossicles carry the acoustical mechanical waves to the inner ear. The eustachian tube equalizes the air pressure inside the middle ear to that of the outer air pressure. The internal ear consists of the cochlea by which the mechanical sound waves are transformed into neural signals, and transferred to the brain by the auditory nerve (Blatrix, 1999).

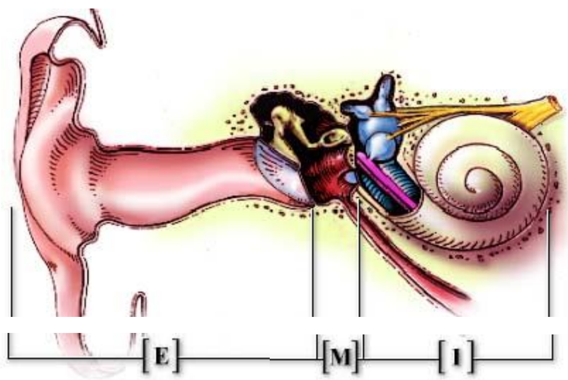

Fig. 1. The three partitions of the ear: the External ear, the Middle ear, and the Inner ear (Blatrix, 1999).

2.1 Auditory parts of the internal ear:

Two auditory parts are found in the internal ear. The vestibule is the equilibrium system, whereas the cochlea is the hearing unit (Pujol *et al.*, 2016). They share a common embryonic origin (optic vesicle), and other morphological or physiological characteristics like end lymph, hair cells, and mechanic-transduction, see Fig. 2: (1) Rear semicircular canal, (2) top canal, (3) side canal, (4) Sacculus, (5) Cochlear duct, (6) Helicotrema, (7) Lateral canal, (8) Retral canal, (9) posterior canal, (10) Oval window, (11) Round window, (12), Vestibular duct, (13) Tympanic duct and (14) Utricle.

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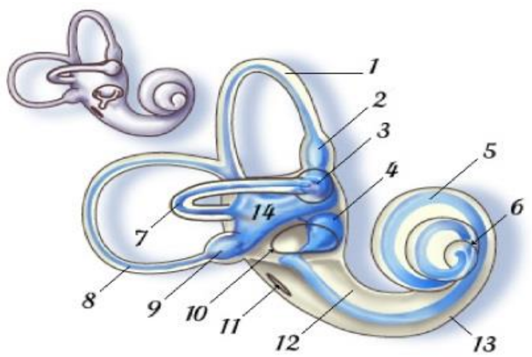

Fig. 2. The drawing represents the osseous (upper left) and membranous labyrinths (Pujol *et al.*, 2016)

2.2 Cochlea

The cochlea is the external unit of the sensual part of the internal ear. Its name comes from its spiral shape looks like a marine snail. Fig. 3 shows the cochlea cross-section. This cross-section shows the coiling of the cochlear duct (1) which contains endolymph, and the scala estibule (2) and scala tympani (scala tympani begin at the oval window) (3) which contain perilymph. The red pointer is from the oval window, the blue pointer points to the round window. Within the modulus, the spiral ganglion (4) and auditory nerve fibers (5) (Blatrix et al., 2007).

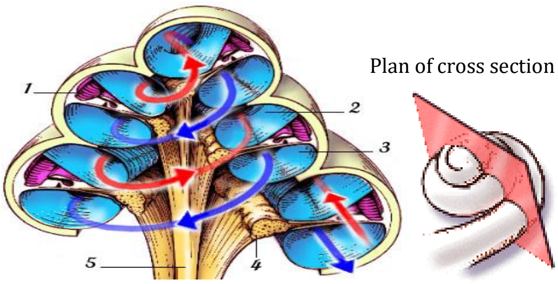

Fig. 3. The cross-section of the whole cochlea (Blatrix *et al.*, 2007).

The frequency arrangement onward the basilar membrane (human cochlea) is shown in Fig. 4. Notice the gradual growth of the basilar membrane (Rebillard *et al.*, 2020).

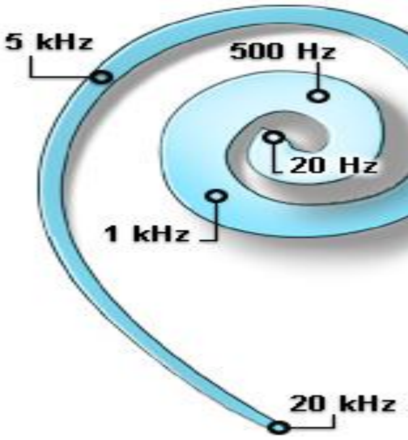

Fig. 4. Some characteristic frequencies from the base (20 kHz) to apex (20 Hz), are indicated (Rebillard *et al.*, 2020) .

2.3 Outer hair cell (OHC) nerves

The OHC nerve cells joints with a few short terminations from type II spiral node nerve cells, shaping the spiral afferent system "colored in green". Consecutively, large nerve cells of the central efferent structure "colored in red", from both sides of the central superior oviform structure, form axo-corporal synapses with the OHC, see Fig. 5.

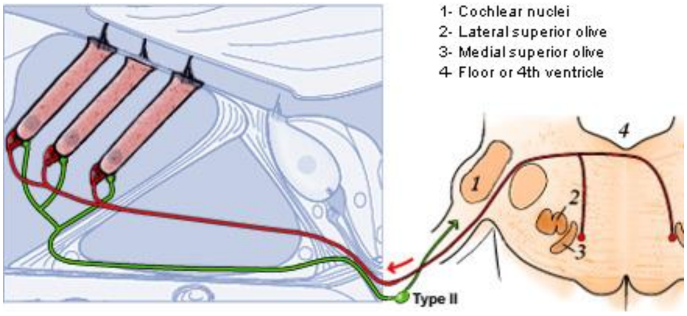

Fig. 5. Outer hair cell (OHC) innervation (Pujol *et al.*, 2018).

Type I spiral node nerve cells (95% of them) have a unique termination in-plane attached to inner hair cells (IHCs) (Pujol *et al.*, 2018). Type II small, missing a myelin coat nerve cells spiral in the basal region after penetrating the Corti organ and subdivide to join around ten OHCs, normally in the same line. A diagram illustrating the receptive hair cell nerves is shown in Fig. 6.

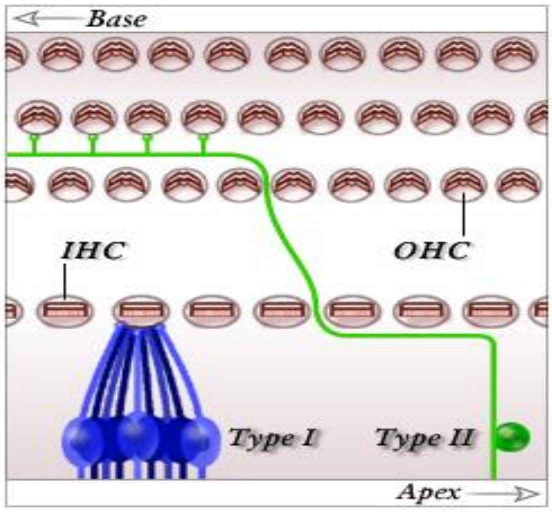

Fig. 6. A schematic representation of the hair cell afferent innervation (Pujol *et al.*, 2018).

2.4 Characteristic frequency (CF)

CF is the minimum energy to excite a sensory nerve at a specific frequency. Diverse nerve fibers have diverse CFs and diverse thresholds. The nerve fiber CF is approximately the same frequency of resonation where it is connected at the basilar membrane.

2.5 Auditory Nerve

When hairs of internal sensory cells tilt, its potential difference changes; as they tilt amply in a single orientation the potential difference is sufficient to discharge neurotransmitter at the joint within the hair cell and the auditory neuronal joints, and the acoustical nerve discharges. It takes around 1 ms refractory period after firing a nerve fiber. Around 10 auditory nerve fibers are attached to each hair cell. They have distinct thresholds. Internal hair cells trigger the incoming hearing nerves; external hair cells normally do not but are stimulated by the outgoing hearing nerves. Different action scan influences the mechanical reaction of the basilar membrane through the external hair cells.

2.6 Response to Single Pure Tones

Increasing the magnitude of the sound, the nerve fiber firing rate at CF overflows. The majority of acoustical nerve fibers have large impulsive rates and saturate fast, yet we have others that have low impulsive rates and saturate gradually. Fibers of fast impulsive rates code intensity variation at low stages and the low impulsive rate ones code intensity variations at high stages as seen in Fig. 7.

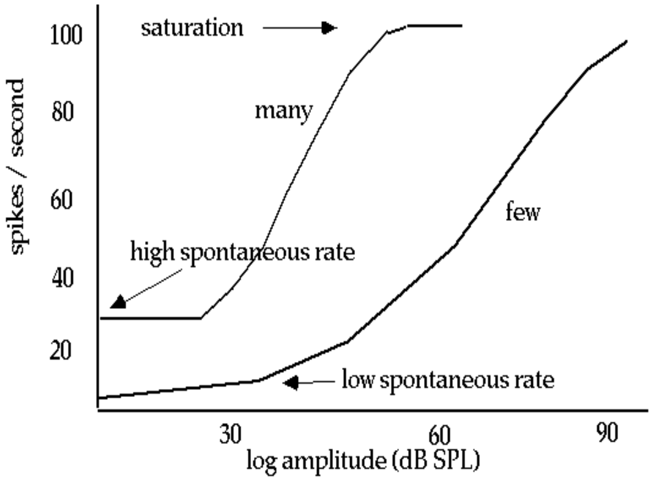

Fig.7. The amplitudes of tones played to the ear (Darwin,1994).

2.7 Hair Cells

Sensory cells (hair cells) in the cochlea, as well as a vestibule, are characterized by a cuticular plate with a group of stereocilia merged into the encircling endolymph. Diagrammatically, internal, and external hair cells vary in form and structure of their stereocilia, see Fig. 8 (Pujol *et al*., 2016).

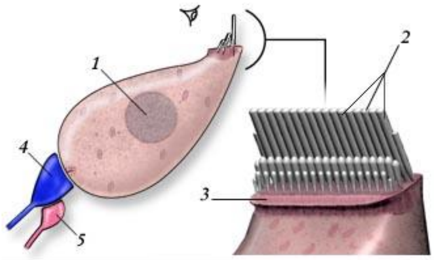

Fig. 8. Inner hair cells (IHC) (Pujol *et* al., 2016).

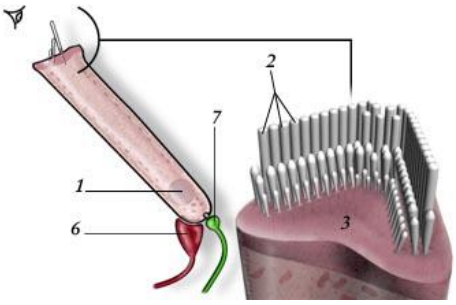

Fig. 9. Outer hair cells (OHC) (Pujol *et al*., 2016).

(1)Nucleus, (2) Stereocilia, (3) Cuticular plate, (4) Radial afferent ending (dendrite of type I neuron), (5) Lateral efferent ending, (6) Medial efferent ending, (7) Spiral afferent ending (dendrite of type II neuron).

Inside the human cochlea, there are approximately 3,500 IHCs and nearly 12,000 OHCs, compared to our photo-receptors (retina) and chemo-receptors (nose) in millions. Hair cells and neurons can't reproduce once separated, see Fig. 9 (Ashmore, 1987; Cody *et al*., 1987; Hudspeth *et al*.,1977; Kachar *et al*., 1986; Sellick *et al*., 1980; Strelioff *et al*.,1984).

2.8 OHC Length Variation as a Function of Frequency

Fig. 10 demonstrates OHCs for various mammals. The length commonly alters as a function of frequency, whilst the diameter is constant, at around 7 µm. Human (C) at 20 kHz and (G) (< 100 Hz). Bat (A) (160 kHz). Cat (B) (at 40 kHz). Guinea pig (D) at (5 kHz), (E) at (2.5 kHz), and (F) at (150 Hz). Mole rat (H) at (15 Hz) (Pujol *et al*., 2017).

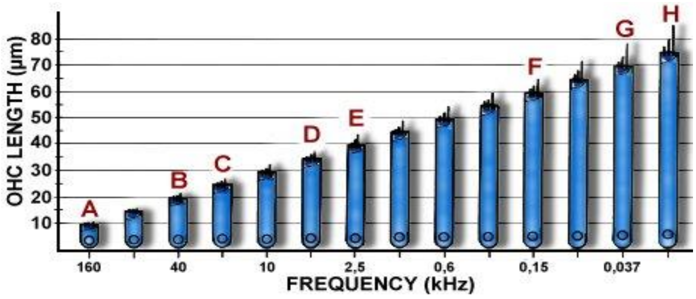

Fig. 10. OHC length varies according to frequency (Pujol *et al*., 2017).

3. How the Cochlear Analyzes Sound

3.1 Frequency Tuning

Békésy used Fourier analysis and linear systems hypothesis to describe the basilar membrane movement. The basilar membrane operates as a time shift-invariant linear system. He applied sinusoidal stimuli to determine the frequency response at various locations on the basilar membrane. Thus, he was capable to anticipate the response for any sound on the basilar membrane. See Fig.11 (Heeger, 2006).

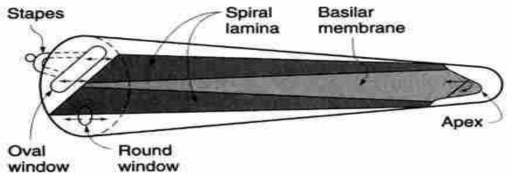

Fig. 11: The basilar membrane is not homogeneous (Heeger, 2006).

This is a simplified diagram of an expanded cochlea. The basilar membrane has not a constant thickness along its membrane. The thickness and elasticity vary as it rolls across the membrane. Thus, various sections of the basilar membrane resonate to a specific frequency. The oscillation amplitude varies from point to point; see Fig. 12 (Heeger, 2006).

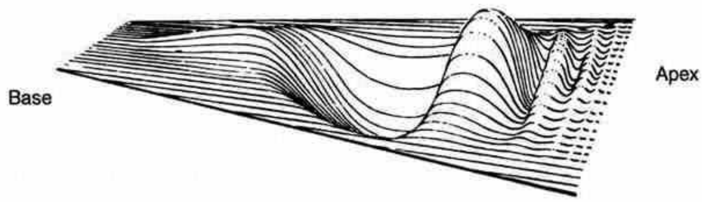

Fig.12. "Snapshot" of the basilar membrane (Heeger, 2006).

Fig.13 shows the movement of the basilar membrane at a particular time.

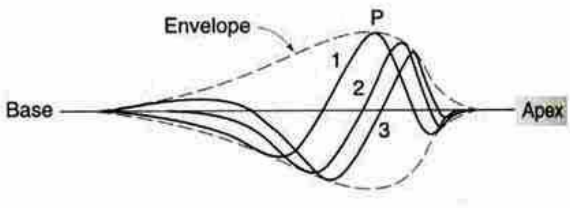

Fig.13: Traveling wave over time (Heeger, 2006).

Progressively, the various parts of the membrane vibrate. This entire movement due to a sound oscillation is defined as a traveling wave. Each point vibrates as a sine wave; different locations oscillate slightly delayed relative to each other, causing the traveling wave. The oval window is the start of the wave, traveling along the membrane till reaches the helicotrema where most of the energy drops. The dashed envelope demonstrates the variation of the membrane, the maximum path of that portion of membrane all over the traveling wave interval (Heeger, 2006; Johnstone *et al.*, 1986; Nobili *et al.*, 1997; Sellick *et al.*, 1982; Gummer *et al.*, 1981). Fig. 14 Illustrates basilar membrane vibration. Each location on the basilar membrane resonates differently according to the sound frequency. High frequencies vibrate greater at the oval windows, whereas, low frequencies vibrate greater at the helicotrema (Békésy, 1960).

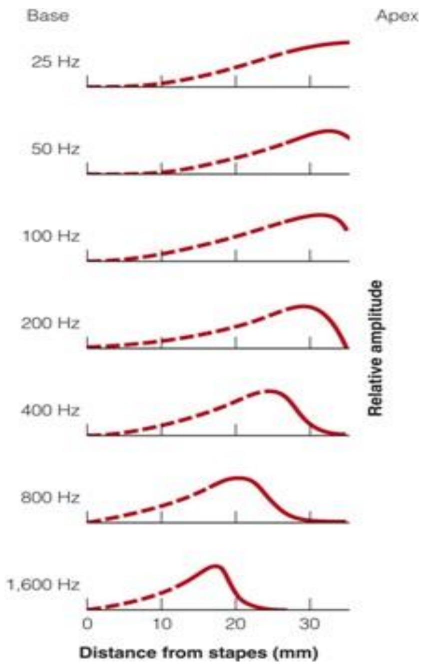

Fig. 14. Envelope for several frequencies (see text)(Békésy, 1960).

Fig. 15 illustrates the point of peak position for different resonance frequencies. These analyses were made on autopsy human ears. The position of the highest vibration depends systematically on the resonant frequency (Békésy, 1960).

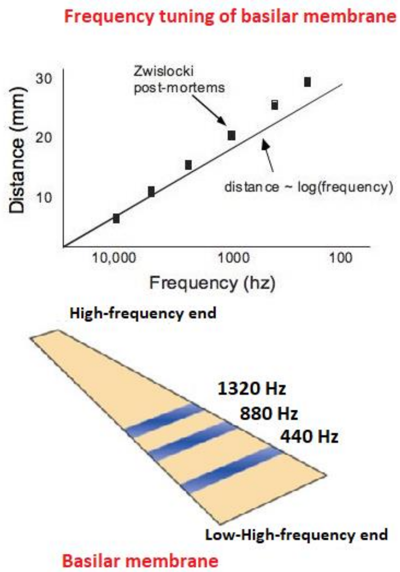

Fig. 15. Cochlear tuning curve (Békésy, 1960).

The appearance of the traveling wave is because the agitation starts at the oval window, and forces the oval window to start vibrating, this oscillation propagates through the cochlea. Each location on the basilar-membrane resonates differently according to the sound frequency, that's why the traveling wave is at a maximum at one place. Fig. 16 shows an auditory nerve frequency tuning. Every nerve is attached to a bunch of adjacent hair cells, this nerve responds to a limited region on the basilar-membrane according to the response of that region to that particular frequency (Heeger, 2006). Fig.16 shows the sensitivity of an individual auditory nerve to a sinusoidal wave of various frequencies. The X-axis denotes input frequency stimulus. The Y-axis denotes the intensity stimulus threshold.

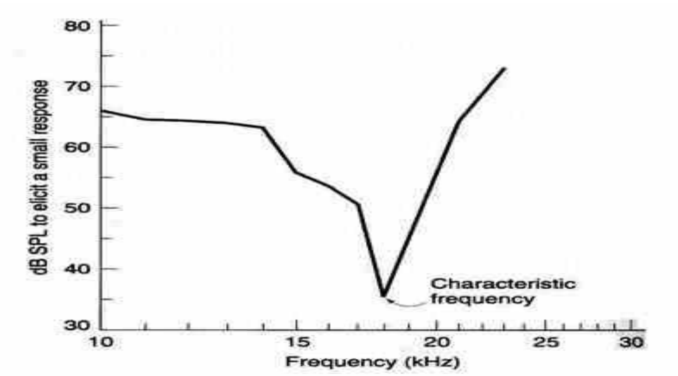

Fig.16. Auditory nerve frequency tuning (Heeger, 2006).

Observe that the response of a neuron is limited to a restricted spectrum of frequencies, around 18 kHz (not from a human nerve fiber), this is known as the frequency property of a neuron. This nerve fiber should be around the oval window due to its response to high frequencies. Whereas, low-frequency response nerve fibers are found near the helicotrema. Table 1 presents the minimal energy level needed in dB to provoke a response.

Table 1

Threshold stimulus intensity for sound pressure and level

SPL dB	Pa	mbar
10	0.000063246	6.3246×10^{-7}
20	0.0002	0.000002
30	0.000632456	0.00000632456
40	0.002	0.00002
50	0.006324555	0.0000632455
60	0.02	0.0002
70	0.063245553	0.000632456
80	0.2	0.002
90	0.632455532	0.00632456
100	2	0.02
110	6.32455532	0.0632456
120	20	0.2

Fig. 17 shows the resonance of three acoustic neurons. Distinct sensory nerve fibers connect to distinct segments of the basilar membrane. The details of every frequency section on the basilar-membrane spread between various neurons. No single neuron can carry all the acoustical details (Heeger, 2006).

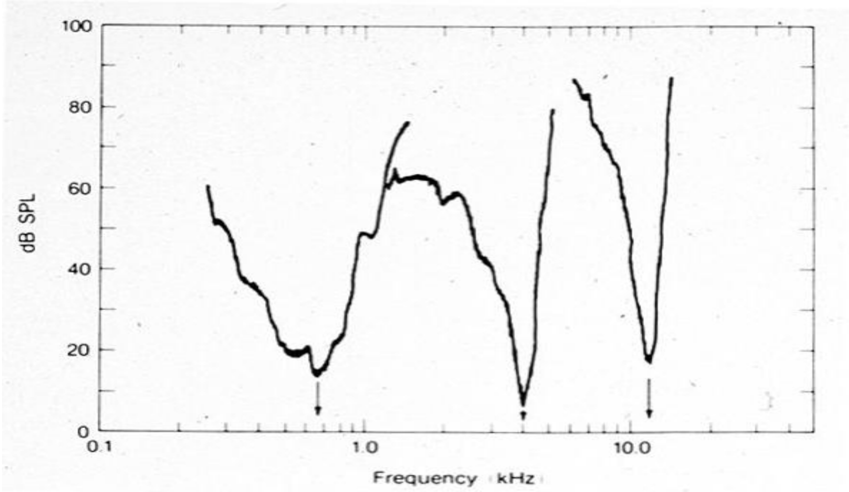

Fig. 17. Frequency tuning of three auditory nerve fibers (Heeger, 2006).

It can be summarized that the data expressed on the basilar membrane and the auditory nerve is different from that expressed at the tympanic membrane. The tympanic membrane distributes to a 100 Hz sound, a 1kHz sound, and a 10kHz sound. It covers the audio spectrum, and truly converts the air pressure alteration by a movement (Heeger, 2006).

On reaching the cochlea and ahead, the acoustical signal is transformed to 40,000systems - the 8th nerve fibers connecting the cochlea and the brain – each nerve fiber encodes a particular part of the stimulus. In addition, each fiber is blind to most of the auditory frequencies range. This disintegration of the responses into various neural channels is like a moving pendulum (Heeger, 2006).

3.2 Place and Temporal Code Theories of Pitch Perception

The sensation of pitch is not a characteristic of the mechanical vibration; it is linked to the sound frequency. Place Code Theory: Helmholtz's pitch theory is founded on the study of ear anatomy. Fig.18 shows the frequencies pitch sensation place code. The theory of place code establishes the position of each pitch over the basilar membrane. It is the relation between place and pitch (Heeger, 2006).

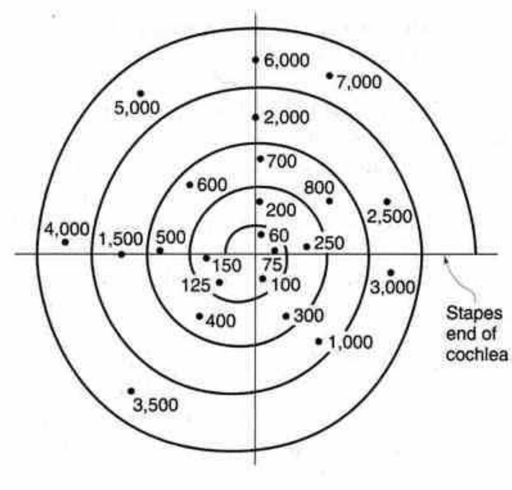

Fig. 18. Place code (Heeger, 2006).

3.2.1 Temporal Code Theory

Based on the hypothesis of temporal code, the place of vibration is not important over the basilar-membrane. Instead, the sound is coded by the rate of acoustical nerve firing. This assumption makes sense. Frequencies of low pitch produce slow-wave movement on the basilar-membrane and generate a low rate of discharge in the acoustical nerve. The same applies to high pitch (Heeger, 2006).

There is a complication with momentary code theory. The human ear is delicate to frequencies from around 20 Hz up to 20 kHz. In any case, a solitary nerve cell can't flag at a pace of 20 kHz. Consequently, the chance of a momentary code sensing the pitch of a 20 kHz tone appears to be not possible because no nerve cells can transmit that rate per second. Furthermore, Hallowell Davis, during the 1930s, demonstrated that the peak auditory neuron response in the feline is around 1000 responses each second (Heeger, 2006).

3.2.2 Cochlear Microphonic

Helmholtz's discovery of the microphonic of the cochlea raises a question on the place theory hypothesis whereas sustains the hypothesis of temporal code. Wever discovered that placing an electrode near the cochlear hair cells could measure a week electrical signal called the microphonic of the cochlea. We can define this signal as the result of the electrical potentials summation of the hair cells. It reflects the mechanical sound arriving at the ear into electrical form. Pitches of low frequencies cause's low modulation of an electrical signal. Pitches of high frequencies cause's high modulation of an electrical signal. The summation of the mechanical frequencies pitches rises in the summation of the electrical potentials of the microphonic of the cochlea. This summation is a shift-invariant linear system, which complies with the scalar and shift-invariance norms.

3.2.3 The Principle of Volley

The Volley assumption supports the certitude that the microphonic of the cochlea reflects the pressure of the sound waves with the uncertainty of the temporal code. Wever pointed that a single neuron could not transfer the temporal code for a 20 kHz pitch, 20 neurons, with overlapped firing rates, could. On average a single neuron would react to each twenties period of the pure pitch, and the merged neural feedback would mutually include the details that a 20 kHz pitch was applied. Fig. 19 demonstrates the Volley Principle (Heeger, 2006).

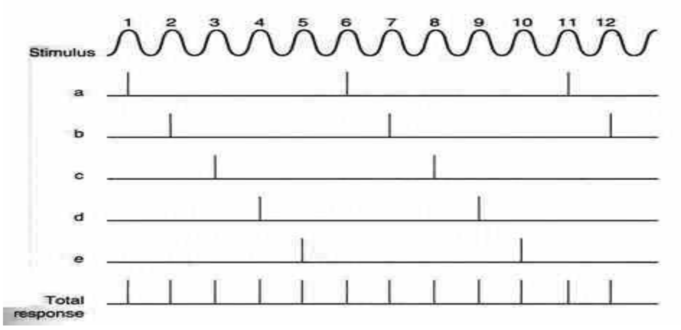

Fig. 19. Volley Principle (Heeger, 2006).

3.2.4 Phase Locking:

Is an experimental observation that approves the Volley principle? When 8th nerve neurons discharge electrical impulses, they react at intervals analogous to a max in the acoustic pressure waveform; a result is several neurons discharging near the max of every period of a pure tone. No single neuron has the ability to react with each period of the sound wave, therefore different neurons fire on consecutive periods. However, when they do react they tend to discharge jointly. Fig. 20 shows Phase Locking (Heeger, 2006).

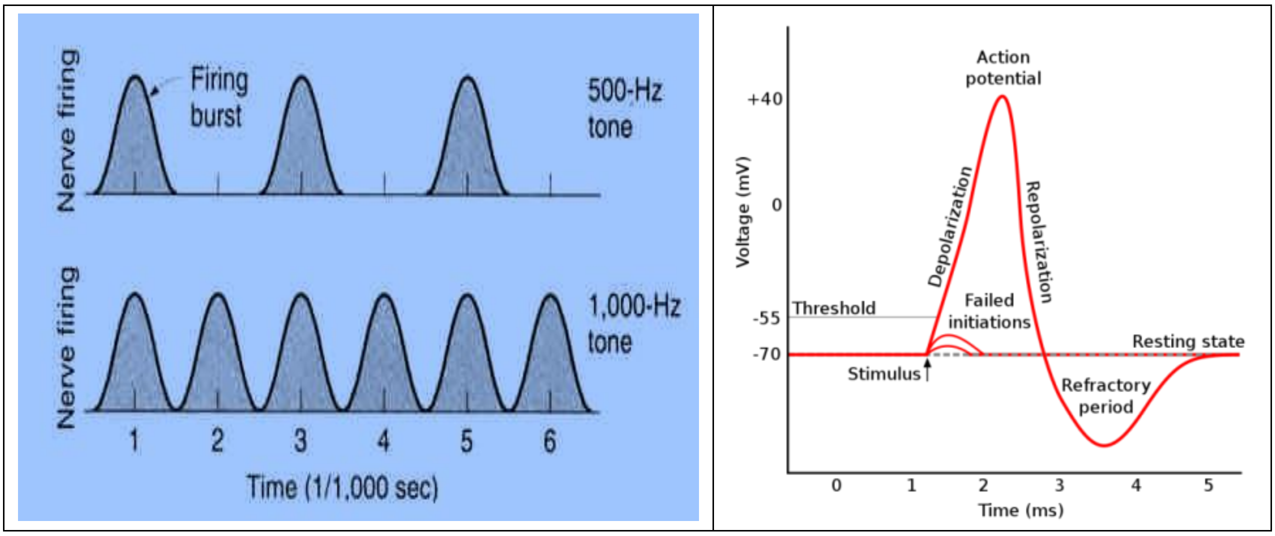

Fig. 20. The observations support the Volley principle (Heeger, 2006).

Why phase locking is relevant?. What is required so neural activities and sound pressure waves are analogous (for the hypothesis of temporal code and the cochlear microphonic explanation). The reaction (over the whole hair cells/cochlear nerves) should seek every ascending or descending of the sound signal pressure level (Heeger, 2006). The postulation of Wever's temporal code (established on the Volley assumption) rejected the postulation of Helmholtz's Place Code, and it was replaced by convincing data (cochlear microphonic and phase locking). Wever states that a single firing neuron is irrelevant, but alternatively, the neurons signaled together contained such information as the sound tone (Heeger, 2006).

3.2.5 White's Cochlear Implants

An electrical engineer John White at Stanford executed experiments that regard these 2 alternative theories. His objective in his research was making cochlear implants to restore hearing loss. The most common infection is called Meniere's disease that can venom and damages the inner ear hair cells, but not the auditory nerves, thus living the remaining of the auditory system unharmed. Therefore, we send a signal straight to the auditory nerve as if the system is fully intact. Fig. 21 shows White's electrodes (Heeger, 2006).

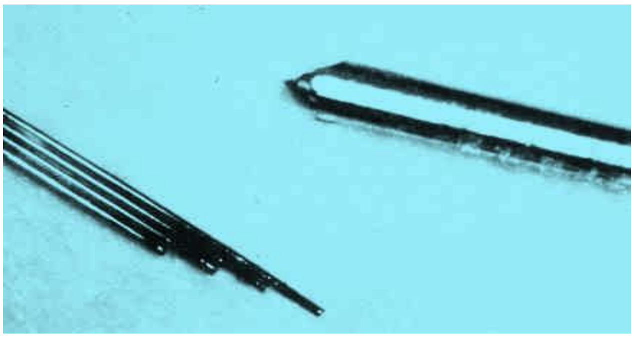

Fig. 21. The White's electrodes (Heeger, 2006).

The first tests made by White with the cochlear implants were meant to experiment with the place and temporal code hypothesis of tone perception. He placed four electrodes along the basilar membrane at various ranges. He experimented with both hypotheses transmitting various electrical stimuli to the patient and asking him to guess the transmitted signal tone through the artificial device. The experiment was carried out in two different ways. He begins the stimulation by choosing different electrodes, which are placed at different locations to test the place code hypothesis (tone dependents). Secondly, he changed the rate of impulses on the electrode (low and high rates) to test the dependence of tone on the rate of electrical impulses to experiment with the temporal code hypothesis. Fig. 22 shows the results of White's experiments (Heeger, 2006).

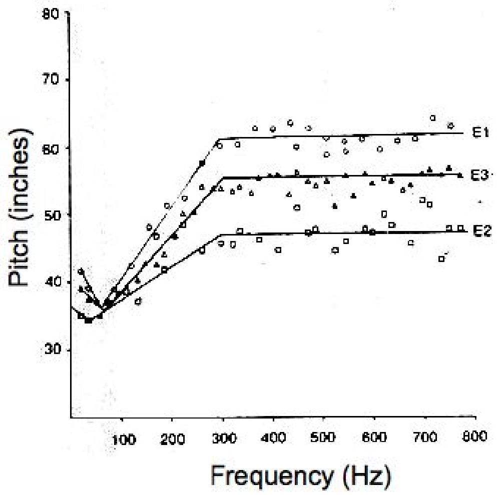

Fig. 22. White's data (Heeger, 2006).

This experiment demonstrated that both technics affects tone perception. Increasing the stimulation rate for one electrode we get a higher tone over a significant range (300 Hz). Changing the electrode also affects the tone perceived, i.e. place code (Heeger, 2006). Actually, these matches. Under 300 Hz place coding is poor due to a wide range of vibration at a low frequency on the basilar membrane as refer to Figs. 12, 13, and 14. Instead, temporal code is more efficient at low frequencies due to fibers can phase-lock well at those frequencies (Heeger, 2006). Caution: from the experiments of electrical stimulations people described the sounds they hear are more noise rather than tones. More like a buzz instead of a pure pitch (Heeger, 2006).

3.2.6 Virtual Pitch

We can compose any sound by summing sine waves by adding base frequency and the multiple of it (harmonics), i.e. 400Hz(base frequency), 800Hz, 1200Hz ... etc. (harmonics). Nearly all sounds are constructed by base and harmonics, see Fig. 23. Notice the complex tone (a), 400Hz plus harmonics. The sensed tone is more like a pure pitch having a fundamental of 400Hz. Now if we remove the base tone 400Hz from (a) we get the complex (c). The base frequency is now 800Hz; you may think that you will hear a tone of 800Hz. You will be surprised that most people will hear the complex tone as a pitch of 400 Hz (Heeger, 2006).

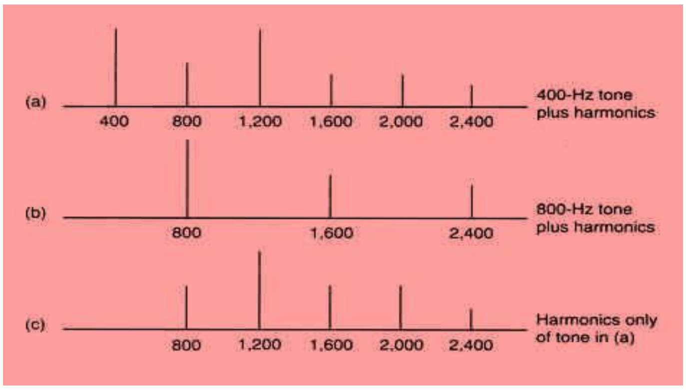

Fig. 23. Fundamental frequency and harmonics (Heeger, 2006).

This result disputes Helmholtz's place theory, we do not have any 400Hz frequency to stimulate the nerve at that location. This result also disputes Wever's volley theory, no 400Hz frequency is present in the cochlear microphonic. Although both hypotheses (place theory and temporal code) are part of tone perception, neither one gives a full clarification of tone perception. Yet, as it looks a simple perceptual characteristic, the tone is still not quietly understood (Heeger, 2006). Shifting the frequency complex up (from 400Hz, 800Hz, 1200Hz to 500Hz, 900Hz, 1300Hz) it will be heard increased a bit in tone. It is a kind of strange phenomenon seeing the new combination is not exact harmonics and the hearing system consents it as a "nearly harmonic" and detects them as a virtual tone, see Fig. 24 (Heeger, 2006). Some people as Roger Shepard and else used this phenomenon of residual tone to produce a hearing illusion giving the feeling that the sound keeps varying in tone, increasing, or decreasing continuously (Heeger, 2006).

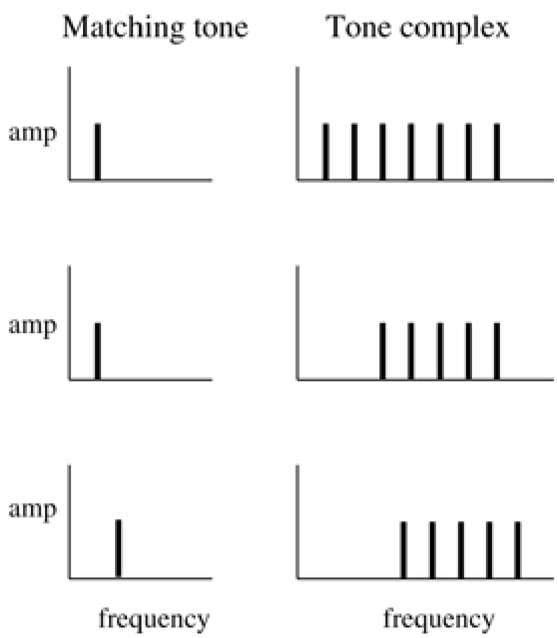

Fig. 24. Shift in virtual pitch (Heeger, 2006).

The strength of every part is defined by a magnitude envelope that decreases at both upper and lower frequencies. Shifting the frequency parts slowly up over time but keeping the parts limited by the non-shifting envelope, see Fig. 25 (Heeger, 2006).

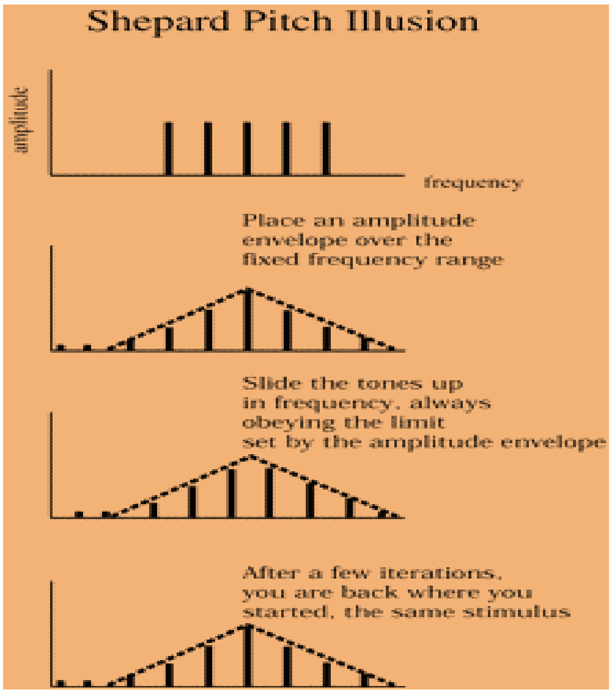

Fig. 25. The Shepard pitch Fourier spectra (Heeger, 2006).

Consequently, step-by-step low-frequency components rises in magnitude and high ones reduce in magnitude giving the sesssssssssssnsation of hearing an increasing tone endlessly, without getting beyond where it has begun (Heeger, 2006).

4. Conclusion

Sound waves propagate on the basilar membrane and each frequency excites a specific part of the membrane and fires the nerve on that position and carries the information to the brain. The waves take a significant time to move from the base (oval window) to the apex (helicotrema) which is around 32 ms. Using the Greenwood function we can find the position of each frequency response on the basilar membrane and we can calculate the time needed to reach that position. Therefore, studying the ear mechanism in analyzing sound will help to improve the function of the cochlear implant devices that are on the market today, making them more realistic in simulating the function of the basilar membrane to improve the way of hearing through these devices.

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