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Research paper

Representation of acoustic signals in the human cochlea in presence of a cochlear implant electrode

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Abstract

Background: In subjects with remaining low frequency hearing, combined electric-acoustic stimulation (EAS) of the auditory system is a new therapeutic perspective. Intracochlear introduction of a cochlear implant electrode, however, may alter the biomechanical properties of the inner ear and thus affect perception of acoustic stimuli.
Study design: Based on histological observations of morphologic changes after cochlear implantation in cadaveric and post mortem studies the effects of basilar membrane (BM) stiffening in the ascending basal and middle turns of the cochlea due to close contact of the BM with the electrode were simulated in a 3D-computational finite element model of the inner ear. To verify our simulated results, pre- and post-operative pure-tone audiograms of 13 subjects with substantial residual hearing, who underwent cochlear implantation, were evaluated.
Results: In the scenario of partial BM-fixation, acoustic energy of middle (2 kHz) and high (6 kHz) frequency was focused basally and apically to the fixed section, increasing BM displacement amplitudes up to 6 dB at a stimulation level of 94 dB (SPL). Lower frequencies were not affected by fixation in the basal and middle turn of the cochlea. In implanted subjects, a small but significant decrease of thresholds was observed at 1.5 kHz, a place in tonotopy adjacent to the tip region of the implanted electrode.
Conclusion: Our model suggests that stiffening of the basilar membrane adjacent to an implanted electrode into the basal and middle cochlear turn did not affect BM movement in the low frequency area. Focussing of acoustic energy may increase perception in regions adjacent to the fixed section. Observations in implanted subjects were concordant with our model predictions. High frequencies, however, should not be amplified in patients using EAS to avoid disturbances in discrimination due to tonotopically incorrect frequency representation.

Keywords: Cochlea; Inner ear; Cochlear implant; Basilar membrane; Model; Electric-acoustic stimulation; Frequency representation; Round window; Impedance

1. Introduction

Cochlear implants transfer acoustic information to the auditory nerve by direct electrical stimulation and are widely used for the treatment of sensory deafness. Increasing performance with cochlear implants has widened indication criteria to patients with more and more residual hearing. This has prompted the idea of combining electric and acoustic stimulation in one ear (von Ilberg et al., 1999). Ever since, combined electric and acoustic stimulation (EAS) has become a new perspective in the treatment of severe to profound high- and mid-frequency hearing loss (Kiefer et al., 2005; Gantz et al., 2005; Skarzynski et al., 2002). The acoustic stimulation of the low to mid frequencies aided by conventional acoustic amplification, is supplemented by direct electrical stimulation of nerve fibres in the basal and middle parts of the cochlea that are coding for high and mid frequencies by means of a cochlear implant.

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The combination of both modalities acts in synergy and increases performance especially under conditions with competing noise (Wilson et al., 2003; Kiefer et al., 2005). EAS requires implantation of a cochlear implant electrode in a partially hearing ear, possibly affecting the biomechanical properties of the inner ear and the motion of the basilar membrane.

The cochlea is a finely tuned biomechanical structure that spatially separates the frequency contents of the signal. The acoustic energy enters the cochlea via the oval window and initiates a travelling wave that extends along the basilar membrane. For each frequency content, the travelling wave builds up a maximum at a designated place along the basilar membrane which corresponds to the characteristic frequency of that location. This is determined by the stiffness and the effective mass of the vibrating structure and can be designed as passive cochlear mechanics, that can in principle be described by a linear mechanical model. In addition, an active process that is mediated by the outer hair cells is initiated. This active cochlear mechanical process serves to amplify the peak of the wave at the characteristic frequency location and to sharpen tuning curves in response to a specific frequency. The active cochlear amplifier is especially of importance for the processing and perception of low intensity sound (0–40 dB HL) whereas at higher levels (>40 dB HL), passive cochlear mechanics are predominant for perception. As outer hair cells are more vulnerable than inner hair cells, they are in general affected at an earlier stage in patients with hearing loss than inner hair cells. Introducing a cochlear implant electrode into the scala tympani may potentially change passive mechanical properties of the basilar membrane as well as the active cochlear mechanics.

From histological studies of cochlear implantation in cadaveric human temporal bone it is known that the electrode array may impact the integrity of fine structures in the inner ear, e.g. the basilar membrane, osseous spiral lamina and spiral ligament (Clark et al., 1995; Gstoettner et al., 2000; Adunka et al., 2004; Eshragi et al., 2003). The impact on the basilar membrane is dependent on the design, mechanical properties, and insertion technique of the different types of electrodes. Straight electrodes are usually located at the outer circumference of the scala tympani. Specifically for the straight electrode that is used in MED–EL cochlear implants, a close contact or even a slight lifting of the basilar membrane through the electrode has frequently been found, even in most atraumatic cochlear implantations. In most cases, however, the contact was limited to a distinct section of the basilar membrane, often in the ascending basal and middle cochlear turn, whereas in adjacent regions, the basilar membrane was not in direct contact with the electrode. More severe forms of trauma included fractures of the osseous spiral lamina, perforations of the basilar membrane, and ruptures of the spiral ligament. These cadaveric studies from temporal bone implantation provide information about the direct mechanical impact of cochlear implant electrodes.

Post mortem histologic studies of temporal bones of patients having used cochlear implants during lifetime are necessary to evaluate further reactions of the body to the implanted electrode and cochlear implant trauma. In general, the reactions are characterized by formation of a fibrous capsule around the electrode body; sometimes also osteoneogenesis. Mostly, fibrosis was most prominent in the region of the cochleostomy and the basal turn near the round window and around the electrode (Nadol and Eddington, 2004). With certain types of rather stiff, straight electrodes – as used, e.g. in the Nucleus 22M cochlear implant system – extensive fibrous reactions were also observed in the tip region.

The aim of this study was to evaluate the functional effects of the morphological changes found after cochlear implantation in cadaveric temporal bones. Based on these results in conjunction with findings from post mortem examinations of temporal bones of cochlear implanted patients, we considered a stiffening of the basilar membrane adjacent to the electrode in the ascending part of the basilar turn caused by mechanical pressure of the electrode against the basilar and possible fibrosis. To study the effects of these histological changes, a formerly developed computational 3D-Finite Element model of the inner ear has been used. It is based on realistic anatomical properties of the cochlea (Böhnke and Arnold, 1999) and it models the *passive* cochlear mechanics only. In our scenario, the effects of the assumed postoperative changes on the micromechanic properties of the cochlea and on the propagation of the travelling wave were investigated. The results obtained in the model were compared to results obtained in a group of subjects, that had preoperative low frequency hearing and were implanted with a MED–EL C40+ Cochlear implant. Postoperatively, these subjects were using ipsilateral combined electric and acoustic stimulation (EAS).

2. Methods

2.1. Computational model

A three dimensional model of the human cochlea based on realistic anatomical data that models the passive cochlear mechanics was developed (Böhnke and Arnold, 1999). Fig. 1 illustrates the geometry of the strongly curved computed structure. It includes the scala vestibuli and scala media as a single compartment, since they are separated by the thin Reissners membrane only; the scala tympani, and the basilar membrane (BM) – idealized as an orthotropic shell as shown in Fig. 2. The stapes footplate with the fibrous annulus and the round window membrane are idealized as elastic structures. The Finite Element method allows implementation of gradients, namely the decrease of BM thickness (exaggerated illustration in Fig. 2) and the continuous expansion of the BM dimension in radial direction from base to apex, opposite to the diminishment of total cochlear cross sectional areas (as seen in Fig. 1).

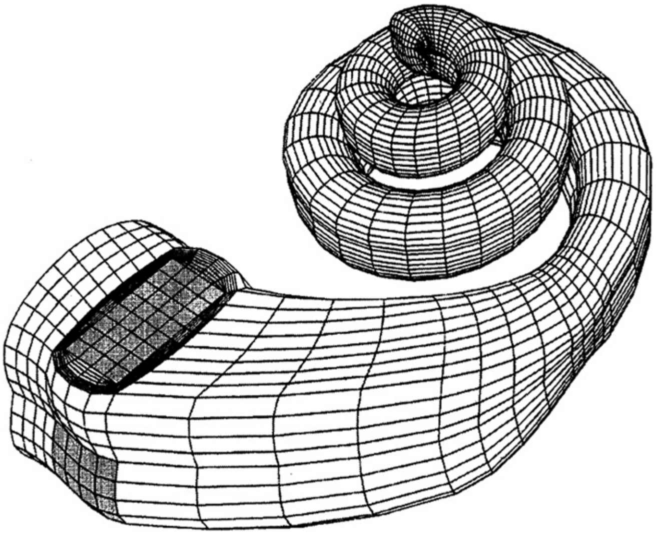

Fig. 1. Finite Element model of the bony shell of the cochlea with oval and round windows.

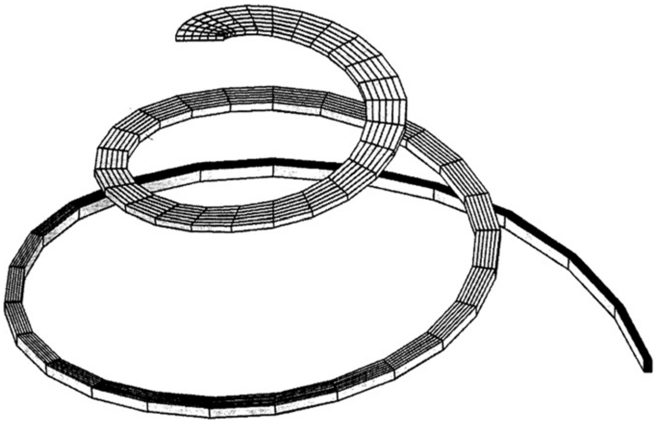

Fig. 2. Finite Element model of the basilar membrane incorporated into the bony shell.

The orthotropic shell has a radial Young's modulus of $E_x = 20$ MPa and a largely reduced longitudinal Young's modulus of $E_y = 100$ kPa, i.e. it is stiffer in the radial direction than in the longitudinal direction as it is the case in the real human basilar membrane (Voldrich, 1978). The boundary conditions for the BM are chosen as clamped at the inner spiral sulcus and simply supported at the spiral ligament. The fluid-structure-coupling is realized and the perilymphatic fluid is idealized as inviscid and nearly incompressible – representing the mechanical properties of water. The bulk modulus $\boldsymbol{K}$ is 2250 MPa and the fluid density is $\rho = 1$ mg/mm^3. The damping of the BM, represented by an elastic orthotropic shell, is considered by material damping, solely. It contributes to the damping matrix $\boldsymbol{C}$ of the finite element model by a portion of the stiffness matrix of the shell material $\boldsymbol{K}_{\text{Shell}}$. The multiplier is $\boldsymbol{\beta} = 3 \cdot 10^{-5}$ and therefore $\boldsymbol{C} = \boldsymbol{\beta} \cdot \boldsymbol{K}_{\text{Shell}}$. Because the fluid is accounted to be inviscid, there is no damping caused by the fluid. With these assumptions there is no need for a fictitious mass, which loads and damps the BM. Therefore the real masses of the BM and the fluid, as given by the idealized geometry and density of the materials are considered.The stapes exerts the driving force that is transmitted to the scala vestibuli/scala media compartment, which then causes displacement of the basilar membrane. For stimulation, external pressure is applied on the stapes footplate in the oval window (Fig. 2). The amplitude and phase of the basilar membrane displacement along the

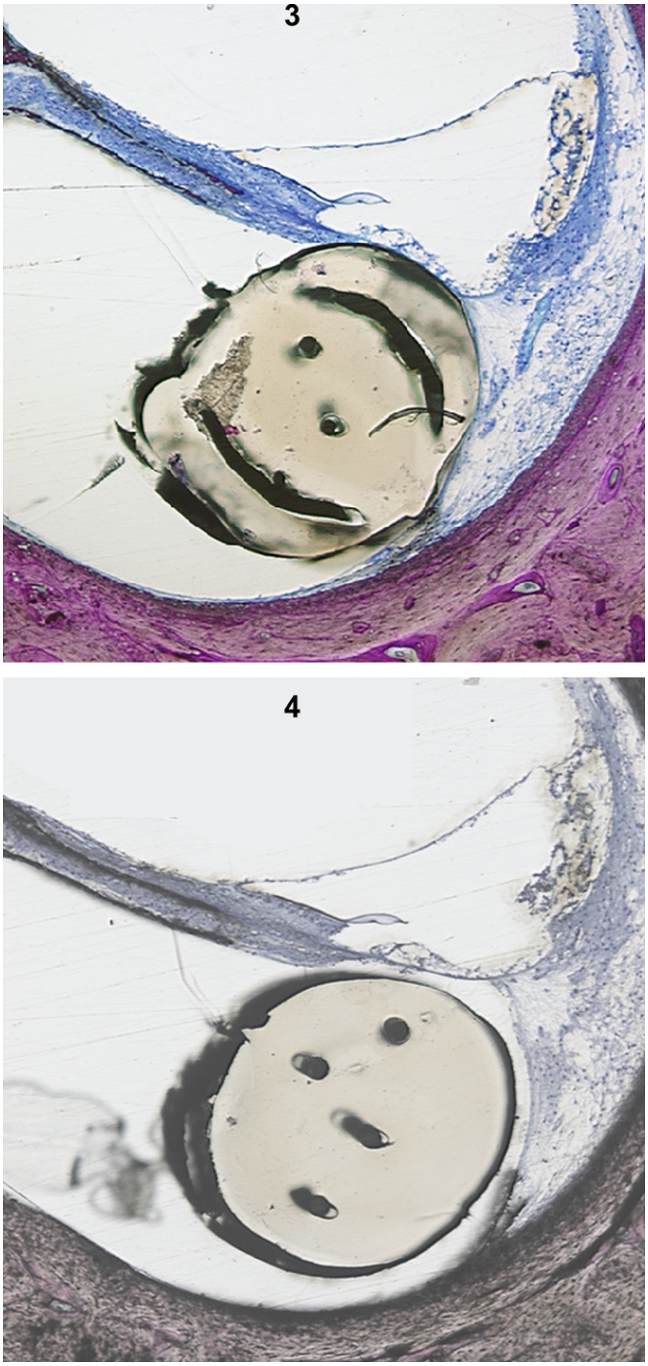

Fig. 3 and 4. Cochlear implant electrode in situ, in distance to the basilar membrane (BM) (Fig. 3), and in close contact – uplifting the basilar membrane (Fig. 4).

cochlea in response to variable frequencies of stimulation were computed. Results with normal undisturbed wave propagation as well as with partially fixed BM were calculated with harmonic excitation and a pressure amplitude of 1 Pa; equivalent to 94 dB (SPL) for acoustic stimulation.

3. Modelling the effect of implanted cochlear implant electrode

3.1. Partial fixation of the BM

We assumed that the electrode is in close contact with the basilar membrane in a distinct section, resulting in stiffening of the BM. In the model, the nodes of the basilar membrane finite elements that are in contact with the presumed electrode were fixed. The electrode itself was not modelled in our present computational model, of course neglecting possible effects of changes in fluid volume and physical effects of the electrode itself.

The section of the basilar membrane between 8.5 mm and 14 mm (length 5.5 mm), measured from the round window, was fixed (Fig. 3). Stimulation frequencies were 6 kHz, 2 kHz, 1 kHz, and 500 Hz. In order to assess the effect of different lengths of the fixed BM section, calculations were repeated with a fixation of basilar membrane from 8.5 to 17.7 mm (length of 9.2 mm).

3.2. Histology

Ten Human temporal bones were harvested from 12 to 24 h post mortem. Cochlear implantation was then performed by two experienced surgeons (JK&OA), using a posterior tympanotomy approach and a MED–EL Flex EAS cochlear implant electrode (Innsbruck, Austria). The Flex EAS electrode was specifically designed for limited intracochlear implantations in hearing preservation surgery. Electrodes were inserted from 20 to 22 mm with Healon® as a lubricant. Any forceful maneuvers were avoided. Each specimen underwent fixation via perilymphatic perfusion of buffered formalin solution and dehydration with an ascending series of alcohol (70–100% ethanol), followed by slow embedding in polymethylmethacrylate at 20°C for about 4 weeks to avoid air–bubble formation. After embedding, all bones then underwent serial sectioning using a special sawing–grinding–polishing technique developed by Plenk (1986). Specimens were stained and evaluated by two of the authors independently (OA&JK). Each specimen was analyzed according to a standardized protocol already used in prior reports (Gstoettner et al., 2000; Adunka et al., 2005). This protocol included evaluation of electrode positions within the cochlea and grading of cochlear trauma according to a grading scheme (Table 1) established by Eshragi et al. (2003).

4. Subjects and audiological measures

Thirteen adults with severe or severe-to-profound hearing loss were included. Inclusion criteria were a hearing loss in the ear to be implanted of less than 60 dB HL in at least two frequencies from 125 to 500 Hz and more than 60 dB HL hearing loss at 1 kHz and above as well as a monosyllabic word discrimination score at 70 dB HL in the best aided condition of less than 40% correct. Mean preoperative thresholds were 45, 65, and 95 dB at 250, 500, and 1000 Hz, respectively. Mean age at implantation was 51 years, ranging from 33 to 77 years (Table 1). Pure tone audiograms were measured preoperatively and three months and one year postoperatively. All patients were implanted with a MED–EL COMBI–40+ cochlear implant system and insertion depths ranged from 19 to 24 mm (mean 20 mm). Preoperative and postoperative audiograms were compared using the two-sided *t*-test for paired samples. The study design was approved by the institutional board of the J.W. Goethe-University of Frankfurt/Main.

5. Results

5.1. Histological results

A detailed description of the temporal bone histology can be found in a previous report (Adunka et al., 2004a). Overall, implantation with the EAS specific electrode

Table 1
Demographic data of cochlear implant subjects with substantial residual hearing

ID	Age at implantation	Length of hearing impairment	Etiology	Implant	Depth of insertion	Side
KH	50	30	Idiopathic	C40+	24	Right
SS	40	15	Aminoglycosides	C40+	20	Right
MB	46	15	Hereditary progressive	C40+	19	Right
BD	64	10	Idiopathic	C40 + M	19	Right
OM	57	22	Hereditary progressive	C40+	22	Right
PI	42	20	Idiopathic	C40 + M	20	Left
DI	46	20	Idiopathic	C40+	19	Right
EZ	31	21	Idiopathic	C40 + M	21	Left
UR	33	25	Ushers syndrome	C40 + M	20	Left
SL	48	28	Idiopathic	C40+	20	Right
KW	77	10	Encephalitis	C40 + M	20	Right
WR	64	12	Skull trauma	C40 + M	21	Right
EM	76	46	Idiopathic	C40 + M	21	Right

carrier resulted in relatively atraumatic 360° scala tympani insertions. Close contact of the array with the basilar membrane, however, was seen in all 10 specimens. A slight lifting of the basilar membrane was seen in one specimen only. Close contact was observed at different extents, however, the section from 90° to 180° of the basal cochlear turn was always involved.

Representative histological results are shown in Fig. 3, in which the electrode is not in contact with the basilar membrane and in Fig. 4, in which the electrode and the BM are in close contact, leading to a slight uplifting of the BM.

5.2. Results of computational model

In the scenario of a normal cochlea without an electrode, stimulation with a frequency of 2 kHz resulted in a maximum BM displacement at 17 mm measured from the RWM. The phase changes were continuous along the BM (Fig. 5a). Fixation of the BM in the segment from 8.5 to 14 mm lead to an increase in amplitude directly to the basal and apical boundary of the fixed section. The increase was 4 dB in the basal and 6 dB in the apical region. Basal as well as apical of the fixed section, the phases of the stimuli were unchanged (Fig. 5b). In the fixed section itself, phase was not defined.

For stimulation with higher frequencies (6 kHz), a similar pattern of increased amplitudes at the basal and apical boundaries was observed (Fig. 6a and b. With lower stimulation frequencies (1 kHz and 0.5 kHz), no significant changes in amplitude and phase were observed.

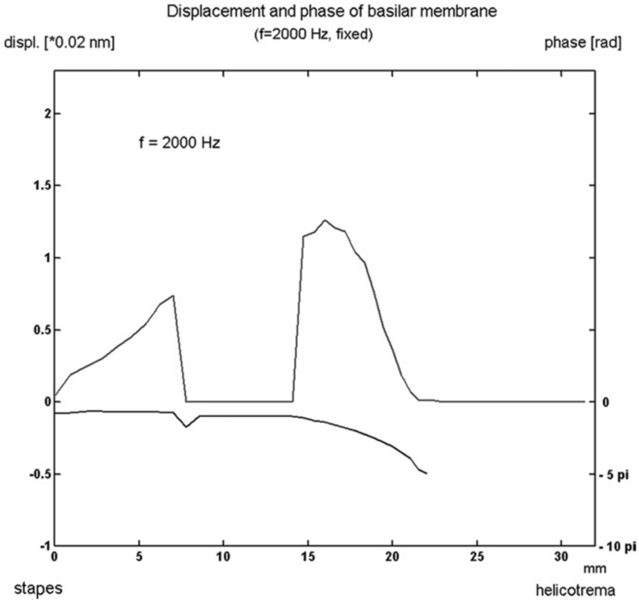

Fig. 5b. Displacement (upper grey curve) and phase (lower black curve) of the basilar membrane (BM) in response to a stimulus of 2000 Hz with fixation of the BM from 8.5 to 14 mm from the stapes. The amplitudes of displacement were found to be increased apically and basally of the fixed section of the BM.

Fig. 7 summarizes the amplitude changes for the different frequencies used – the fixed section being constant. Changes in amplitude basal as well as apical to the fixed section are shown. Changes were greatest, when the maximum displacement of the specific frequency is located within the fixed section. In contrast, in cases where the

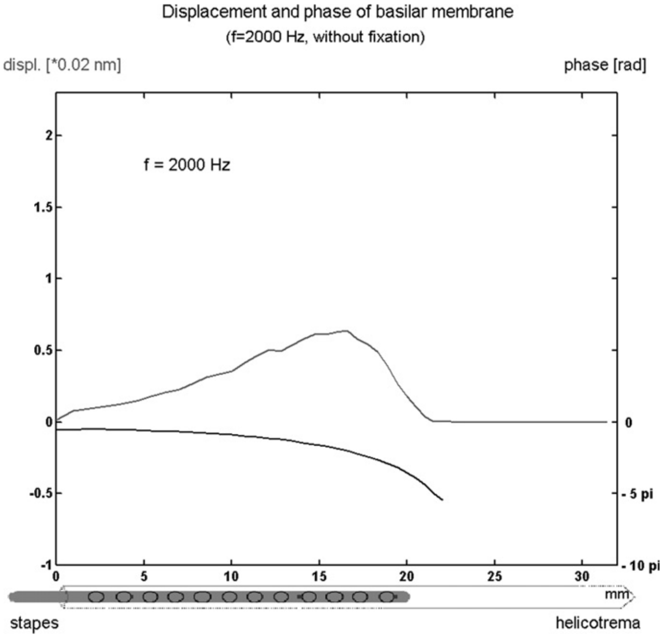

Fig. 5a. Displacement (upper grey curve) and phase (lower black curve) of the basilar membrane in response to a stimulus of 2000 Hz without fixation of the BM. The position of a cochlear implant electrode for EAS-patients is schematically indicated in an unrolled cochlea.

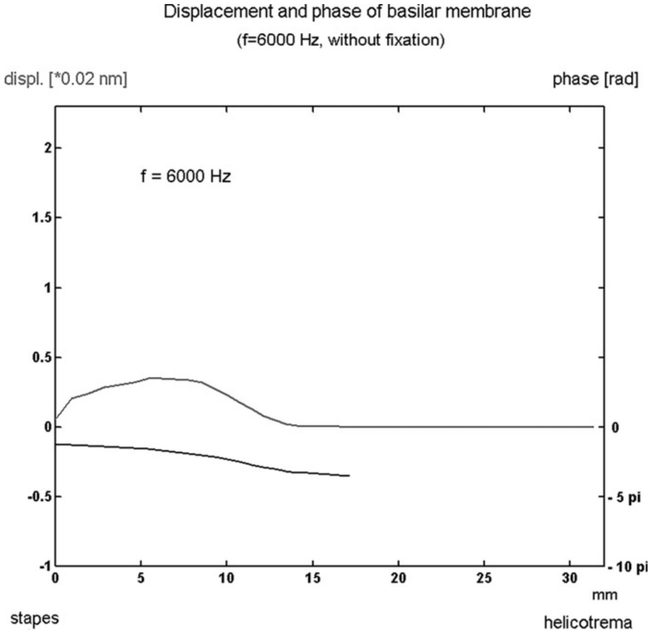

Fig. 6a. Displacement (upper grey curve) and phase (lower black curve) of the basilar membrane in response to a stimulus of 6000 Hz without fixation of the BM.

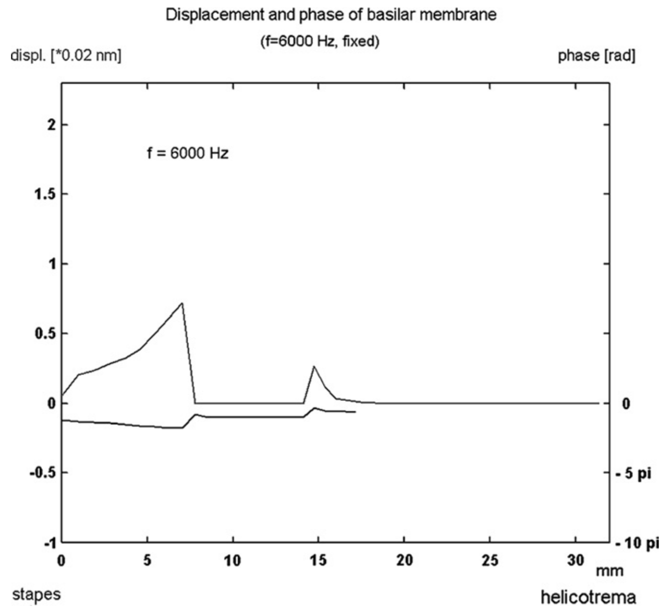

Fig. 6b. Displacement (upper grey curve) and phase (lower black curve) of the basilar membrane (BM) in response to a stimulus of 6000 Hz with fixation of the BM from 8.5 to 14 mm from the stapes. The amplitudes of displacement were found to be increased apically and basally of the fixed section of the BM.

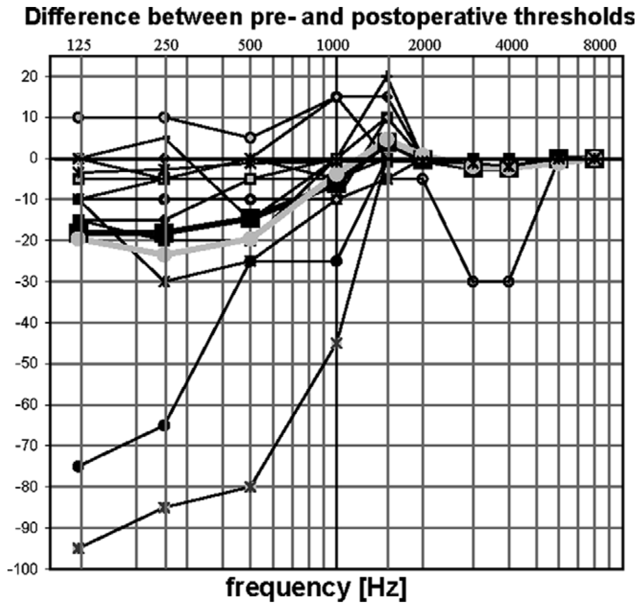

Fig. 8. Difference audiogram of 13 implanted subjects with preoperative residual hearing. Negative values indicate a hearing loss, positive values indicate better thresholds after implantation. Single subjects data (after 3 months) and mean values after 3 months (black bold line) and 1 year (grey bold line) are presented.

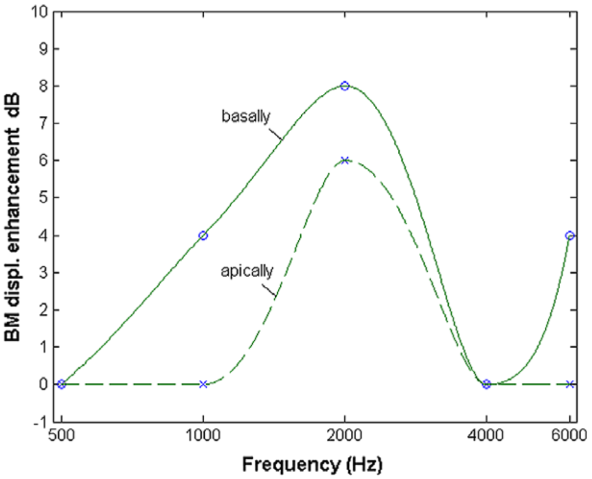

Fig. 7. Maximum changes in displacement amplitudes of the BM before and after fixation (8.5–14 mm from the stapes) in response to various frequencies. The upper, continuous line indicates the displacement changes basally to the fixed section, the lower line apically to the fixed section. The largest effect basally to the fixed region for the frequency of 2 kHz.

maximum displacement would normally be found outside the fixed section, only small or absent effects were found.

In order to compare the effects of the extension of the fixed section, the distance of fixation was enhanced from 5.5 to 9.2 mm. Results obtained were essentially similar as for the shorter distance.

5.3. Audiometric results in subjects

To assess changes in audiometric thresholds after implantation, the differences between pure tone threshold before and after implantation were evaluated for each patient. Differences are plotted in Fig. 8. Values greater than 0 indicate a gain in hearing (better hearing) whereas values below 0 indicate a hearing loss. At 1.5 kHz, 5 of 13 subjects had positive values, ranging from 5 to 20 dB, 5 subjects had unchanged thresholds, and two patients had a hearing loss of −5 dB. At 1.5 kHz, mean gain in thresholds was 4 dB ($p < 0.1$, *t*-test). In the lower frequencies, mean hearing loss was 15–20 dB.

6. Discussion

Implantation of a CI-electrode can introduce various changes in the inner ear. We may distinguish between acute, mechanically induced morphological changes such as impingement on the basilar membrane, fractures of the osseous spiral lamina, or ruptures of basilar membrane or of the spiral ligament that can be observed in cadaveric temporal bone studies and reactive changes to trauma such as fibrosis or osteoneogenesis that may only be observed in temporal bone studies of patients, who received their implant during lifetime.

Acute morphological changes are determined by a number of factors including the type of electrode, route of access (e.g. cochleostomy versus round window (Adunka et al., 2004b)), the electrode type (e.g. straight versus curved, stiff versus flexible (Gstoettner et al., 2000; Eshragi et al., 2003), and the depth of insertion. In view of our initial question, whether an implanted CI-electrode influences the mechanical properties for the perception of acoustic stimuli in combined electric and acoustic stimulation or not, we assumed a case of implantation with a straight and flexible electrode (as the MED–EL C40+ electrode) and a limited insertion depth, causing minimal trauma to the basilar membrane as evidenced by our histological results. However, even in cases of minimal cochlear trauma, contact between the electrode and the BM or a slight lifting of the basilar membrane by the electrode array, are frequently observed. As the cochlear implant electrode consists of wires running in the longitudinal axis and electrode contacts at the surface, that are embedded in silicone, the stiffness of the electrode is much greater than the longitudinal stiffness of the basilar membrane. Stiffening of the basilar membrane may also be the result of local fibrosis around the cochlear implant electrode. We therefore assume, that in many cases the basilar membrane will be stiffened or fixed – at least in certain parts of the cochlea. Another consistent finding in histology of the human cochlea following implantation is the formation of connective tissue, being most prominent in the region of the cochleostomy near the round window (Nadol and Eddington, 2004). In our computational model, sections of the basilar membrane, in which the tight contact has usually been observed in our histological studies were stiffened. In case of a partially fixed basilar membrane, we found that acoustic energy was focused at the basal and apical boundary zone of the fixed section, when the expected maximum of displacement falls within the fixed sections or adjacent to it. This resulted in enhancing the amplitude of BM displacement in these sections. For low frequency stimuli, the acoustic energy was transmitted to apical regions without being influenced by the partial fixation of the BM more basally. In view of a possible combination of electric and acoustic stimulation (EAS), in which low to mid frequency acoustic stimulation is combined with electric stimulation of mid to high frequencies, our model predicts little disturbance of low frequency acoustic perception. Enhanced BM displacement adjacent to a fixed section can be regarded as amplification of a frequency content. If this amplification occurs at the right tonotopic place, e.g. a 17 mm for a 2 kHz pure tone, subjects may even benefit from the effect as they will experience better thresholds and increased loudness. If it occurs in the high frequency cochlear regions, where patients using EAS have very high acoustic thresholds, no effect on acoustic perception would be expected.

Only in cases, in which the normal maximum displacement would fall within a fixed section, our model predicts two new peaks of BM-displacement: one basal and one apical to the fixed section, i.e. at tonotopically incorrect places. If peaks are high enough, e.g. after acoustic amplification, they might be perceived by the patients. Then frequency contents would be perceived at incorrect places as so called "off frequency listening" and may create disturbances in acoustic perception.

In case the model assumptions are correct, acoustic amplification in the high and mid frequency range, where little or no acoustic perception can be expected, should be avoided for EAS patients as they may create undesired off frequency listening effects. Clinically, at least in our experience, this phenomenon may occur occasionally, e.g. one patient with little residual hearing reported hearing only a single, medium pitched tone when stimulated at levels above her threshold, for several stimulation frequencies. However, the rate of occurrence and possible implications for speech understanding have not been investigated and reported so far to the best of our knowledge.

In subjects, who underwent implantation with insertion depths of 19–24 mm, we found a small decrease in thresholds specifically at 1.5 kHz, i.e. in the region adjacent to the apical end of the electrode in the transition zone between electric and acoustic hearing.

At present, we have no means to look into the cochlea of implanted subjects and verify if the electrode might be in touch with the basilar membrane or not; however, as we may assume that hair cells are not regenerated after implantation, a possible explanation would be the change in basilar membrane behavior, e.g. the electrode fixes at least part of the basilar membrane and energy, e.g. of 2 kHz is redistributed and amplified to lower frequency regions, where it can be perceived. Increased auditory awareness and better overall sensitivity of the auditory system, that can be found in children after implantation (Kiefer et al., 1998), would affect the overall frequency range and could not explain the effects we have found that are limited to a specific frequency region.

One of the limitations of our model is the fact that active cochlear mechanics are not taken into account, however, the subjects implanted so far have high thresholds in the mid-to high frequency range, that are due almost entirely to passive cochlear mechanics. In lower frequencies, some of the better hearing subjects may still have active cochlear mechanics. Redistribution of energy from high frequency regions to low frequency regions with active cochlear amplifiers still present would presumably result in increased BM-displacement, off frequency listening effects would then be enhanced. Perception of low frequency sounds would probably not be altered, if the BM in the low frequency region is not affected by changes and the active cochlear mechanics can act undisturbedly.

In regard to threshold shifts after implantation, the partial fixation of the BM that was assumed in our model could account for a loss of residual hearing in this specific frequency area, i.e. mid to high frequencies, threshold in low frequencies should not be affected. Overall changes in the fluid compartment due to fibrosis or fluid displacement by the electrode carrier that may influence thresholds also in the low frequency regions have not yet been investigated in our model. In our EAS-study subjects, a mean hearing loss of approximately 15 dB was observed. Hearing loss after cochlear implantation, that can well exceed the observed average loss and even be total in some cases may be attributed to a number of additional other etiological factors such as direct mechanical trauma, e.g. rupture of the basilar membrane with mixture of endolymph and perilymph, stress or noise induced damage to the sensory cells, leading to apoptosis, or to subsequent inflammatory reactions to the introduction of a foreign body or microbacterial contaminations. Stiffening of the BM in basal part of the cochlea would only be accountable for local hearing loss in the correspondent tonotopic region of the cochlea.

7. Conclusion

In the case of partially fixed basilar membrane our model predicts extinction of basilar membrane displacement in the fixed, non-motile region (as expected), increases of amplitudes of BM-displacement directly before and behind the fixed section, and shifts of maxima in case the normal tonotopic maximum without fixation would fall into the fixed region. Movement of the basilar membrane in the apical part of the cochlea is not affected by fixation in the ascending basal and middle turn of the cochlea in our model. Clinically, we seem to have found a correlate of better threshold in EAS-patients. In view of speech perception, amplification of BM-displacement in tonotopically correct regions with impaired hearing adjacent to the tip of the electrode should not be detrimental to acoustic perception, whereas amplification of BM-displacement representing high frequency information in the wrong, low frequency place might impair speech understanding. Therefore, acoustic amplification in the high and mid frequency range, where little or no acoustic perception can be expected, might be detrimental for speech perception in EAS patients.

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