



Resonance in the Theory of Hearing

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Abstract

This paper discusses issues concerning Békésy's theory regarding the resonance between longitudinal waves in the cochlear fluid and the transverse natural vibrations of the basilar membrane coupled with the organ of Corti. The traveling-wave theory also relates to the accurate transmission and reception of speech-related information by the auditory receptor. Discrepancies are noted between experimental findings and the signal transmission times to the receptor predicted by Békésy's theory. The paper describes the transmission path of complex tones to the receptor, involving resonance and the basilar membrane. The existence of mechanical amplification in the inner ear was critically evaluated.

Introduction

In the 19th century, the physician, physiologist, and professor of physics, Hermann Helmholtz (1821-1894), used the phenomenon of sound wave resonance to explain the mechanism of hearing. In 1863 he published the resonance theory of hearing. He accepted the thesis that the basilar membrane in the inner ear, due to its structure, which is different along its length, resonates with sound waves in the cochlear fluid, at the appropriate frequency. He found that high frequencies resonate close to the oval window. The closer to the cochlear apex, the lower the frequencies at which resonance occurs. This genuine relationship is known as tonotopy. Subsequent histological studies did not confirm the existence of transverse fibers in the basilar membrane responsible for frequency resonance. Tonotopy does exist, but a different mechanism determines it.

In 1928, Georg von Bekesy (1899-1972) announced his own theory of hearing called the "traveling wave theory" [1]. The basis of this theory was the hydrodynamics of the cochlear fluids, amplification of the sound wave in the middle ear, and resonance between the sound wave in the fluid and the natural vibrations of the basilar membrane. The tip-links mechanism is responsible for transmitting information to the receptor. The basilar membrane is responsible for frequency discrimination and the amplitude of the sound wave. The principle of tonotopy has been preserved. There was no information about the functioning of the hearing receptor and the hair cell itself. Bekesy's groundbreaking discovery, recognized by the Nobel Committee in 1961, consisted in observing a traveling wave through an opening in the wall of the labyrinth while sounds were being presented to the ear. It seems difficult to observe a traveling wave on a thin, compliant membrane extending along the entire length of the cochlea and attached to the organ of Corti. According to the medical literature, this membrane is 0.08-0.16 mm wide at the base of the cochlea, while at the apex its width is 0.42-0.65 mm. The thickness of the basilar membrane is 0.005-0.0075 mm at the base and 0.0015-0.0025 mm at the apex. The mass of the basilar membrane is 0.05-1.0 mg/cm² at the base and 0.2-0.4 mg/cm² at the apex. The height of the basilar membrane together with the organ of Corti, which vibrates along with it, is 0.04-0.05 mm at the base and 0.1-0.15 mm at the apex. (This is evidence that the basilar membrane is attached to the organ of Corti and cannot vibrate freely; it vibrates together with the organ of Corti.) It is unlikely that a basilar membrane, 0.08 mm wide at the base, separates the cochlear canal from the tympanic canal, which is 3.4 mm in size, and supports the massive organ of Corti. Bekesy calculated that, given these dimensions of the basilar membrane, resonance correspondence with sound waves in the cochlear fluid would occur at frequencies within the range audible to humans.

He did not take into account the fact that other mammals can hear up to 100 kHz. It is difficult to calculate how thin and narrow the basilar membrane should be in these mammals to enable resonance of sound waves in the cochlear fluid with the natural vibrations of the basilar membrane of these mammals.

It has been known for 25 years that the resonance of the longitudinal wave in the cochlear fluid with the transverse wave of the basilar membrane's natural vibrations is a serious challenge to this



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theory. The Nobel Prize does not change this.

Rationale

If the hearing organ is to physiologically fulfil its function, auditory information must reach the receptor with 100% accuracy and at the right time - quickly. The signal-to-receptor pathway adopted by Bekesy does not provide these conditions. Electrophysiological studies prove that the signal travel time from the external auditory canal to the receptor is 1.5-1.8 ms (Prof. Kochanek). Could Prof. Kochanek be wrong? NO!!! [2].

This is not the pathway through the cochlear fluids, resonance and basilar membrane. Since 2000, I have postulated a different, direct, and rapid pathway. For expressing such a thesis, in 2000, Professor Antoni Pruszewicz asked me to leave his office in Poznań, even though I had known the professor since 1975 - during my studies, he had conducted laryngology classes. In 2000, Prof. Grzegorz Janczewski accepted my remarks on the theory of hearing (I have written proof). These remarks were published thanks to Prof. Janczewski's help in *Otolaryngologia Polska* No. 3/2003, pp. 449-453, and the second paper "Processing and transmitting auditory information" - *Otolaryngologia Polska* No. 2/2004, pp. 377-383, [3] and in *Otoscope* 1/2005 "Nanomechanisms of hearing". So many years have passed.....

Let's see what the signal path looks like through the cochlear fluids, the longitudinal-transverse wave resonance, the basilar membrane and the tip-links mechanism.

For a frequency of 100 Hz, the first deflection of the basilar membrane from its resting position, caused by the energy of the longitudinal wavefront traveling toward the resonance site near the cochlear apex, occurs after 2.5-5 ms.

The transfer of 100% energy occurs after approximately 1-2.5 wave cycles. 1 cycle of 100 Hz = 10 ms. Thus, the duration of a complete, established resonance falls within the range of 10-25 ms, with a complete match between the frequencies of the driving and driven waves. Each change in frequency automatically and precisely changes the resonance duration. The time of full resonance depends on the damping, which affects the energy transfer. Without damping, the resonance would increase indefinitely. If the resonant frequency differs significantly, resonance does not occur. In the theory of classical resonance without damping, the amplitude grows linearly to infinity and the energy transfer takes many cycles [4]. The human ear is a highly damped system due to the viscosity of the cochlear fluids.

If the ear were not damped, resonance would build up over seconds, and sounds would become "smeared" over time, making it impossible for us to distinguish rapid changes in speech or music.

Due to strong damping, the steady state is reached after only 1 to 2.5 wave periods, i.e. within 10-25 ms at 100 Hz.

But at 20 Hz, this corresponds to 50-125 ms - i.e., 1-2.5 wave cycles (resonance according to Bekesy). Each subsequent wave period transfers only part of the energy to the driven wave. Therefore, wave resonance requires time, and for complete transmission, a phase difference of one-quarter of the wave period = 90° is required. With a smaller phase difference or a larger one, the resonance will last longer. With an opposite phase, resonance will not occur.

An amplitude of 500 nm at a frequency of 100 Hz represents a high-energy vibration, corresponding to a loud sound, approximately 80-90 dB. At such a large amplitude, the system behaves more like a

passive resonator, which paradoxically shortens the time required to achieve maximum energy transfer.

Dynamic Parameters Summary

The onset of energy transfer by the driven wave depends on the resonance frequency - that is, on the wavelength of the driving wave.

Time to establish full forced resonance: 10-25 ms

Frequency tells us how many cycles (vibrations) happen in one second. A period is the time it takes to complete exactly one cycle. The second harmonic of a 1000 Hz wave is created at a musical distance of one octave, reaching a frequency of 2000 Hz, and the duration of one of its complete cycles (wave period) is exactly 0.5 milliseconds (ms).

Duration of 1 frequency cycle - wavelength in cochlear fluid: 20 Hz = 50 ms - 29 m 50 Hz = 20 ms - 72.5 m 100 Hz = 10 ms - 14.5 m 1000 Hz = 1 ms - 1.45 m 10 000 Hz = 0.1 ms - 0.145 m

Each frequency change automatically and precisely changes the duration of one cycle in milliseconds. In order for a sound wave with a frequency of 20 Hz to be received and to evoke a receptor potential according to Bekesy's theory, 50 to 125 ms are needed for the full resonance of the waves and the transmission of auditory information (energy). Resonance occurs when the frequency of the driving force is close to the natural frequency of the system, resulting in a substantial increase in the amplitude of vibration. If the frequency of the force is much smaller or higher than the natural frequency, the system vibrates with a small amplitude driven by this force, and resonance does not occur.

These findings in the literature on music and acoustics are reported for resonance occurring when the directions of the driving and driven waves are aligned. Unfortunately, in the ear these directions are perpendicular to each other, which results in deterioration of resonance parameters. So-called parametric resonance may occur, but over a longer period and with lower precision, which does not ensure complete transmission of auditory information. This is important. A polytone is a sound that is not a pure tone (a simple sinusoidal wave), but rather consists of many different frequencies.

Harmonic polytone: It contains a fundamental tone and its integer multiples, i.e., harmonic components (aliquots).

When a polytone wave reaches the resonator, energy is transferred only to those components whose frequency coincides with the resonant frequency of the system.

We live in a world of harmonic polytones and non-harmonic polytones. Outside of laboratories, there are no simple harmonic tones in our environment. Human speech is a mixture of harmonic and non-harmonic polytones.

In a harmonic polytone, there is a fundamental tone at a given frequency and a series of harmonic tones (aliquots) whose frequencies are successive integer multiples of the fundamental frequency.

For example, if the fundamental tone is 500 Hz, the second harmonic is 1,000 Hz, followed by harmonics at 1,500 Hz, 2,000 Hz, 2,500 Hz, and 3,000 Hz.

Please note - this only happens in Bekesy's theory - that the fundamental tone and each successive harmonic component resonate with the basilar membrane at a different location of the membrane and at a different time.

The highest-frequency component, 3,000 Hz, resonates first, at a location closest to the base of the cochlea. The fundamental tone resonates last, closer to the apex of the cochlea. It is known that, according to Bekesy, the velocity of the traveling wave varies along the cochlea, from 50 m/s at the base of the cochlea to 2.9 m/s near the cochlear apex. Therefore, the temporal intervals between successive tones are variable. As a result, in this example, six points of maximum basilar-membrane deflections arise sequentially at different time intervals along the basilar membrane, which are assumed to generate fluid flow that deflects the hairs of the auditory hair cells. This is extremely difficult, if not impossible, particularly because the basilar membrane is attached to the organ of Corti and there is no space for fluid between the basilar membrane and the organ of Corti. The entire mass of the organ of Corti vibrates. In such a case, it is necessary to calculate the natural vibrations of the entire vibrating element, not just the delicate basilar membrane.

The problem becomes even more pronounced when the auditory system is simultaneously exposed to several, a dozen, or even several dozen polytones. How many maximum deflections are produced at the basilar membrane - if the basilar membrane is responsible for frequency and intensity discrimination? But the length of sound and phase of each tone are also important, so that the phase shift to the driven wave is 90° - for the optimal transfer of resonance energy. Wave superposition does not solve this problem.

During our speech, there is also non-harmonic resonance of voiceless consonants, alongside harmonic resonance. This makes hearing speech very complicated, according to Bekesy's theory. In some words, voiceless consonants predominate. Understanding these words becomes impossible. E.g. strengths, texts, sixths.

Non-harmonic polytone: Non-harmonic polytone resonance involves the simultaneous excitation of many different, mathematically unrelated natural frequencies of the system. Unlike classical harmonic resonance, in which the component frequencies are integer multiples of the fundamental tone, here each component oscillates independently, creating a complex, asymmetrical, and irregular structure. Resonance peaks appear at random, uneven intervals rather than in a regular mathematical sequence. The graph has many sharp peaks, each corresponding to a different non-harmonic component. There is no periodicity: Because the individual component waves do not "meet" regularly at the same phases, the resulting waveform is complex, asymmetrical, and does not repeat over time. Closely spaced non-harmonic frequencies often overlap, resulting in irregular fluctuations in amplitude. The resonance of non-harmonic polytones with the basilar membrane of the inner ear is based on the simultaneous excitation of multiple distinct, independent locations along the basilar membrane, in accordance with the principle of frequency analysis (tonotopy) according to the traveling-wave theory.

In the case of a non-harmonic polytone, each of its component frequencies excites its own separate traveling wave on the basilar membrane - in accordance with the traveling wave theory.

On the basilar membrane, as many distinct, isolated deflection maxima (resonance points) are created as there are non-harmonic tone components - provided that the phase of the waves is consistent and their frequencies are sufficiently distant from each other. Each point is supposed to generate a flow of cochlear fluid! How many fluid streams are generated? Is this movement - the flow of fluid - supposed to bend the hairs of the hair cells? Is it supposed to encode

all the auditory information transmitted to the receptor? Is this how we hear?

The resonance of voiceless consonants in the cochlea occurs at the very beginning of the fluid pathway in the cochlea, i.e. near the oval window. This follows directly from the laws of acoustics and the so-called tonotopy (the spatial separation of frequencies) in the inner ear. Voiceless consonants (such as *p, t, k, f, θ, s, ʃ, ʈ, ʡ*) are characterized by very high-frequency noise, often from 4 kHz to even above 8 kHz. They do not have a fundamental tone [5].

Fricative consonants with the highest frequencies (*s* and *f*): They resonate closest to the oval window - frequencies of 6000-8000 Hz or even higher. **Sibilant consonants (*s, ʃ, ʈ*):** This frequency range is slightly lower (approximately 3,000-5,000 Hz), so the resonance point shifts slightly farther from the base, while still remaining in the basal region. **Plosive consonants (*p, t, k*):** They produce a short, impulsive resonance with an explosive character, involving a broad but still predominantly high-frequency region of the cochlear base. The vowel "a" (harmonic) has a fundamental laryngeal frequency of 120 Hz in men and 220 Hz in women. The first resonance formant (F1), following resonance in the larynx, pharynx, and oral cavity, is 700-800 Hz. For example, in the word "strengths", "texts", "sixths", and similar words, there is one vowel with a fundamental tone and aliquots, as well as voiceless consonants, without a fundamental tone, which are only short, impulsive noises (in the Bekesy resonance), impossible to recognize. We recognize it well, we hear it, just like a whole series of voiceless consonants, because they are not perceived by the wave resonance with the basilar membrane, but directly by the receptor.

The basilar membrane attached to the organ of Corti does not vibrate on its own. If it vibrates, the entire organ vibrates together with the membrane; therefore, all auditory hair cells vibrate simultaneously, as do the auditory receptors and the hairs of the hair cells. The mass of the vibrating element conducting the sound wave determines the inertia in the wave motion. High frequencies require a very large amount of energy in such a system.

What else is important for the transfer of energy to the receptor - namely, the lengthening and complication of the direct pathway: The total distance traveled by the vibrating particles of the medium during the transfer of sound-wave energy depends on the frequency and amplitude of the wave.

If we consider the motion of a particle over a specific period of time (e.g., one second), the frequency is crucial: In oscillatory motion, during one complete period, an oscillating particle travels a distance equal to four times the amplitude of the wave. Therefore, in one second the particle travels a total distance equal to the amplitude of 4 wave periods. The higher the frequency at the same amplitude, the greater the total distance the particle travels because it makes more "trips" back and forth.

Particle motion - the total distance travelled over a given period of time depends on the frequency and amplitude of the wave = $\text{frequency/s} \times \text{amplitude} \times 4$

The particle speed of a 100 Hz and 1 nm wave is 400 nm/s

The particle speed of a 200 Hz and 1 nm wave is 800 nm/s

The particle speed of a 1000 Hz and 1 nm wave is 4000 nm/s

The particle speed of a 1000 Hz and 10 nm wave is 40,000 nm/s

The particle speed of a 1000 Hz and 100 nm wave is 400,000 nm/s

The particle speed of a 1000 Hz and 500 nm wave is 2,000,000 nm/s. This translates into the energy required to hear the given frequencies carried by the sound wave. When the wave is transmitted through a structure with mass (the ossicles or the organ of Corti together with the basilar membrane), this result depends on the vibrating mass, the amplitude, and the square of the frequency (molecular vibrations). Why the square of the frequency? Because 2 speeds mean returning from maximum deflection to zero and this does not require energy.

This may explain the problems with high-frequency transmission after stapedotomy.

Basilar membrane width

At the base of the cochlea: approx. 0.08-0.16 mm

At the apex of the cochlea: approx. 0.42-0.65 mm

Basilar membrane thickness

At the base of the cochlea: approx. 5-7.5 μm

At the apex of the cochlea: approx. 1.5-2.5 μm

The height of the entire vibrating complex, *i.e.*, the basilar membrane together with the organ of Corti, ranges from approximately 40-50 μm at the base to more than 100-150 μm at the apex.

Vibrating mass (basilar membrane + organ of Corti) At the base of the cochlea: approx. 0.05-0.1 (mg/cm²) At the apex of the cochlea: approx. 0.2-0.4 (mg/cm²) The vibrating mass increases towards the apex of the cochlea. This is due to the fact that although the basilar membrane itself becomes thinner there, the organ of Corti (supporting cells, hair cells) vibrating on it becomes much larger and higher, which drastically increases the total mass of the mechanical system responsible for the reception of low frequencies.

Fastest energy transfer (one-quarter to one-half of a wave cycle initiates the transfer of energy to the stationary basilar membrane): The first deflection of the basilar membrane (conversion of the kinetic energy of the sound wave to the potential energy of the membrane deformation) occurs already after 2.5-5 ms from the moment the longitudinal wave front reaches the appropriate resonance point (for 100 Hz this is the region of the cochlear apex).

Human speech is a mixture of harmonic and non-harmonic polytones.

This is because voiced vowels such as "a", "e", "o" and voiced consonants "m", "n", "z" are produced by regular vibrations of the vocal folds. Voiceless consonants (e.g., "s", "p", "t") are non-harmonic and resemble noise because they are produced by air turbulence in the speech cycle, not by vibrations of the vocal cords.

Intracellular amplification [6, 7]: In all senses there is an intracellular, controlled molecular amplification. Most chemical reactions and energy transfer between small molecules take place in 10⁻¹⁴s. These are reactions at the atomic and electron level. 'Difficult' reactions are 1000 times slower, but it is still 10⁻¹¹s. Intracellular amplification means a whole complex of factors such as: phosphorylation and dephosphorylation of ion channels responsible for cell membrane conductance, ATP concentration, cAMP levels, cGMP, cell pH, osmotic pressure, presence of ligands, operation of Ca⁺⁺ATPases pumps. These cellular membrane-associated pumps play a major role in maintaining the fluctuating calcium levels in the cell. Intracellular intensification is also related to the work of calcium-binding proteins, where calmodulin, which influences the production and breakdown of cAMP and cGMP, plays an important role. It activates protein kinases and phosphatases and controls the calcium pump. It influences the contraction of muscle and non-muscle cells through activation of cAMP-independent myosin light chain kinase. Calmodulin also affects transmitter's exocytosis. The binding of 4 calcium atoms by calmodulin will increase its action by 1000 times. Enzyme production or the rate of enzyme degradation is subject to regulation.

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