Flexibility - an important feature of the human middle ear's ossicular chain

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When the function of a damaged middle ear is to be reconstructed by using prostheses, the surgeon has not only to choose an appropriate shape, but also an effective kind of coupling. Usually he tries to fix the prosthesis as rigidly as possible. On the other hand, the ossicular chain of the natural middle ear is not at all rigid. Particularly the incudostapedial joint introduces a rather elastic element. It is an interesting question to ask whether the elasticity has a functional meaning or simply originates from the lacking ability of "mother nature" to realise more precise guideways. To address such questions, the mechanical and geometrical conditions in a middle ear have to be varied in a well-specified manner. Systematic variations cannot be accomplished by experiments in temporal bone preparations, but only by means of computational models. The model underlying this paper is a circuit model which is able to simulate threedimensional vibrations of the ossicular chain. Vibrations can be excited by normal acoustic stimulation via the eardrum or by mechanically shaking the total temporal bone. It turns out that the modes of vibration considerably change depending on frequency and on the kind of excitation. This proves a remarkable degree of flexibility. Several "computational experiments" including partial stiffening of elastic elements and changes of geometry reveal the importance of the high flexibility found in the ossicular chain.

1 Introduction

The main task of a middle ear is to transmit the acoustic energy from the ear canal to the fluids of the inner ear as effectively as possible. The solution of this task, observed in the middle ears of mammals, reptiles and birds, is provided by an impedance transformer which matches the impedance levels of air and fluid. The most prominent feature of the acoustic transformer is an appropriate ratio of the sound collecting tympanic-membrane area to the working surface of a piston-like ossicle driving the inner ear fluids.

The connection between the two surfaces which form the transformer can be very simple. In reptiles and birds we find an ossicle, a "columella", which has the shape of a simple rod. Thus the question arises why humans and the other mammals possess a fairly complicated ossicular chain consisting of three ossicles - malleus, incus, and stapes - connected via joints. It is surprising that the ossicles of the human middle ear are not at all as light as possible. Particularly the incudomalleal joint is surrounded by fairly voluminous bony masses, the head of the malleus and the body of the incus. Due to the inertial properties of the ossicles one would expect a negative effect on the transmission characteristics of the middle ear, namely a low-pass filter with a quite low cut-off frequency.

On the other hand, the human middle ear is not likely to have actually unfavourable properties. In fact, if we compare mammalian middle ears having a three-ossicle chain with columella middle ears, we find out that an ossicular chain is superior to a columella. Whereas mammals can hear up to several ten kilohertz (humans 20 kHz, bats even 50 kHz), birds and reptiles have upper frequency limits below 10 kHz (chickens can just reach this limit). Thus we have to explain the surprising fact that ossicular chains with higher masses can produce higher cut-off frequencies than lighter columella ears.

2 Computational model

To get insight in the mechanics of the middle ear one can try to measure instructive details of the ossicular vibrations in experiments. However, for systematic investigations the usage of a computational model is to be preferred because only in this case parameters can be more or less easily changed in order to study resulting effects - provided that the model is able to give correct predictions.

A simple model that has only one degree of freedom at any considered point is certainly unable to explain the mass effect just mentioned. An explanation of the altered inertial properties must be somehow related to the mode of vibrations of the ossicular chain. Therefore we need a three-dimensional model capable to describe spatial vibrations. Often finite-element models (e.g., [1]) are used in such cases. Here we refer to another model which is based on an earlier model published in [2]. The model is formulated as a circuit model, but not as a simple one-dimensional circuit as can be obtained from electromechanical analogies. We call it a generalised-circuit model because it deals with generalised forces (three Cartesian components of forces and torques) and generalised (translatory and rotatory) velocities at any desired point. Such a model has much less parameters than a realistic finite-element model. This allows a very fast computation of spatial vibrations and - even more important - an easy variation of...
model parameters. This includes mechanic (stiffness, inertial moment) as well as geometric (size, position in space) parameters.

The capacitors in figure 1 represent inertial properties, the inductances elastic and damping elements. The circles with vertical bars are mechanic sources which can feed in motions due to vibrating walls of the tympanic cavity. The only circle with a horizontal bar represents the acoustic drive by the pressure difference at the eardrum.

**Figure 1:** The ossicles of a human middle ear and a corresponding structure of a generalised circuit model.

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### 3 Ossicular vibrations for acoustic excitation

First the response of the ossicular chain to the normal acoustic stimulation at the ear drum is regarded. In this case all the mechanic sources are switched off. This means that only the internal impedances of these sources given by the elastic ligaments suspending the ossicles affect the vibrations.

#### 3.1 Vibrations und normal conditions

At low frequencies up to several 100 Hz the ossicles rotate about an axis which is determined by the posterior incudal ligament and the anterior malleal ligament. This conforms to the "classical" notion of a rotation about the so-called main axis through these ligaments. But the simple motion breaks up if the frequency reaches the first resonance of the middle ear.

At higher frequencies the purely rotatory motion is superimposed by a translatory motion which results in rocking and gyrating vibrations around varying axes. Starting at about 5 kHz the elasticity of the joints and the ossicles becomes important. Deflection of the ossicles and relative motions within the joints produce an eye-catching counter motion of the manubrium of the malleus and the long incudal process. The appearance of the vibrations becomes increasingly irregular when the stimulating frequency grows. But at high frequencies the vibration approaches an almost stable mode. Instead of the axis of rotation at low frequencies a "centre of rotation" is formed which is located in the incudomalleal joint. At high frequencies not only the manubrium and the long incudal process is involved in the counter motion just mentioned. In addition also the short incudal process participates in this motion. All those changing vibrational modes are enabled by elastic elements within the ossicular chain. More exactly, it is the elasticity of the joints as well as the bending stiffness of the ossicles which finally produce the changing modes of vibration.

**Figure 2:** Vibrations of the ossicular chain at 16 kHz for 1 Pa stimulation at the eardrum.

The change of the vibrational modes is best seen by looking at animations. In this paper a graphic representation (figure 2) is used which shows the motions of certain points as trajectories. The phase relations of the vibrations can be imagined if the grey tones of the trajectories are considered. Equal grey tones belong to equal time instants. The effective displacements at different locations are also given numerically.

**Figure 3:** Stapes displacement perpendicular to the footplate and three characteristic frequency ranges observed in the vibrational modes of the ossicular chain.
Of course, also the stapes is involved in the complex motions. The head of the stapes moves along circling trajectories. In spite of such irregular motions the resulting frequency response of the stapes is surprisingly smooth. In figure 3 the displacement perpendicular to the stapes footplate is represented.

At first sight one would assume that irregular motions should not be very effective in transporting sound energy via the middle ear. On the other hand, the smoothness of the frequency responses is a first indication that the transmission is not too bad. The general decrease of the displacement at frequencies above the first middle ear resonance is an unavoidable low-pass filter effect. A simple one-dimensional circuit model predicts a high-frequency slope of 40 dB per decade or of 60 dB per decade depending on the order of the filter represented by the model.

It is very instructive to compare the normal human middle ear transmission to that of a columella ear. In figure 4 the pressure gain from the eardrum to the cochlea (pressure in the vestibule) is given for a normal middle ear and a columella ear. Also the response of the columella ear is calculated from a generalised circuit model. However, it was not tried to find a model which approaches a real columella. Instead the columella was modelled as a simple rigid body and the mechanic parameters of the model were chosen aiming at similar transfer functions of the ossicular chain and the columella.

Figure 4 shows that it is actually possible to match the behaviour of both types of middle ear. Thus it is possible to give the columella-ear model a higher upper cut-off frequency than actually found in reptiles and birds. A better approximation of real columellae could be obtained by introducing an additional elastic element not mentioned so far. It is introduced by a certain part of a real columella ear which is called extracolumella. It is this element which causes the worse cut-off frequencies of real columella ears. So the question arises why such an extracolumella exists although figure 4 predicts that a simple rigid connection without an extracolumella would work better?

3.2 Vibrations under impaired conditions

We can find answers to such questions if we also consider impaired transmission conditions. Generally, a "well-designed" middle ear should be affected as little as possible by small changes. If our middle ear would be very sensitive to external variations, e.g., variations of the static pressure, we would suffer from permanent changes in hearing.

Besides such intraindividual variations also strong interindividual differences in hearing would occur. In real biological systems the shape and position of all elements are subject to certain variations. With respect to geometric parameters this means that the size and the shape of the ossicles and the relative positions vary from person to person. For instance, the position of the stapes is never ideally perpendicular to the oval window. Ossicles can be aligned better or worse.

The effect of misalignment was simulated by tilting the position of the oval window in three steps about the three Cartesian axes. The positions of the centre of the oval window and the stapes remained unchanged. For simplicity, the three angles were chosen identical. Figure 5 shows that considerable effects can occur for large angles, but the impairment for small angles is very low. In a range of angles up to 20 degrees which can be supposed in real middle ears the impairment is hardly noticeable. Obviously the displacement transfer function of the middle ear is extremely insensitive to changes of the stapes position in the oval window. We will see that this statement can be widely generalised. All the transfer functions of the middle ear are very insensitive to changes of many geometric and mechanic parameters.

The key feature which can explain this general trend is the flexibility of the total ossicular chain, particularly
the flexibility of the incudostapedial joint. Let us consider a simplified arrangement which elucidates the function of a columella. On the left panel of figure 6 the columella is represented by a horizontal rod terminated by plates at both ends. The plate on the left is coupled to a larger membrane which corresponds to the tympanic membrane. The plate on the right is something like the stapes footplate suspended by an elastic element which stands for the annular ligament. At the "footplate" the stiffness in direction to the edges of the "oval window" is very high. In the direction perpendicular to the "footplate" the stiffness is much lower. At the "eardrum" the conditions are basically the same, but altogether on a lower stiffness level.

The idealised columella shown in the left panel of figure 5 will work quite satisfactory up to high frequencies, which is in full agreement with figure 4. But the design has a bad drawback. If the relative position of the "footplate" in the "oval window" is slightly altered blocking occurs as elucidated in the right panel. Such blocking would dramatically impair the transfer function of a middle ear. Obviously the behaviour of an idealised columella is not at all insensitive to variations in geometry, but, in contrast, extremely sensitive.

It has become clear that blocking effects have to be avoided. This answers the question why an additional extracolumella must exist in real columella ear. The extracolumella provides an elastic element which allows the columella to draw aside. It gives the columella construction flexibility that is necessary to ensure good functionality also under real conditions. Unfortunately, the extracolumella has the undesired effect of lowering the upper cut-off frequency of the system.

As a further example that illustrates the parameter insensitivity of the human middle ear we consider the effect of stiffenings in the ossicular chain and its suspending ligaments. In the model all elastic elements are taken into account by six components, three translatory and three rotatory components of stiffness. In most cases the six stiffness components are very different because the elements to be modelled have preferred modes of vibration. A good example is the incudostapedial joint which is rather stiff in the direction of energy transmission (in the axis through the the processus lenticularis and the stapes head) but otherwise surprisingly compliant. Both other orthogonal translatory components and all the rotatory components are significantly more compliant than the component in the direction of transmission.

The effect of various kinds of stiffenings, alone and in combination with others, can be regarded in figure 7. There are so many alternatives to vary the stiffness of different components at different points that a comprehensive examination of stiffening effects cannot be given. Instead resulting transfer functions for only a few meaningful conditions are represented in the figure. In contrast to the results shown in figure 5 here only severe changes are studied. Either an element is stiffened in all its components or some of the components are completely stiffened, i.e., their compliances are set to zero. Therefore large effects are to be expected in general.

The weakest change is observed for the case that both main axis ligaments are stiffened with respect to the translatory components. This is not thus surprising as the ligaments essentially rotate. On the other hand, a small degradation is observed which reveals that the motion of malleus and incus is never purely rotatory, not even at low frequencies. A similar degradation is found if the annular ligament is "partly stiffened": the annular ligament is made compliant only in the main direction of vibration perpendicular to the stapes footplate. If the stapes would act as a piston which ideally vibrates perpendicular to the oval window, the model would predict no effect at all. Thus the existing degradation proves that also the stapes vibration deviates from the ideal one even at very low frequencies.

Complete stiffening of the incudostapedial joint reduces the vibration amplitude by a factor of about three. An effect of the same order is obtained for the combination of stiffening the main axis ligaments in all
the translatory directions and the annular ligament in all directions except the main direction. On the one hand this reveals that the flexibility of the incudostapedial joint is of particular significance. On the other hand it shows that, even if the most important contribution to the over-all flexibility - stemming from the incudostapedial joint - is completely removed, the middle ear works surprisingly well. The most severe impairments arise if in addition to the incudostapedial joint another element is stiffened.

More insight into the mechanisms occurring in the middle ear is obtained by regarding animations of the vibrations. As a general result it is found that the ossicular chain is able to change the mode of vibration if obstructions of any kind are present. If only one element in the middle ear is disabled, often a fairly favourable mode of vibration is "found" by the ossicular chain which maintains the functionality to a certain extent. In other words, the flexibility of the chain allows the ossicles to escape blocking conditions as long as the restrictions are not too severe. Such conditions arise if two or more obstructions act in combination.

4 Ossicular vibrations for mechanic excitation

In this section the vibrations of the ossicular chain are examined for the case that the whole temporal bone is shaken. In the following figure a (too) simplified one-dimensional model of such conditions is given.

![Figure 8: Simplified model of suspended ossicles excited by vibrations of the tympanic cavity walls.](image)

All the ossicles are concentrated to a single rigid mass \( m_{\text{oss}} \). If the tympanic cavity vibrates with a velocity \( v_{\text{tc}} \) the motion is transmitted to the ossicles via a lossy compliance \( (n_{\text{susp}}, w_{\text{susp}}) \) representing the total suspension. At low frequencies the ossicles can follow the excitation; at higher frequencies their mass reduces the amplitude of the ossicle vibrations. The transfer function from the tympanic-wall vibrations to the ossicle vibrations forms a low-pass filter. However, with respect to the auditory perception, not the absolute vibration \( v_{\text{oss}} \) of the ossicles is decisive, but the relative motion of the ossicles in the oval window \( (v_{\text{oss}} - v_{\text{tc}}) \). The transfer function for this relative motion follows a high-pass filter as illustrated in figure 8.

Middle ear transfer functions for mechanic stimulation are relevant under two points of view. (a) The ossicular chain has to be protected against external impact working on the skull. In other words, the ossicles should have good shock insulation. (b) The vibrations of the skull caused by external acoustic stimulation or by the own voice-generating system are transmitted to the cochlea and therefore perceived. A "well-designed" middle ear should suppress this bone conduction.

4.1 Vibrations und normal conditions

At first we consider the mechanic transmission in the middle ear under normal conditions. Using the generalised circuit model of figure 1 it is possible to calculate mechanic responses at any point on any ossicle for any desired stimulation. For the reasons just given we are interested in the relative vibrations of the stapes in the oval window. Only the component perpendicular to the window is relevant because the other components have little effect on the resulting volume velocity which finally governs the perception.

In order to obtain a typical response the stimulation of the tympanic cavity must be unspecific concerning its direction, i.e., directions producing particular effects have to be avoided. The relative response of the stapes for such a "general" stimulation is called bone conduction function \( H_{bc} \).

![Figure 9: Bone conduction function \( H_{bc} \) of the normal middle ear and the idealised columella ear.](image)

In figure 9 the bone conduction function of a normal middle ear is compared with that of the idealised columella already considered. Surprisingly it turns out that the normal middle ear is also superior in this respect, in spite of the higher mass of its ossicles. The total mass of the ossicular chain is about 56 mg, whereas the columella was modelled having 10 mg. According to the simplified model of figure 8 the cut-off frequency of the human middle ear should be lower than that of the columella ear, the factor being about 2.4. Instead the correct model predicts an increase of the cut-off frequency by a factor of more than 1.5.
A closer inspection shows that the improved shock insulation is caused by a characteristic change of motion if an acoustic excitation is replaced by a mechanic one. In the case of low-frequency acoustic stimulation, malleus and incus vibrate as a unit about the main axis. Therefore the long incudal process effectively pushes the stapes head in the direction to the oval window. The conditions are completely altered when the chain is excited mechanically. In this case the inertial forces are largest at the heavy masses of the malleus head and the incus body. Consequently a shaking excitation produces a predominantly translatory motion of these masses. If the excitation is directed parallel to the stapes footplate the malleus-incus unit draws the stapes head laterally and almost no net volume velocity in the oval window occurs. The most mechanic energy is transmitted if the tympanic cavity is shaken in the direction perpendicular to the footplate. But even in this case the transmission remains fairly low because the fraction of the inertial force working on the mass centre around the incudomalleal joint is much larger than the fraction working on the stapes head. As a result the rotatory motion about the normal main axis is replaced by a mixed translatory-rotatory motion where the axis of rotation passes through the incudostapedial joint. The mass centre rotates about this point instead of pushing onto the stapes head via the long lever formed by the long incudal process. Again the flexibility of the incudostapedial joint turns out to be very advantageous.

4.2 Vibrations under impaired conditions

Finally we consider the effect of impairments on the bone conduction function. It was stressed that the favourable properties under normal condition originate from the high flexibility of the ossicular chain. Thus it is to be expected that stiffening the incudostapedial joint should alter the bone conduction function considerably. But figure 10 reveals that a stiff incudostapedial joint alone has surprisingly little effect. Even if the annular ligament is also stiffened in lateral directions, no dramatic changes occur. Again, this is due to a general flexibility. A look on animations of the vibrations shows that the chain is able to switch to another mode of vibration that also suppresses a strong volume velocity in the oval window: the axis of rotation is relocated to the long axis of the stapes footplate.

A strong increase of cut-off frequency occurs if the chain is simultaneously stiffened at several relevant points. The cut-off frequency can be further raised by additional geometric changes. The impairments have a positive effect on the bone conduction function because the shock insulation is improved. But, of course, the total effect is negative because the air conduction via the middle ear is correspondingly decreased.

5 Summary

It was shown that the ossicular chain of mammals is superior to columella ears of birds and reptiles in several respects. Good air conduction is maintained up to higher frequencies. Also the insulation against external shocks and skull vibrations remains effective up to higher cut-off frequencies. Moreover, a generally low sensitivity with respect to many parameters governing the middle-ear transmission is found. This ensures favourable properties also in middle ears deviating from the "optimum design" to a certain extent. The most relevant feature creating the excellent properties of the middle ear is a general flexibility of the ossicular chain realised by compliant joints, suspensions and non-rigid ossicles. Also columella ears need an elastic element, the extracolumella, to avoid blocking. But it reduces the upper cut-off frequency. The superior behaviour of the ossicular chain is based on a more sophisticated design which combines elastic elements with a favourable shape and mass distribution of the ossicles.

References
