



Wave Resonance in the Inner Ear

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Abstract

The paper discusses the mechanism of wave resonance in the inner ear. The mechanism underlying the generation and propagation of the traveling wave on the basilar membrane, as described by Bekesy, was analyzed. Critical observations were presented regarding sound-wave amplification in the middle and inner ear, as well as the hydrodynamics of the cochlear fluids. Attention was drawn to the problem of encoding auditory information by cochlear fluids and the tip-links mechanism. The existence of another signal-to-receptor pathway described in the Submolecular Theory of Hearing has been pointed out. A new mechanism for encoding auditory information in the sound wave as it travels toward the auditory receptor, consistent with the principles of quantum physics, is proposed.

Keywords: Inner Ear

Introduction

Problems of resonance of sound waves in the ear:

In 1859, Helmholtz proposed his resonance theory, according to which sound waves entering the ear resonated with the corresponding sections of the basilar membrane. Wave resonance was proposed as the mechanism responsible for frequency discrimination of sounds [1].

In subsequent years, further theories of hearing based on wave resonance emerged: The standing-wave theory and Hurst's traveling-wave theory, proposed in 1894, were subsequently developed. In 1928, Georg von Bekesy (1899–1972) published his traveling-wave theory of hearing. A groundbreaking experiment involved observing the traveling wave on the basilar membrane through an opening made in the cochlear wall. In his experiments, Bekesy used an electromechanical driving device to generate simple harmonic tones. We hear sounds that are not simple harmonic tones. It is difficult to observe a wave on a thin, flabby membrane that is coupled to the organ of Corti along its entire length. There is no possibility of free vibrations of the membrane within the cochlear fluid.

For his calculations, Bekesy straightened the spiral-shaped cochlea into a straight tube and removed the Reissner's membrane, effectively connecting the vestibular duct with the cochlear duct so that the sound wave could propagate on both sides of the basilar membrane. In such a configuration, the sound wave propagating from the oval window would pass through the organ of Corti and its sensory receptors without transmitting auditory information to the receptors, since its proposed role would be to generate a traveling wave on the basilar membrane.

Wave resonance occurs in accordance with Newton's Second Law of Motion, which states that a force produces a change in an object's motion in the direction in which the force acts: "An object moves in the direction of the applied force" [2]. In the ear, the driving force is the energy of the longitudinal wave in the cochlear fluid. The vibrating structure is the basilar membrane, which, according to Bekesy's calculations, has natural vibrations ranging from 16 to 20 kHz.

In mammals capable of hearing frequencies up to 100 kHz, there is a problem with matching the natural vibrations of the basilar membrane to the frequencies of the sound wave. Studies of the natural vibrations of human tissues have shown that their values range from 5 Hz to 100 Hz [3]. In wave resonance, damping depends on the difference between the frequencies of the interacting waves, the mass of the vibrating element, and the elasticity and tension of that element. When the damping exceeds the energy of the driving wave, resonance does not occur. When listening to sounds at the threshold of hearing, the damping of the wave exceeds the energy of the wave. No resonance occurs, yet hearing is preserved. This suggests that the auditory signal reaches the receptor through an alternative pathway [4]. When conducting sounds from the middle ear to the vestibular duct, high frequencies cause rocking movements of the stapes. At the same time, one part of the stapes plate generates a forward-propagating wave, while the other part of the plate generates a backward-propagating wave. This results in destructive interference between the sound waves carrying the encoded auditory information. The high-frequency sound wave becomes distorted and is therefore no longer accurately represented.

According to Bekesy, the speed of the wave in the cochlear fluid, 1,450 m/s, is 29 times greater than the speed of the traveling wave near the base of the cochlea and 500 times greater than the speed of the traveling wave near the cochlear apex. The information is compressed by a variable factor ranging from 29-fold to 500-fold and, according to Bekesy's theory, is transmitted to the endolymph. The fluid movement is proposed to regulate, through the tip-links mechanism, the flow of K^+ ions through the receptor's mechanically gated potassium channel into the auditory hair cell, thereby initiating cellular depolarization. The frequency-dependent location of wave resonance on the basilar membrane, together with the varying velocity of the traveling wave, means that each frequency is assumed to resonate and produce the greatest deflection of the basilar membrane at a different location and at a different time.

We hear sounds, not simple harmonic, sinusoidal tones, having a certain frequency, amplitude and phase. Every sound is made up of tones. These are fundamental tones and their harmonic components, whose frequencies are integer multiples of the fundamental frequency. The number of components called aliquots is unlimited, but the most important are the first, those closest in frequency to the fundamental tone. When the ear receives a large number of sounds simultaneously, it consequently receives many more harmonic components. If the waves transmitted to the auditory receptor contain numerous sounds — for example, during a musical concert — and consequently a much larger number of harmonic components, the transmission of information through the cochlear fluids and the basilar membrane would, according to Bekesy's theory, become impossible. This would be due to the

simultaneous occurrence of a very large number of maximal basilar-membrane deflections, which are assumed to transmit information to the endolymph.

The sound wave in the cochlear fluid is a longitudinal wave. The wave of natural vibrations of the basilar membrane is a transverse wave. The force vectors associated with these waves act in a perpendicular direction, making the transfer of energy more difficult.

The frequency of a string-like structure (such as the basilar membrane) depends on its length, tension, and vibrating mass. The greater the vibrating mass, the lower the resonant frequencies. In the ear, the width of the cochlear canals decreases threefold from the oval window toward the cochlear apex. According to Bekesy, the width of the basilar membrane increases threefold in the same direction (?). The basilar membrane has no tension, is attached to the organ of Corti, and therefore cannot vibrate independently. There is no fluid-filled space between the basilar membrane and the organ of Corti in which fluid flow could arise from the maximum deflection of the basilar membrane. Fluid movement and tip-links are supposed to determine frequency discrimination. If the whole organ of Corti vibrates, together with the auditory cells and their hairs, then the energy of the sound wave, carrying the auditory information, according to Huygens' principle, reaches the receptor, without the need for endolymphatic fluid flow and the action of the tip-links mechanism.

The coupling of the basilar membrane to the massive organ of Corti increases the effective vibrating mass, which affects inertia during wave motion, particularly at high frequencies. The inertia in wave motion is directly proportional to the amplitude of the vibration and to the vibrating mass and proportional to the square of the frequency of the sound wave.

The issue of resonance becomes much more complicated when the ear perceives our own voice. The average fundamental frequencies of voices are: bass – 200 Hz, baritone – 300 Hz, tenor – 400 Hz, alto – 500 Hz, mezzo-soprano – 600 Hz, and soprano – 700 Hz [5]. Each fundamental tone has several harmonic component tones that are successive multiples of the fundamental tone. All fundamental tones and harmonic components entering the ear at the same time are simultaneously detected by the auditory receptor. But Bekesy's theory says something completely different. The basilar membrane is assumed to receive each frequency at a different location where the driving wave resonates with the driven wave. There are an infinite number of frequencies in the driving wave. The maximum deflections of the traveling wave, necessary for frequency discrimination, would have to occur at a very large number of different locations, with no upper limit. The frequency of each individual tone, as well as the varying speed of the traveling wave along the basilar membrane, has an influence. This makes all the deflections of the traveling wave arise at different times, which contradicts experimental studies on the sounds perceived by the auditory system. The paradox is that the vocal sounds transmitted to the inner ear are, according to the theory, separated by resonance, with the most distant harmonic components, i.e. those with the highest frequencies, resonating on the basilar membrane closest to the oval window. Harmonic components closer to the fundamental tone produce their maximum deflection of the basilar membrane progressively closer to the cochlear apex. Finally, the fundamental tone, with the lowest frequency, reaches resonance. If the ear receives many sounds simultaneously, there is insufficient

space along the basilar membrane for the maximum deflections of the traveling wave to occur. These deflections are supposed to transmit information to the cochlear fluids and further to the receptor - in accordance with the hydrodynamics of the cochlear fluids - according to Bekesy's theory [6].

If wave resonance, endolymph flow, and the location of the maximum deflection of the traveling wave on the basilar membrane are responsible for frequency resolution, it is necessary to explain how many fluid streams are generated by the basilar membrane at the same time. Is it possible? For resonance to occur, a repeatability that is exact or close to the frequency of the driving energy is necessary. In speech, vowels have a duration of 60–200 ms, while consonants have a duration of 40–200 ms. The duration of syllables ranges from 200 to 300 ms. The duration of the harmonic tones is identical to the duration of the entire vowel and ranges from 100 to 250 ms (according to AI). This contradicts Bekesy's theory, which states that the place and time of resonance of the wave with the basilar membrane depends on the frequency of the wave. Voiceless consonants do not have aliquots, because they do not have a fundamental tone. They have a continuous spectrum, as air passes through the open larynx without vibration of the vocal cords. They are produced by aerodynamic noise generated as air flows through the vocal tract, without vibration of the vocal cords. The components of this sound are aperiodic. Such a sound, acting as a driving force, cannot produce resonance. Voiceless consonants are heard without resonance and without the involvement of the basilar membrane. By what pathway? [7] According to the traveling-wave theory, the basilar membrane is involved in mechanically amplifying the sound wave in the inner ear through OHC contraction and pulling on the basilar membrane. The outer hair cell has no direct connection to the basilar membrane, which is coupled to the organ of Corti. Pulling the basilar membrane together with the organ of Corti lifts the hair cell itself along with its hairs, which would preclude the action of the tip-links mechanism. Putting a massive structure into vibration requires a large amount of external energy. This is not provided by the electrochemical potential across the cell membrane, nor by the piezoelectric effect. The energy for prestin is not derived from ATP.

Energy required to amplify a 20 dB, 10 kHz sound wave by 40 dB: [AI]

The initial level was 20 dB, while the final level was 60 dB (20 dB + 40 dB). 20 dB corresponds to 100 times the reference energy.

60 dB corresponds to 1,000,000 times the reference energy.

The ratio of the final energy to the initial energy is exactly 10,000. To increase the signal level by 40 dB, it is necessary to provide an external energy of 10,000 times greater than the initial energy of 20 dB..

Intracellular amplification, at the molecular level, does not require such energy: [8]

In all senses there is intracellular, regulated, molecular amplification. Intracellular amplification is a whole complex of factors such as: phosphorylation and dephosphorylation of ion channels responsible for the conductivity of cell membranes, ATP concentration, cAMP level, cGMP, cell pH, osmotic pressure,

presence of ligands, activity of the sodium-potassium pump, Ca⁺⁺ATPase. Intracellular amplification is associated with the activity of calcium-binding proteins, where an important role is played by calmodulin, which affects the production and breakdown of cAMP and cGMP. It activates protein kinases and phosphatases, regulates the activity of the calcium pump. It affects the contraction of muscle and non-muscle cells by activating a cAMP-independent myosin light-chain kinase. Calmodulin also affects the exocytosis of the transmitter. The process of production of enzymes or the rate of their breakdown is regulated in the cell. Calcium is a second messenger in the cell that acts more rapidly than other second messengers, such as cAMP, cGMP, DAG, and IP₃. The production of second messengers is one of several mechanisms involved in intracellular signal amplification. One enzyme molecule can produce several hundred second messengers. Chemical reactions involved in amplification within the auditory cell itself take place within 10⁻¹⁴ s. More complex reactions may take up to 1,000 times longer, but this is still only 10⁻¹¹ s.

Sound waves reaching the receptor, regardless of the pathway — either through the basilar membrane and the cochlear fluids (low frequencies) or through the bony shell of the cochlea — transfer energy and information to the receptor and the auditory cell in accordance with the laws of quantum chemistry and quantum physics [9].

A sound wave should be regarded as a stream of packets of energy in the form of multiples of energy quanta, encoding auditory information.

A serious problem arises at the time of listening to musical concerts, when countless sounds and tones are simultaneously transmitted to the auditory receptor. The resonance of the waves, the basilar membrane and fluid flows, together with the tip-links mechanism, is unable to cope with this task [10].

There is no explanation for this mechanism, invented by Nature.

The AI-generated explanation that a sound wave can simultaneously transmit different tones and sounds from different sources through the principle of wave superposition is incorrect.

Wave superposition applies to cases in which the waves have the same frequencies and propagation velocities, but arbitrary amplitudes and phases. When waves of different frequencies overlap, a complex wave is produced, which is not a harmonic or sinusoidal wave.

Voiced consonants and vowels have a fundamental tone and harmonic components at different frequencies; therefore, they cannot be subject to superposition.

Voiceless consonants are not subject to resonance.

Therefore, there must be a method of simultaneous transmission of an unlimited number of tones of different frequency and speed, of different amplitude and phase.

According to the Submolecular Theory of Hearing, such a possibility is provided by a mechanism whereby the quantized energy of a sound wave is transmitted to the auditory receptor by molecules of the medium through which the sound waves generated by the vocal cords, musical instruments, a tuning fork, or other sources propagate. In the auditory receptor and auditory cell, the mechanical energy of sound waves is converted into the energy of chemical bonds and subsequently into an excitatory

postsynaptic potential and an action potential, which is conducted along the auditory nerve to the brain.

Molecules are composed of atoms linked by chemical bonds, either covalent (atomic) or ionic. A change in the total energy of a molecule causes changes in the valence bond angles, i.e. the angles between adjacent valence bonds, which may decrease or increase as the energy changes. A dihedral (torsional) angle is the angle of rotation about the axis of a non-covalent bond; changing it requires less energy than changing a valence angle. Changes in molecular geometry occur mainly through changes in torsional angles, resulting in conformational changes.

The number of possible molecular conformations depends on the size of the molecule. For example, a molecule consisting of 20 atoms can have as many as 10^{20} possible conformations. For a molecule consisting of 100 atoms, the number of possible conformations is 10^{100} !

This enormous range of possible conformations of information-transmitting molecules allows an unlimited amount of information to be transmitted simultaneously.

The potential energy of a molecule is associated with its chemical bonds and is minimal when each bond in the molecule has a certain length and is free from strain. Each bond has its own characteristic length and energy.

The total energy of a molecule is the sum of its translational, electronic, rotational, and vibrational energies. While maintaining the optimal bond lengths, the angle between the bonds may change. A change in the angles causes a change in the distances between atoms, which in turn causes a change in the potential energy of the molecule. A molecule that is not acted upon by any force is in its native, ground state and has the lowest possible energy. The application of external energy disturbs this equilibrium. Depending on the amount of energy quanta, the conformational changes of the molecule are graded.

Information about the smallest change in the molecule, under the influence of minimal external energy, is given by femtosecond spectroscopy. Identifying this point (I) is extremely important for assessing the rate of the reaction to the factor causing conformational changes. A second important piece of information obtained from femtosecond spectroscopy is the assessment of the molecule's relaxation time following a conformational change. The relaxation time is measured in femtoseconds. $1 \text{ femtosecond (fs)} = 10^{-15} \text{ s} = 0.000\,000\,000\,000\,001 \text{ seconds!}$

A molecule sensitive to a certain type of energy at a certain frequency, receives this information, but cannot accumulate energy permanently in the molecule. This energy must be removed quickly. The molecule strives to reach its native state as quickly as possible. Energy cannot simply disappear; it must be transferred to

the next wave, and then to the subsequent wave, until it reaches the receptor. The excitation of the molecule as well as its relaxation takes place in a few femtoseconds. This gives the possibility of transmitting high frequencies. One period of atomic and molecular vibrations is 10^{-15} s . If two molecules have, at certain locations on the periphery, identical electron fields with the same potential, a supramolecular complex is formed that is capable of accepting external energy. This results in conformational changes in the complex and enables it to perform work.

Such a complex can influence the gating of sound wave-dependent potassium ion channels.

The procedures involved in the reception and transmission of sound wave energy take place at the submolecular and atomic levels.

These are nanostructures and nanomechanisms. Therefore, the theory explaining these processes has been called the "Submolecular Theory of Hearing".

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