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The Standing Acoustic Wave Principle within the Frequency Analysis of Acoustic Signals in the Cochlea

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Abstract

The organ of hearing is responsible for the correct frequency analysis of auditory perceptions coming from the outer environment. The article deals with the principles of the analysis of auditory perceptions in the cochlea only, i.e., from the overall signal leaving the oval window to its decomposition realized by the basilar membrane. The paper presents two different methods with the function of the cochlea considered as a frequency analyzer of perceived acoustic signals. First, there is an analysis of the principle that cochlear function involves acoustic waves travelling along the basilar membrane; this concept is one that prevails in the contemporary specialist literature. Then, a new principle with the working name "the principle of standing acoustic waves in the common cavity of the scala vestibuli and scala tympani" is presented and defined in depth. According to this principle, individual structural modes of the basilar membrane are excited by continuous standing waves of acoustic pressure in the scale tympani.

Keywords: Cochlea function; Acoustic signals; Frequency analysis; Travelling wave principle; Standing wave principle

Introduction

The frequency analysis of auditory perceptions takes place in the cochlea of the inner ear. The cochlea's task is to transform the entrance vibrations of the oval window into individual frequency components of the acoustic signal entering the outer ear. This frequency analysis is provided by a coupling between the overall acoustic wave in the perilymph and the vibrations of the basilar membrane. With regard to the analyzed transformation of signals, the scala vestibuli, scale tympani, basilar membrane and organ of Corti are of the highest importance, the latter of which transforms deformations of the basilar membrane into tension pulses that are further conveyed to the relevant part of the brain. The cavities of the scala vestibuli and scale tympani are filled with the same liquid-perilymph. They are interconnected with a narrow opening called the helicotrema. Both the studied cavities have approximately the same length and form one common cavity with the common helicotrema opening. On the entrance side of the scala vestibuli is the oval window, through which vibrations enter from the middle ear side. On the other end of this common cavity is the round window. Each of the two windows fulfills a specific function.

When the oval window vibrates, acoustic waves of a specific character are generated in the perilymph. The spectral and modal properties of the basilar membrane enables the decompose the entering acoustic signal into individual frequency components. The signal's individual frequency components that have been "decoded" in this way are transformed in the organ of Corti into electrical signals that are conveyed to the relevant area of the nervous system through the structure of nervous fibers. However, the principle governing the transformation of the membrane vibrations in the oval window into basilar membrane vibrations presents a fundamental problem which has yet to be completely satisfactorily resolved. The aforementioned problem is truly critical in nature, as its incorrect description and definition may give rise to various misleading considerations and concepts of the system and further may become a possible cause of subsequent related errors and constructs. This may then result in totally non-functioning diagram of the function and transformation of acoustic signals while passing through the cochlea.

We will now discuss the two most influential present-day views on cochlear function and therefore on the transformation of the analysed overall acoustic signal into individual frequency components.

The following is a description of the theories in question:

1. Helmholtz's place theory [1], also known as the sympathetic resonance theory.

2. Békésy's travelling wave theory [2].

The sympathetic resonance theory views the basilar membrane as an array of tiny sequentially tuned resonators distributed along the membrane. This theory was originally proposed by Helmholtz and states that the tiny resonators of the basilar membrane are set directly into motion by sound pressure changes in the perilymph. There is, however, another competing theory of hearing, called the travelling wave theory. Von Békésy found that the point at which the displacement of the basilar membrane was the greatest was dependent on the frequency of the sound wave and considered the travelling wave mechanism to be responsible for the sound analysis performed by the cochlea. The theory of hearing (or of sound perception) based on this concept is called the travelling wave theory. Both of these theories belong to a larger group of theories of hearing called the place theories, which support the tonotopic organization of the basilar membrane. There are a number of theoretical and experimental studies which support either the travelling wave [3-6]; Cooper and Rhode [7] or the resonance theory of hearing [8,9].

However, there is still a lack of complete agreement in the literature as to whether the travelling wave is directly responsible for the motion of the basilar membrane, or whether it is a secondary effect caused by the direct stimulation of the basilar membrane's resonators by sound pressure propagating through the perilymph [8,10].

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The Travelling Acoustic Wave Principle

The travelling acoustic wave principle is currently the most frequently quoted theory in the international specialist literature [11-22].

Nonetheless, numerous specialists engaged in the problems concerned express some serious objections to the theory. This has to do with the fact that the travelling acoustic wave principle is not sufficiently and thoroughly defined. The number of unresolved properties and characteristics of the examined theory thus give rise to some justified doubts about the correctness and validity of this principle. Therefore, we will first describe the substance of the theory behind the travelling acoustic wave principle. Then, we will outline its flaws and try to generally question its functionality, applicability and validity as a whole.

Fundamentals of the travelling acoustic wave principle

Practically everything we know about waves in the cochlea was discovered in the 1940s by Georg Von Békésy [23], who carried out experiments on cochleae extracted from human and animal cadavers. The "classical" view on wave propagation is that propagating waves are possible in both directions along the length of the basilar membrane and that they have identical properties. Von Békésy studied the cochlea as a passive mechanical filter that utilizes a system of elastic components immersed in a fluid for the analysis of incoming sounds. He observed that a pure tone input generates a travelling wave which propagates along the basilar membrane. The wave amplitude rises gradually, reaching a peak at a specific location along the membrane, after which it decays rapidly.

It was observed that a pure tone input generates a travelling wave that reaches its peak at a specific location along the basilar membrane: the position of the peak depends on the frequency of the tone. Complex sounds composed of several pure tones evoke a basilar membrane response that is similar to a superposition of the membrane's responses to the constituent frequencies [4,15,19,22,24]. The peak location depends on the frequency of the input tone, with high frequencies peaking close to the stapes and the lower frequencies further towards the apex. This "place principle" is a crucial mechanism of frequency analysis in the cochlea.

The oval and round windows of the cochlea are both covered with elastic membranes that can bulge in and out of the cochlea. An inward motion of the stapes into the scala vestibuli causes some of the perilymph to move from the scala vestibuli into the scala tympani. After the fluid passes through the helicotrema at the apex of the cochlea, the round window membrane bulges out to accommodate the increased amount of fluid in the scala tympani. A motion of the stapes away from the scala vestibuli causes the perilymph to move from the scala tympani into the scala vestibule; the membrane of the round window consequently bulges inwards. The motion of the inner ear fluid caused by the inward and outward motions of the stapes creates a travelling wave motion along the basilar membrane.

The basilar membrane responds differently to sound stimuli of different frequencies, causing the location where it reaches its maximum displacement to depend on the frequency of the sound wave. There is a systematic shift in the point of maximal vibration from the apex toward the base as the frequency increases. The motion of the basilar membrane proceeds in an orderly fashion from the base to the point of maximum displacement, beyond which the wave damps out relatively quickly (Figure 1).
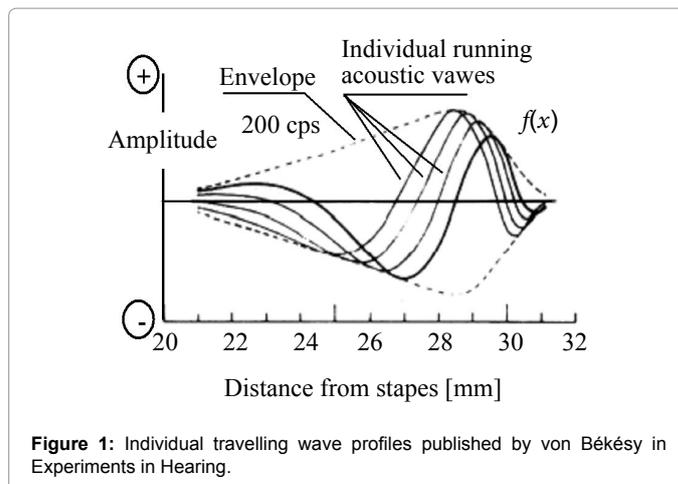

Figure 1: Individual travelling wave profiles published by von Békésy in Experiments in Hearing.

Békésy proposed that frequency coding took place at the cochlea level. Anatomically, the basilar membrane gets wider towards the top, resulting in a gradation of stiffness along its length, going from the base (close to the stapes), where it is stiffest, to the apex (helicotrema), where it is the least stiff. As a result of this stiffness gradient, sound transmitted to the cochlea develops a special kind of wave pattern which travels from the base towards the apex. In other words, travelling waves are the mechanism that translates signal frequencies to the place of stimulation along the basilar membrane. High frequencies are represented towards the base of the cochlea, and successively lower frequencies are represented close and closer to the apex.

Inconsistencies in the principle of travelling acoustic waves in the perilymph

It should be mentioned that the basilar membrane is physically located in the scala tympani. Equally, it must be emphasized that acoustic signals cannot mutually pass through the walls of the individual cavities-as is frequently described in the literature. As it is located in the scala tympani, the basilar membrane cannot be excited by a travelling acoustic wave while a wave is still in the scala vestibuli, but only when it reaches the scala tympani.

This is a serious and very frequent flaw occurring in the description of the travelling acoustic wave principle. The length of a travelling acoustic wave in the perilymph within the frequencies of 20 to 16000 Hz is within the wavelengths of 75 m to 0.1 m. Therefore, the length of any possible wave will not wholly fit within the length of the basilar membrane, as it exceeds it in length. Hence, the diagram of waves represented in (Figure 1) is not consistent with reality.

It is necessary to state that each individual structural mode of the basilar membrane vibrates at a relevant resonance frequency around an equilibrium position which corresponds to, and is identical to, the basilar membrane position at rest. Individual shapes of vibrations oscillate with an appropriate amplitude and with the basilar membrane resonance frequency and the corresponding frequency of the analysed signal. Individual shapes of vibrations do not move along the length of the basilar membrane, but vibrate in their given positions on the basilar membrane. It is therefore impossible, based on the shapes of vibrations thus defined, that a structural wave travelling along the basilar membrane can be generated.

On the basis of the examined principle we can further state:

- According to this principle, acoustic waves pass through the perilymph from the oval window in the scala vestibuli as far as the helicotrema and continue further through the scala tympani, where they travel along the basilar membrane.

- This results in an undesirable "mixing" of individual travelling acoustic waves; they interfere with each other or become amplified depending on the phase circumstances of the two or more travelling waves in both the scalas. It follows that one entering acoustic wave may, according to this principle, move back and forth and rebound in both the scalas several times, which would certainly cause chaos among the individual travelling waves.

- This repeated manner of motion of the relevant waves along the basilar membrane cannot cause an excitation of the structural mode corresponding to the frequency of the analysed waves of the signal.

- It follows from the above outline that the system of travelling acoustic waves could certainly cause chaos and collisions as it generates changing maxima and minima positions of the acoustic pressures on the basilar membrane (motion in phase and antiphase).

- Based on the above arguments, there are no reasons for the creation of an envelope of acoustic waves in the perilymph, or an envelope of the basilar membrane.

- A travelling acoustic wave could only be generated in the common cavity in the case that the scale tympani on the round window side were open and acoustic waves could leave into the surrounding environment. The round window is closed, however and does not enable a travelling acoustic wave.

Based on the arguments presented above, and some others, it is evident that the principle involving the travelling of acoustic waves along the basilar membrane is not a relevant one; indeed, it is mere fiction. The principle of travelling acoustic waves applied until now therefore cannot function: it cannot enable the reliable decomposition of the overall entranced acoustic signal into individual frequency components.

The Principle of Standing Acoustic Waves in the Common Cavity of the Scala Vestibuli and Scala Tympani

Common cavity, spectral and modal properties

The presence of two cavities (the scala vestibuli and the scala tympani) connected via the helicotrema allows us to define a principle different from the one generally presented in the contemporary specialist literature and widely accepted by the professional public until now. We will outline a completely different principle of excitation of the basilar membrane by acoustic waves (not travelling waves) generated by the vibrating membrane of the oval window [25-28].

As we mentioned in the introduction, both the cavities (the scala vestibuli and the scala tympani) can be considered as one "common cavity" with the helicotrema in the middle (Figure 2). The vibrating membrane in the oval window can be considered as a source of the longitudinal kinematic excitation of the perilymph in the common cavity of the two scalas in the form $x_{ex}=x_0.e^{i2\pi ft}$; x_0-amplitude, f-frequency, t-time.

With regards to the analysis of only the longitudinal oscillations of the perilymph, it is suitable to use a model of the common cavity in a straight line as shown in Figure 2. For an analysis of the passage of the excitation signal from the oval window through the scala vestibuli, helicotrema and scala tympani, a planar model (2D model-Figures 6 and 7) or a more complex model, i.e., a three-dimensional one (3D model - Figures 2, 4 and 8), can be used. Both variants are used in the presented investigation.

The parameters of the inner ear cavities for the 3D model-see (Figure 2):

Φd=6 mm; ΦdH=2 mm; ℓ=30 mm; diameters of the oval and round windows

ΦdOW=ΦdRW=3 mm;

perilymph density ρP=700 kg/m³;

sound velocity in the perilymph cP=2200 m/s.

Parameters of the inner ear cavities: Φd=6 mm, – diameters of scala vestibuli and scala tympani; ΦdH=2 mm - diameter of helicotrema; $\Phi d2$=4 mm, ΦdOW=ΦdRW=3 mm - diameters of the oval and round windows; ℓ=30 mm-cavity lengths; x=(0 ~ 2ℓ); perilymph density ρP=700 kg/m³; sound velocity in the perilymph cP=2200 m/s; x_{ex}=$x_0.e^{i2\pi ft}$ - the oval window excitation; x_0=0.0001 mm-amplitude of kinematic excitation; p(x) – acoustic pressure distribution in the perilymph.

While the oval window membrane vibrates, the whole column of the perilymph (which is a flexible medium) starts oscillating with longitudinal vibrations in the common cavity at the frequency of the analysed acoustic signal. In this way, "standing waves" arise in the common cavity perilymph. At the same time, the distribution of acoustic pressures in the column of the perilymph is continuous and corresponds to the longitudinal subresonance distribution of pressures. This means that it corresponds to the frequency of the analyzed signal, which is lower than the first (i.e., the lowest) natural frequency of the longitudinal acoustic mode of the perilymph common cavity.

The generated continuous distribution of acoustic pressures in the common cavity (and mainly in the scala tympani) is the cause of the excitation of the corresponding flexural vibration of the basilar membrane, whose natural frequency equals the frequency of the analysed acoustic signal.

This consideration, however, applies to any frequency of the analysed signal, i.e., it also includes those outside the individual resonance frequencies and shapes of the corresponding structural modes of the basilar membrane.
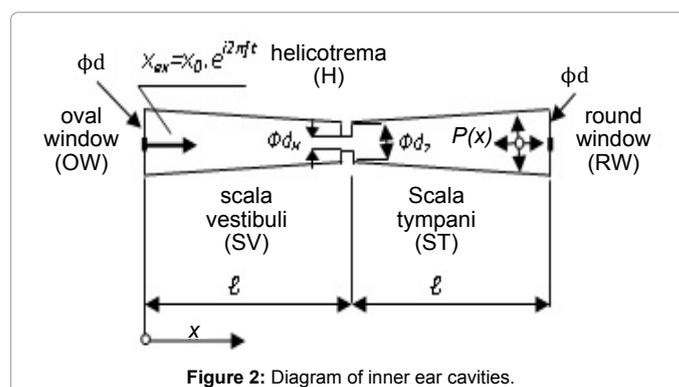

Figure 2: Diagram of inner ear cavities.

From the aspect of the necessary creation of standing waves in the perilymph in the common cavity of the scala vestibule and scala tympani, the boundary conditions of the pressure in this common cavity are important:

for x=0 (oval window) and for x=2ℓ (round window) there are maximum acoustic pressures, while at the location of the helicotrema there is zero acoustic pressure.

The distribution of amplitudes along the whole length of the scala tympani is essential from the aspect of the characteristics of the whole auditory organ.

The maximum acoustic pressures on both sides of the common cavity are based on the following consideration:

a) The membrane in the oval window performs a forced motion depending on an incoming signal at a given frequency and amplitude; the oval window must be considered as the closed end of the common cavity.

b) The membrane in the round window fulfils a safety function, preventing deformation or rupture of the common cavity; when the acoustic pressures in the perilymph are at normal operating values, the membrane in the round window can also be considered as sufficiently rigid.

c) The resonance frequencies of both window membranes are above the upper frequency border of audibility.

Comment: FEM 3D model was used to calculate the spectral and modal properties of the common cavity [26,29] see Figure 2 Parameters: number of elements 25300, number of nodes 25420, width of helicotrema 0.3 mm. The resonance frequencies of the longitudinal vibrations of the perilymph in the common cavity were calculated as follows: f_{01}=16440 Hz, f_{02}=36830 Hz. The first natural frequency of the longitudinal vibrations is very high, i.e., above 16000 Hz. The frequency f_{01} is above the upper boundary line of audibility. The corresponding first mode of perilymph vibrations contains one acoustic node where the helicotrema is located – see Figure 3. The second mode of vibration contains two acoustic nodes you can see in Figure 3.
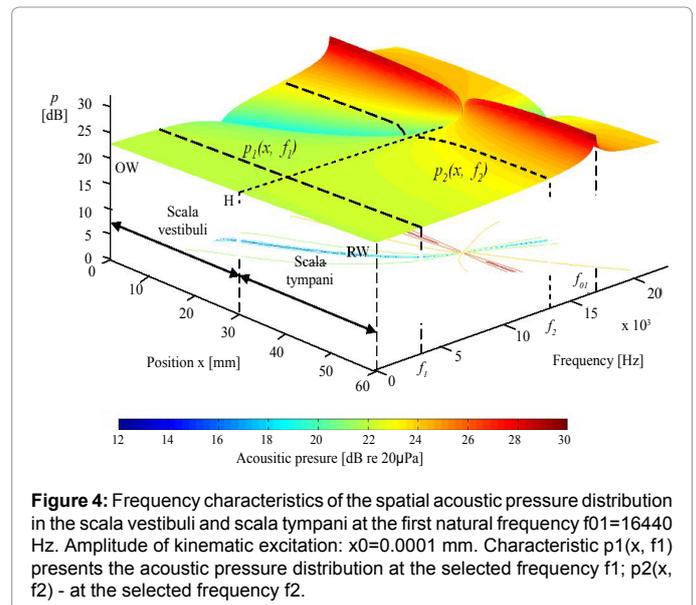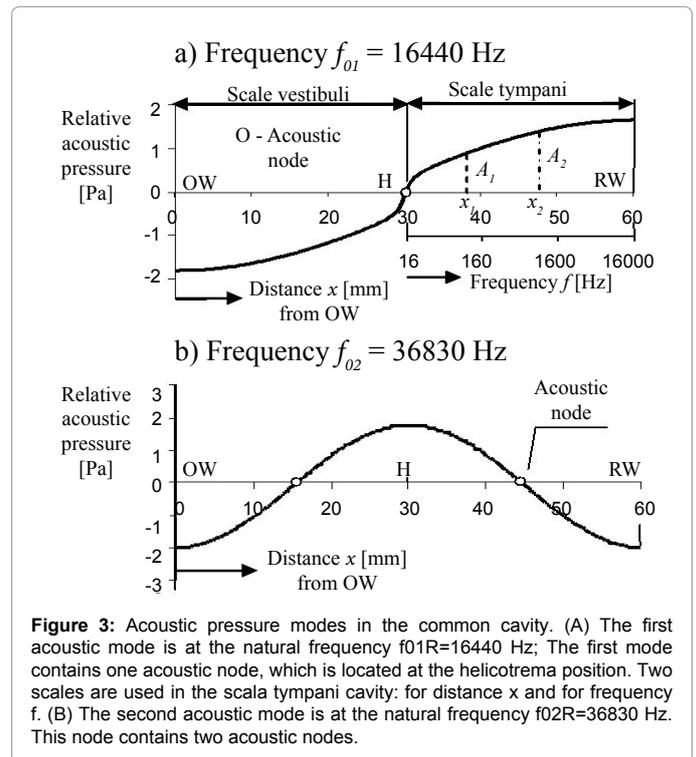
The maximum acoustic pressures are on the sides of the common cavity where the oval and round windows are located; zero acoustic pressure (acoustic node) is present where the helicotrema is located. The amplitudes of the acoustic pressures A1, A2 change with their positions x1, x2 on the basilar membrane. The distribution of the amplitudes of the acoustic pressures along the length of the scala tympani is crucial with regard to the characteristics of the whole organ of hearing. Only a portion of the characteristics presented in Figure 3 are convenient and usable for the frequency analysis of acoustic signals-and even then this applies to the scala tympani only. This characteristic defines various values of perilymph amplitude on the basilar membrane.

Amplitude characteristics of acoustic pressure distribution in the common cavity

The human ear uses a frequency range of 20 to 16000 Hz, i.e., the subresonance frequency range of the common cavity. The audible frequency range of the human ear cannot include resonance and higher than resonance frequencies as the node of the perilymph vibration shape would then be located in the scale tympani, i.e., in the area of the basilar membrane. If this were true, it would be impossible for the basilar membrane to be excited by around the lowest frequencies of signals. This is surely inconsistent with reality as the ear records signals at frequencies as low as 16 to 20 Hz. The excitation and response take

place in the subresonance frequency area of the common cavity. The distribution of the amplitudes of acoustic pressures in the common cavity and for the frequency range of 0 to 22000 Hz is shown in the diagram of spatial amplitude characteristics in Figure 4.

Each individual frequency is consistent with a specific distribution of the acoustic pressures in the common cavity, i.e., a matching characteristic. The frequency axis is in the range of up to 22000 Hz, so the diagram of the amplitudinal frequency characteristics of acoustic pressures contains the first resonance peak of the system (Figure 4). The aforementioned characteristics define a very important condition with regard to the correct analysis of acoustic signals, namely the absence of

Figure 3: Acoustic pressure modes in the common cavity. (A) The first acoustic mode is at the natural frequency f01R=16440 Hz; The first mode contains one acoustic node, which is located at the helicotrema position. Two scales are used in the scala tympani cavity: for distance x and for frequency f. (B) The second acoustic mode is at the natural frequency f02R=36830 Hz. This node contains two acoustic nodes.

Figure 4: Frequency characteristics of the spatial acoustic pressure distribution in the scala vestibuli and scala tympani at the first natural frequency f01=16440 Hz. Amplitude of kinematic excitation: x0=0.0001 mm. Characteristic p1(x, f1) presents the acoustic pressure distribution at the selected frequency f1; p2(x, f2) - at the selected frequency f2.

any acoustic node in the scala tympani area. Therefore, it is possible to analyze acoustic signals from a frequency of almost zero. This ensures the reliable analysis of signals using the fastening up structural modes of the basilar membrane.

The progressions of acoustic pressures in the perilymph at the f_1, f_2 frequencies of the signal are p1(x, f1) and p2(x, f2) (Figure 4). The progressions of these pressures change with the positions x and frequencies of the signal. The progression of p1(x, f1) pressure appears almost linear on a decibel scale of p [dB] pressure. On the other hand, the progression of p2(x, f_2) substantially differs as a result of its proximity to the f_{01} resonance frequency.

Further, we can summarize that, with a greater number of frequency components of signals entering the oval window and thereby the common cavity of the scala vestibuli and the scala tympani, the same greater number of sub-resonance progressions of acoustic pressures will be excited in the common cavity. Each individual frequency signal component is adjusted with regard to amplitudes by a relevant frequency characteristic according to the diagram of characteristics in Figure 4. This means that higher and very high frequencies of signals are amplified with a higher intensity than is the case with signals with lower and very low frequencies.

The influence of the helicotrema on the progression of acoustic pressure in the perilymph

The presence of the helicotrema in the common cavity system favourably affects the progression of acoustic pressures in the scala tympani, particularly in the area of low frequencies (Figures 3 and 5). If the common cavity did not contain the helicotrema, the common cavity would then just have the shape of a Φd diameter cylinder. The acoustic pressure progression in this cavity would then correspond to a cosine curve. As a result, low frequency signals would be excited with a substantially lower intensity - Figure 5.

With the presence of the helicotrema, the distribution of acoustic pressures in the perilymph in the low frequency area is higher and therefore more favourable than the pressure distribution without the helicotrema. This has a favourable effect on the quality of the perception of mainly the lower and lowest frequency components of a signal.

The consequences of the presence of the helicotrema:

a) The analysis of the monitored acoustic signals must take place in the frequency range from (0 to 16000) Hz. The frequency analysis of the signals itself takes place via the basilar membrane, whose length has to correspond to the length of the scala tympani only.

b) According to the characteristics in Figure 5 it is obvious that in the case of the standing wave of a signal (or signals), there is a continuous distribution of acoustic pressure amplitudes along the whole range of the length of the scala tympani and thus also the length of the basilar membrane - Figure 5. This equality is "a basic condition for the possible function" and transformation of signals from the longitudinal vibrations of the perilymph into the flexural vibrations of the basilar membrane.

c) The following definitions are therefore possible:

- The continuous progression of acoustic pressure in the perilymph in the scala tympani is the "active part" of the excitation of the basilar membrane

- "The passive part" of the signal is the continuous progression of the acoustic signal in the perilymph in the scala vestibuli.

Transformation of acoustic pressure distribution in the perilymph into flexural vibrations of the basilar membrane

Transformation of one acoustic signal-2D model: Signals generated by means of oval window vibrations have the following parameters: frequencies and relevant amplitudes. For the next analysis we will only examine one signal, with parameters as follows: the f_2 frequency, and the amplitude x0 of displacement of the oval window membrane. The parameters of this signal with the common cavity system comprising the scala vestibuli and the scala tympani are transformed into a p(x, f_2) progression according to the characteristics in (Figure 4).

We will now study the properties and characteristics of the signals for the scala tympani only. Figure 6 shows a vertically hatched area in the scala tympani that defines the decomposition of amplitudes of acoustic pressures along the basilar membrane at the analysed f_2 frequency. This means that all points on the basilar membrane are excited by the same frequency, while the decomposition of pressures
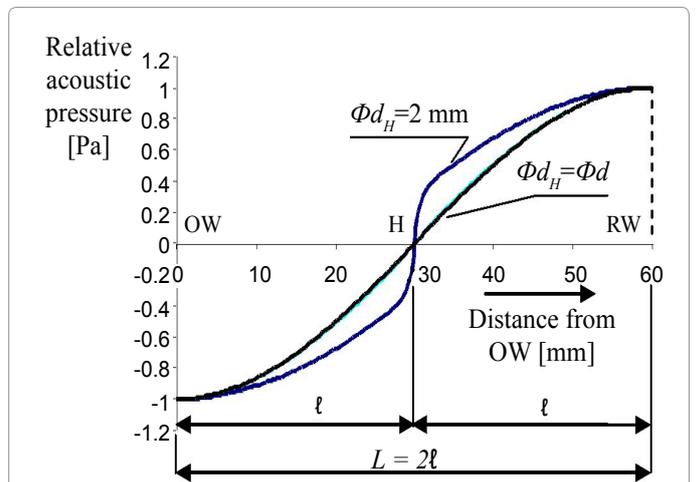

Figure 5: Acoustic modes of the common cavity with a changed diameter ΦdH [mm] of the helicotrema H; the length of the common cavity equals L=60 mm. The diameter ΦdH=2 mm of the helicotrema improves the acoustic pressure distribution in the perilymph in the low frequency area.
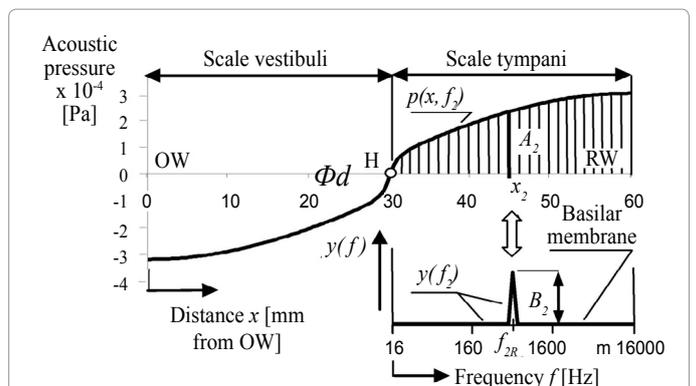

Figure 6: Decomposition of the distribution of p(x, f2) acoustic pressures in the scala tympani at a f2 signal frequency; allocation of an f2R frequency to a structural mode of the basilar membrane with the same f2R ≡ f2 resonant frequency. Through the interaction of the perilymph standing waves and the basilar membrane's spectral properties, the frequency of the relevant structural mode of the basilar membrane will "become identical" to the frequency of the signal analyzed: f2R ≡ f2. Parameters: A2, x2 on the pressure characteristic p(x, f2); B2, f2R on the characteristic y (f2): pozition on the basilar membrane.

in the perilymph along the basilar membrane is defined by the $p(x, f_2)$ characteristic - see Figure 4. The scale on the basilar membrane shows two types of values: the scale of length for the common cavity (x values) and the frequency scale (f values) for the scala tympani - see Figure 6.

The basilar membrane is excited along its whole length by the distribution of $p(x, f_2)$ acoustic pressures. The fundamental rule describes the condition that a continuously decomposed acoustic pressure at an f_2 frequency is only able to excite a structural mode of the basilar membrane with an f2R natural (resonant) frequency according to the $y(f_2)$ characteristic in Figure 6. Through the interaction of the perilymph standing waves and the basilar membrane spectral properties, the frequency of the relevant structural mode of the basilar membrane will "become identical" to the frequency of the signal analyzed: $f2_R \equiv f2$. The f2 frequency of the signal is "uniquely defined by the aforementioned selection". The corresponding acoustic intensity is identified by the B2 amplitude on the vibrating basilar membrane

It generally follows from the diagram in Figure 6 that a specific x position on the basilar membrane matches a relevant structural mode and its resonance frequency. This condition enables the transformation of that x position into a frequency value – both of them being present in the scala tympani. The aforementioned analysis applies to any other frequency component, i.e., generally to all frequencies of signals.

Comment: FEM 2D model was used to calculate the spectral and modal properties of the common cavity [26,29] see Figure 2. Parameters: number of elements 1335, number of nodes 1562, width of helicotrema 0.3 mm. The first resonance frequency of the longitudinal vibrations of the perilymph in the common cavity was calculated as follows:

f01=17850 Hz. The first natural frequency of the longitudinal vibrations is very high, i.e., above 16000 Hz.

Transformation of two acoustic signals-2D model: The characteristics in Figure 6 define amplitudes of varying size in relation to the position of the monitored point on the basilar membrane p(x,f2).

In order to gain a better overview of the issue, we will carry out an analysis of the parameters of two acoustic signals, p1(x, f1) and p2(x, f2). In the case of the first signal, the unknown parameters are frequency f1 and amplitude B1, while in the case of the second signal the parameters are f2 and B2 shown in Figure 7.

Comments:

a) The characteristics shown in Figures 6 and 7 are evaluated for the parameters of a planar model of the cochlear system (2D model). The characteristics are evaluated using SYSNOISE software [29]. Figure 4 shows that no acoustic node is present in the area of the scala tympani.

b) The amplitudes for the acoustic pressure of the perilymph grow as the signal increases in frequency.

c) Characteristics pi(x, fi) for i=1, 2 are shapes and other properties of the monitored common cavity of the scala vestibuli and scala tympani which are constant and are defined for the individual frequencies fi.

General analysis of a signal with different number of frequency components-3D model: The principle of longitudinal standing waves of perilymph in the common cavity of the scala vestibuli and scala tympani is further applied to general variant involving signals with any number of frequency components - Figure 8.
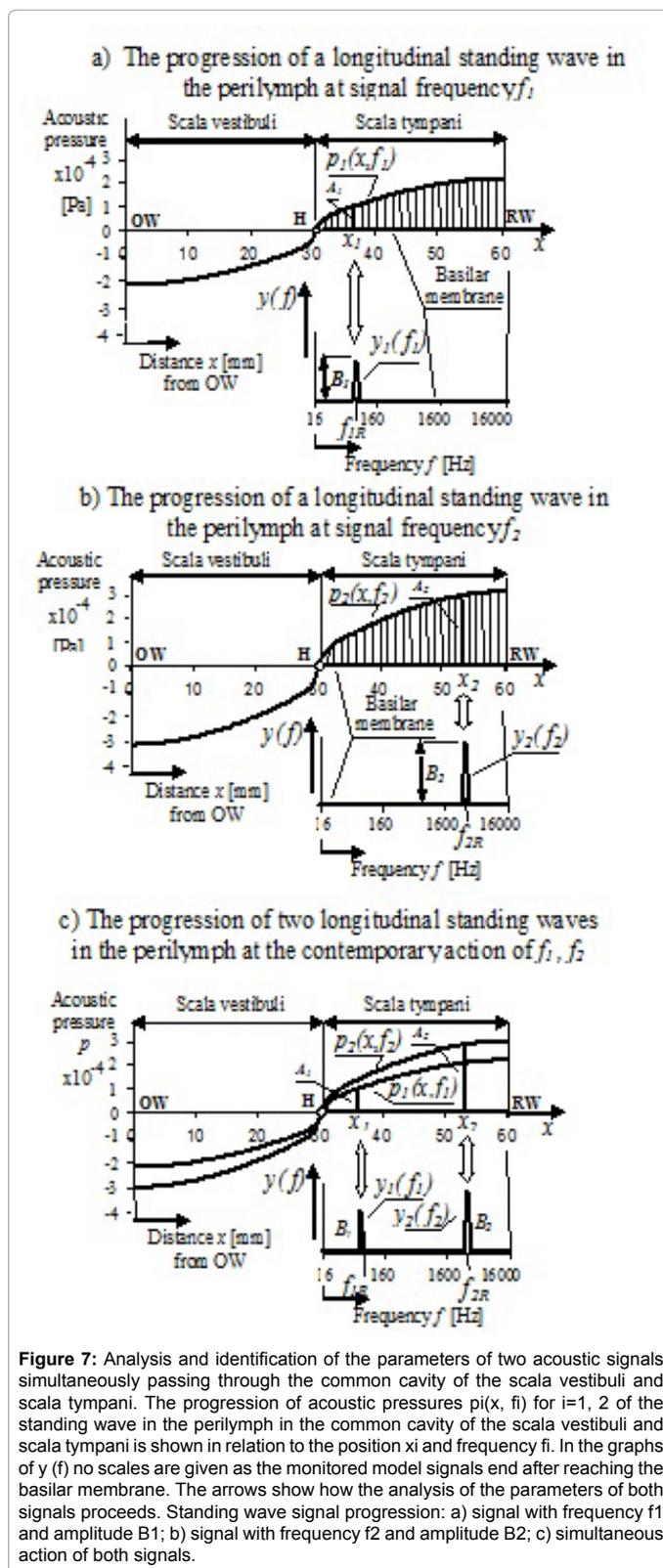

Figure 7: Analysis and identification of the parameters of two acoustic signals simultaneously passing through the common cavity of the scala vestibuli and scala tympani. The progression of acoustic pressures pi(x, fi) for i=1, 2 of the standing wave in the perilymph in the common cavity of the scala vestibuli and scala tympani is shown in relation to the position xi and frequency fi. In the graphs of y (f) no scales are given as the monitored model signals end after reaching the basilar membrane. The arrows show how the analysis of the parameters of both signals proceeds. Standing wave signal progression: a) signal with frequency f1 and amplitude B1; b) signal with frequency f2 and amplitude B2; c) simultaneous action of both signals.

The individual frequency components of each signal are defined by a set of acoustic pressures pi(x, fi) for frequencies fi (i=1, 2, N; N-total number of monitored structural bending modes of the basilar membrane). All characteristics pass through the helicotrema H (Figure 7). Continuous
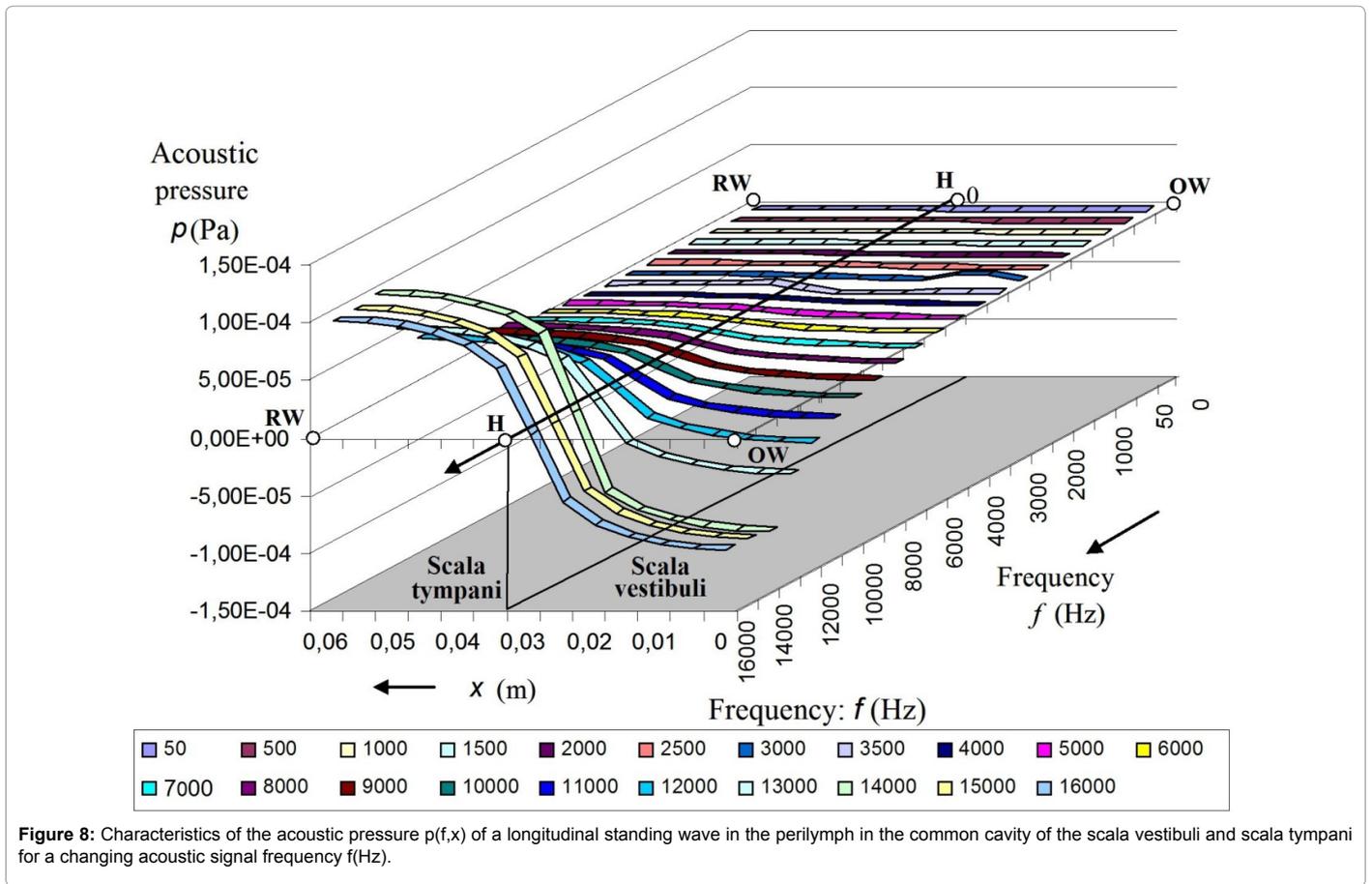
Figure 8: Characteristics of the acoustic pressure p(f,x) of a longitudinal standing wave in the perilymph in the common cavity of the scala vestibuli and scala tympani for a changing acoustic signal frequency f(Hz).

progressions of acoustic pressures in the scala tympani are the cause of the excitation of corresponding resonance frequencies of flexural vibrations of the basilar membrane (BM), which occurs at the signal frequency $fi \equiv fiR$. The search for the resultant parameters of a given analyzed signal (frequency fi and amplitude Bi (i=1, 2, N)) proceeds in the manner depicted in the presented graphs. The initial characteristics are modelled as the dependence of the position of resonance frequencies on the basilar membrane-$f_{iR}(x)$.

Transformation of the progression of the acoustic pressure of the perilymph in the common cavity of the scala vestibuli and scala tympani (with pressure propagating in all directions) is the cause of the excitation of flexural vibrations of the basilar membrane in the scala tympani. The BM is excited along its whole length from the helicotrema up to the round window (RW). At a certain frequency of incoming signal from the oval window (OW), a structural resonance flexural vibration of the BM is then excited with the same frequency as the incoming signal. Through this transformation, the individual frequency components of the signal (the frequency, including the amplitude) are changed into the appropriate and corresponding positions of resonance peaks of flexural vibrations of the basilar membrane.

A diagram of the cavities of the inner ear is according to Figure 2. The source of longitudinal kinematic excitation of the perilymph in the common cavity of both scalas is the harmonious motion of the oval window in the form:

$$x_{ex} = x_0 \cdot e^{i2\pi ft};$$

x_0-amplitude,

f-frequency,

t-time.

The growth of the amplitudes of acoustic pressures towards higher frequencies is the result of frequencies approximating the first natural frequency f01 of longitudinal oscillations of the perilymph (f01=16440 Hz).

The individual characteristics are evaluated for defined frequencies within the range of (50 to 16000) Hz. The progressions of acoustic pressures in the given depiction are positive in the scala tympani and negative in the scala vestibule. Figure 6 Symbolical expressions: (RW–RW)-Round Window, (H–H)-Helicotrema, (OW-OW)-Owal Window. Note to Figures 6, 7 and 8:

From the perspective of the cochlea function, the presence of the two scalas, i.e., the scala vestibuli and the scala tympani, needs to be defined correctly and properly. Both scalas are directly connected through the helicotrema. The same perilymph pressure values are present on both outer ends of these scalas during longitudinal vibrations of the perilymph. There is zero acoustic pressure at the location of the helicotrema. The pressures in both scala change from positive to negative alternately with the frequency of the monitored signal during longitudinal vibrations of the perilymph. For the ear to function correctly it is necessary for the helicotrema to be in the middle of the whole system of both scalas. However, only a portion of the continuous signals generated in the whole scala tympani is actually utilized because the whole basilar membrane is present in the scala tympani: the function of the BM is to register the frequencies

and corresponding amplitudes of monitored signals. In actual fact the part of the continuous signal which is present in the scala vestibuli "doesn´t immediately take part in the transfer of the signal itself to the basilar membrane". However, the presence of the scala vestibuli in the system is absolutely necessary for the correct function and enablement of the registration of monitored signals. This property is the result of the necessary closure of both ends of the common cavity of the scala vestibuli and scala tympani.

The most important characteristics and properties of signals when passing through the cochlea: For the purpose of analysis, the only frequency components of acoustic signals that can be used are those whose frequencies are located below the first natural (resonance) frequency of the longitudinal perilymph vibrations in the common cavity of the scala vestibuli and the scala tympani. Frequencies higher than that cannot be used.

Based on the above-defined principle of cochlear function, we can summarize as follows:

- after transformation, while passing through the outer and middle ears, the analysed acoustic signal is transformed into vibrations of the oval window; vibrations are characterized by a frequency and a relevant signal amplitude,

- Both cavities, the scala vestibuli and the scala tympani, form a common cavity; both scalas are connected to each other by the helicotrema; the presence of this common cavity is an essential condition for the cochlea's function as the frequency analyzer of signals,

- Vibrations of the oval window set the perilymph oscillating longitudinally in the common cavity.

- Longitudinal perilymph vibrations in the scala tympani cause flexural vibrations of the basilar membrane; this transformation is enabled by the property of fluids (Pascal's law), i.e., the transmission of pressure in fluids occurs equally in all directions.

- Transformation of the entering total acoustic signal and its distribution into individual frequency components is provided by the interaction of the pressures of longitudinal perilymph vibrations in the common cavity and the flexural vibrations of the basilar membrane in the scala tympani.

- with regard to cochlear function, the continuous distribution of acoustic pressures in the scala tympani is important; this distribution clearly shows that, at any signal excitation frequency, the basilar membrane is excited along its whole length. This allows for the excitation of any specific frequency on the basilar membrane.

- For a structural mode on the basilar membrane to be excited, its natural frequency must be identical to the frequency of the analysed signal.

- The system of outer hair cells in the organ of Corti captures deformations in the basilar membrane and transforms them into electrical signals that are transferred by a system of nervous fibres to the relevant part of the brain.

- This new concept of cochlear function is based on the principle of "standing acoustic waves in the common cavity of the scala vestibuli and the scala tympani".

- The presented principle is enabled by the spectral and modal

properties of the basilar membrane situeted in the scala tympani only.

Conclusion

The paper presents two different views on cochlear function while an acoustic signal passes through the cochlea. The first view, at present treated by many as an 'official theory', defines the transformation of acoustic waves in the perilymph of the cochlea into structural vibrations of the basilar membrane as such the longitudinal acoustic and structural waves travel along the membrane. The incorrectness of the "acoustic travelling wave principle" has been demonstrated by numerous arguments whose detailed overview is included in the relevant section.

Based on the flaws in the existing principle of acoustic waves travelling along the basilar membrane, the authors have defined an essentially different principle. The basis for the new concept of cochlea function lies in "the principle of the standing wave motion of acoustic waves in the common cavity of the scala vestibuli and the scala tympani". The individual frequency components of the analyzed acoustic signal create the corresponding longitudinal distribution of acoustic pressure inside the scala vestibuli and the scala tympani. In order to excite basilar membrane structural modes and thereby to carry out the signal frequency analysis itself, only the distribution of acoustic pressures in the scala tympani is used.

The presented principle is enabled by the spectral and modal properties of the common cavity of the scala vestibuli and the scala tympani, these being connected by the helicotrema. Correspondingly, it is based on the basilar membrane only being present in the scala tympani. The described method lays the foundation for a new conception of the function of the cochlea as a frequency analyzer of signals entering the auditory system of the ear. The submitted method provides a consistent and complete view on the function of the cochlea with regard to acoustic signal analysis. The method uses subresonance forced perilymph vibrations in the system of the common cavity of the scala vestibuli and the scala tympani.

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