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Parameter study on a finite element model of the middle ear

Parameterstudie an einem Finite-Elemente-Modell des Mittelohrs

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Abstract

Models of the middle ear basing on the finite element method (FEM) have contributed to a better understanding of the function of its different components. The geometry, the choice of boundary conditions and material properties have a crucial influence on the model. The influence of individual parameters was investigated. Based on a magnetic resonance imaging data set, a finite element model (FEm) of the middle ear was established. The transfer function (TF) at a sound pressure level of 90 dB and a frequency range from 100 Hz to 10 kHz was determined. Altogether, 24 parameters were varied individually and the influence on the TF was investigated. The parameter study was based on varying the stiffness and damping of each material as well as on anatomic variations, such as thickness and anisotropy of the tympanic membrane and sliding within the joints. It could be shown that each parameter had influence over the entire or sections of the frequency range in different magnitudes. A chart was derived to show the influence of each parameter depending on the frequency. The results allow improved distinguishing between parameters being relevant for a FEM simulation of the middle ear and those that can be neglected. This could contribute to further improvement of FEms of the middle ear.

Keywords: boundary conditions; joints; ligaments; material properties; transfer function.

Zusammenfassung

Modelle des menschlichen Mittelohrs, basierend auf der Finite-Elemente-Methode (FEM), haben wesentlich zu dessen Verständnis beigetragen. Entscheidenden Einfluss bei solchen Modellen haben neben der Geometrie die Wahl der Randbedingungen sowie Materialeigenschaften, wobei sich letztere jedoch oft nur unzureichend experimentell bestimmen lassen. Es wurde daher der Einfluss einzelner Parameter auf das Modell untersucht. Ausgehend von einem Magnetresonanztomographie (MRI)-Datensatz wurde ein Finite-Elemente-Modell (FEm) des Mittelohrs erstellt und die Übertragungsfunktion (TF) bei einem Schalldruck von 90 dB im Frequenzbereich 100 Hz bis 10 kHz bestimmt. Insgesamt 24 Parameter dieses Modells wurden daraufhin jeweils einzeln verändert und der Einfluss auf die TF untersucht. Die Variationen bezogen sich dabei auf Steifigkeit (E-Modul) und Dämpfung der einzelnen Materialien. Weiterhin wurden anatomische Fragestellungen, z.B. der Einfluss von Dicke und Anisotropie des Trommelfells, sowie Gleitbewegungen im Bereich der Gelenke untersucht. Es konnte gezeigt werden, dass die einzelnen Parameter unterschiedlich starken Einfluss über Teile oder das gesamte Frequenzspektrum haben. Daraus konnte eine Tabelle abgeleitet werden, die Auswirkungen der jeweils variierten Parameter in Abhängigkeit von der Frequenz angibt. Die Ergebnisse ermöglichen es, besser zwischen wichtigen und unwichtigen Parametern für eine FEM-Simulation des Mittelohrs zu unterscheiden. Dies kann dazu beitragen, FEms des Mittelohrs weiter zu verbessern.

Schlüsselwörter: Bänder; Gelenke; Materialeigenschaften; Randbedingungen, Übertragungsfunktion.

Introduction

Owing to minuscule dimensions and reduced accessibility, experimental studies on the material properties of many structures of the human middle ear are severely limited. Hence, functionality of the incudomalleolar (IM) joint as well as the incudostapedial (IS) joint remains a topic of current discussion [5, 9, 13, 14, 16, 17, 19–21, 25, 27, 32, 33]. Models based on the finite element method (FEM) support investigations on these properties and thus can improve the understanding of micro-mechanics of the middle ear [7, 11, 22]. The iterative approach to match the transfer function (TF) of the simulation to the one determined experimentally is a standard method [11, 12, 22, 23, 30] but is questioned by Willi [32]. Although the entire system might behave according to experimental findings, individual components of the system might fail to describe the mechanics accurately. This can lead to incorrect conclusions. Thus, the influence of the most important parameters on the TF will be investigated comprehensively. Hence, different models can be better compared encouraging further experimental measurements of particular material properties.

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Materials and methods

Geometry

A virtual reality modeling language (VRML) model of the human middle ear, based on magnetic resonance imaging data, was obtained from McGill University [8] and was imported to Catia V5R18 (Dassault Systèmes, Vélizy-Villacoublay, France). The geometry was found to be in good correlation with the anatomy established in the literature [2, 28, 29]. The ligaments of the middle ear, joints and annulus fibrocartilagineus (an. fib.) were implemented in the model based on the literature [2, 28, 29]. This refined CAD model (Figure 1) was imported to ANSYS Workbench 11 (Ansys Inc., Canonsburg, PA, USA) to perform FEM simulation.

Boundary conditions and model set up

For simulation, the outer ear canal was neglected as described by Ferrazzini [7] because it was assumed that the influence of each parameter is independent from this anatomical structure. A fixed bearing was applied to the an. fib., the ends of the ligaments and muscles. The ligamentum anulare at the footplate of the stapes could be replaced by combining 25 spring and damping elements. The cochlea was replaced by a cubical mass and 10 additional spring and damping elements (Figure 2), similar to the approaches of Ferrazzini [7] or Gan et al. [11]. Material properties, such as densities, Young's modulus, Poisson's ratios and damping coefficients were obtained from the literature [1, 7, 11, 21, 22], mainly from Gan et al. [11]. All values are listed in Appendix 1. For simulation, the tympanic membrane (TM) was excited by a sinusoidal sound pressure level (SPL) of 90 dB over a frequency range of 100 Hz to 10 kHz. As a result, the perpendicular displacement of the stapes footplate (peak amplitude) depending on the frequency was determined. Motions in other directions or rotations were neglected. For further details, refer to Appendix 1.

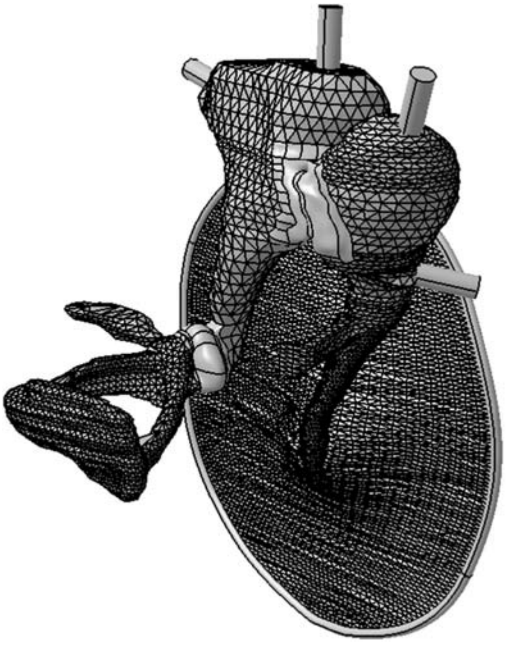

Figure 1 CAD model of the human middle ear, derived from a VRML data set [8].
Incudomalleolar (IM) and incudostapedial (IM) joint, ligaments and annulus fibrocartilagineus were supplemented.

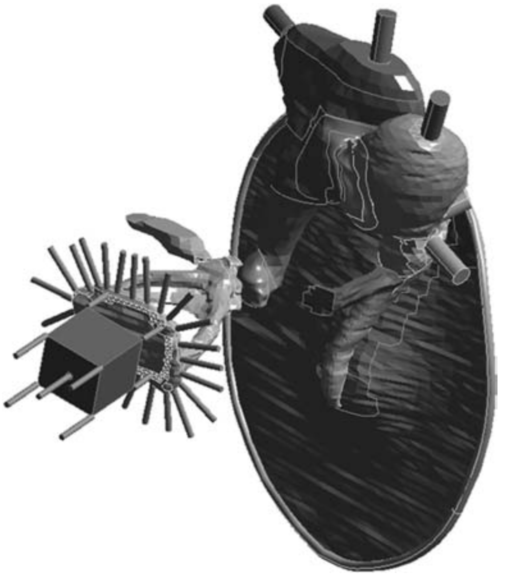

Figure 2 FEm of the middle ear.
A fixed bearing was applied to annulus fibrocartilagineus and the ends of the ligaments and muscles. L. anulare and cochlea were replaced by spring damper elements and a mass (cube).

Variation of parameters

The initially established model, named OTO-μ, was defined as reference. Then, 24 parameters, all listed in Table 1, were varied individually. The recalculated TF was compared with that from the reference to determine the aberration in percentage.

Results

Reference model

The TF of the model OTO-μ was in agreement with other FEms as well as with experimental measurements (Figure 3) [6, 7, 11, 12, 15, 22, 31]. The curve of phase shift obtained was in agreement with Kringlebotn and Gundersen [25] (Figure 4). Hence, the established model could be validated and can be established as reference.

Influence of parameters

It could be determined that the influence of each parameter was different and highly dependent on frequency. Those

Table 1 Survey on all parameters varied combined with the resulting influence on the TF depending on the frequency.

Type and dimension of variation	100 Hz–~500 Hz	~500 Hz–1 kHz	~1 kHz–2 kHz	~2 kHz–4 kHz	~4 kHz–6 kHz	~6 kHz–10 kHz
Damping (±25%)	0	+	+ +	+ +	+	0
Damping (Rayleigh) (with and without)	0	+ +	+ + +	+ + +	+ + +	+ + +
Ossicles, density (±25%)	0	0	0	0	0	+ +
Ossicles, density (in- and homogeneous)	0	0	0	0	+	+ +
M. stapedius (with and without)	+	+	+	+	0	0
M. tensor tympani (with and without)	+ + +	+ + +	+ +	+ +	+ +	+ +
M. tensor tympani, stiffness (±25%)	+ +	+ +	+	+	0	0
Ligamentum incidus posterius (with and without)	+ +	+ +	+	+	0	0
Ligaments (with and without)	0	0	0	0	0	0
Ligaments, stiffness (±50%)	+	+	0	0	0	0
Ligaments, alignment	+ +	+ +	+ +	+ +	+ +	+ +
TM–manubrium contact (at ends vs. full length)	+	+	++	++	++	+ + +
Stria mallearis (with and without)	+ + +	+ +	+ + +	+ + +	+ + +	+ + +
TM, stiffness (±50%)	0	+ +	+ + +	+ + +	+ + +	+ + +
TM, thickness (±25%)	0	0	0	0	0	0
Annulus fibrocartilagineus (with and without)	+ +	+ ++	0	0	0	+ +
Annulus fibrocartilagineus stiffness (+25% and -70%)	0	0	0	0	0	0
IS joint, (stiff and flexible)	+ + +	+ + +	+ + +	+ + +	+ + +	+ + +
IS joint, gliding (with and without)	+	+ +	+ + +	+ + +	+ + +	+ + +
IM joint, stiffness (2 MPa and 14.1 MPa)	+	+ + +	+ + +	+ + +	+ + +	+ + +
IM joint, gliding (with and without)	+ +	+ +	+ +	+ +	+ +	+
Inner ear, stiffness, (±50%)	0	0	0	0	0	0
Inner ear, damping, (±50%)	0	0	+	+	+	+
Ligamentum anulare, stiffness (±50%)	0	0	0	0	0	0
Ligamentum anulare, damping (±50%)	0	0	0	0	0	0
Cochlea, mass (±50%)	0	0	0	0	0	0

The impact is evaluated according to the scheme presented in Table 2.
IM, incudo-malleolar; IS, incudostapedial M., Musculus; TM, tympanic membrane.

showing the most relevant effect are discussed in detail. Table 1 lists the results of all parameters, classified according to the scheme of evaluation explained in Table 2.

TM rigidity Shear modulus and Young's modulus were increased by 50% and decreased by 50% and 100%, respectively. These changes showed significant influence on the TF.

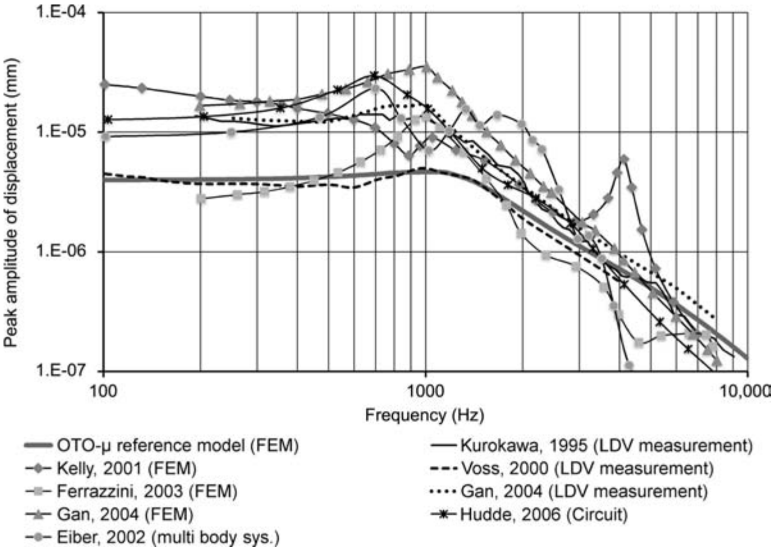

Figure 3 TF of the established FEm OTO-μ.
The curve is in agreement with those from other models as well as those from experimental measurements [6, 7, 11, 12, 15, 22, 30].

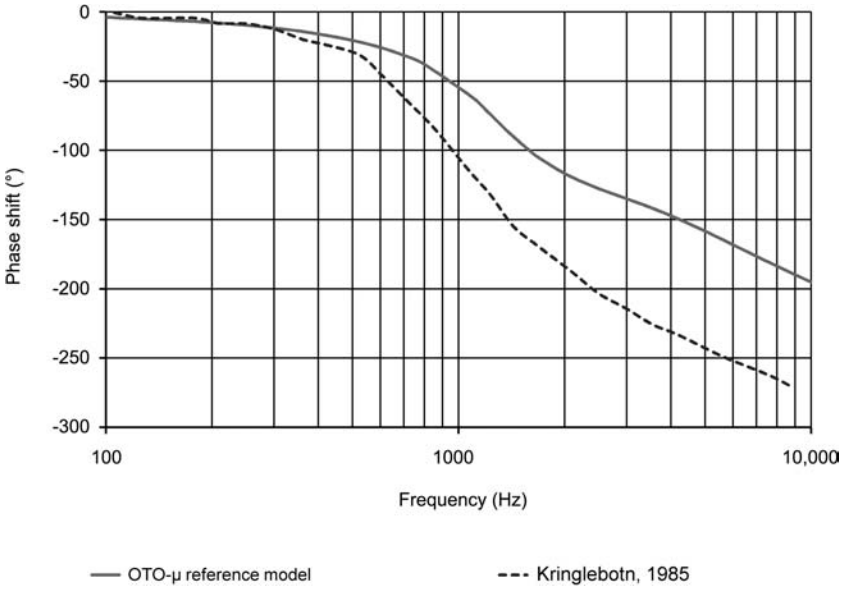

Figure 4 The curve of phase shift obtained was in agreement to that determined by Kringlebotn and Gundersen [25].

When decreasing rigidity, the curve was increased at frequencies below ~1.2 kHz and decreased at higher frequencies. The effect of higher rigidity was opposite. Applying the values used by Ferrazzini [7] the aberration reached 50% (Figure 5A).

TM thickness The thickness of the TM was increased and decreased by 25%, respectively. The effect was shown to be negligible over the entire frequency range. The TF was influenced significantly only when using non-physiological values such as 30 µm or 200 µm (Figure 5B).

Stria mallearis In the reference model a direct contact between the full length of the manubrium and the TM was assumed. This bonding was realized by a membrane, spanned by the arc of the manubrium from the umbo to the Prominentia mallearis, simulating the Stria mallearis. The Youngs's modulus of this tissue varied from 0.06 MPa to 0.12 MPa. This showed significant influence on the TF as the graph was lowered, mainly at frequencies below 400 Hz or above 800 Hz (Figure 5C).

Table 2 Criteria defined to evaluate the impact of parameter variations on the behavior of a FEM middle ear model.

Scheme of evaluation		
Aberration (%)	Level	Character
<5	Negligible	0
5–10	Medium	+
10–25	Important	+ +
>25	Crucial	+ + +

Ligaments To understand the influence of each ligament on the system, every single ligament (L. mallei superior, lateral and anterior as well as L. incudis posterior, and superior) was removed individually from the system. Only the L. incudis posterior showed noticeable influence on the TF (Figure 5D). However, varying the stiffness of all ligaments by ±50% showed a moderate influence on the TF (Figure 5D).

Musculus tensor tympani The Musculus tensor tympani was removed from the model. This showed crucial influence on the TF. For frequencies below ~1.5 kHz, the aberration reached values up to 400% (Figure 5E).

IM joint Gliding within the joint, as considered in the reference model, was blocked. In a second step, the initial stiffness of 14.1 GPa initial was lowered by 80% and increased by 300%, respectively. Among these variations, only blocking showed an important influence. When applying for stiffness the value used by Ferrazzini [7] (2 MPa), the aberration became significant, mainly around the region of 1 kHz being relevant for audiology (Figure 5F).

IS joint In the reference model, the IS joint was considered to be stiff, similar to a tight bony connection between incus and stapes. This rigid bonding was replaced by a flexible structure simulating a bonding via cartilage with a stiffness of 0.6 MPa and thickness of 100 µm. This showed crucial influence on the TF that was almost multiplied by three for frequencies below 1 kHz (Figure 5G). For further investigations on the IS joint, the stiffness of the new flexible bonding (cartilage-like) was increased by 25%, and in a second step replaced by a slipping joint (removal of cartilage, direct friction contact between incus and stapes) with a coefficient

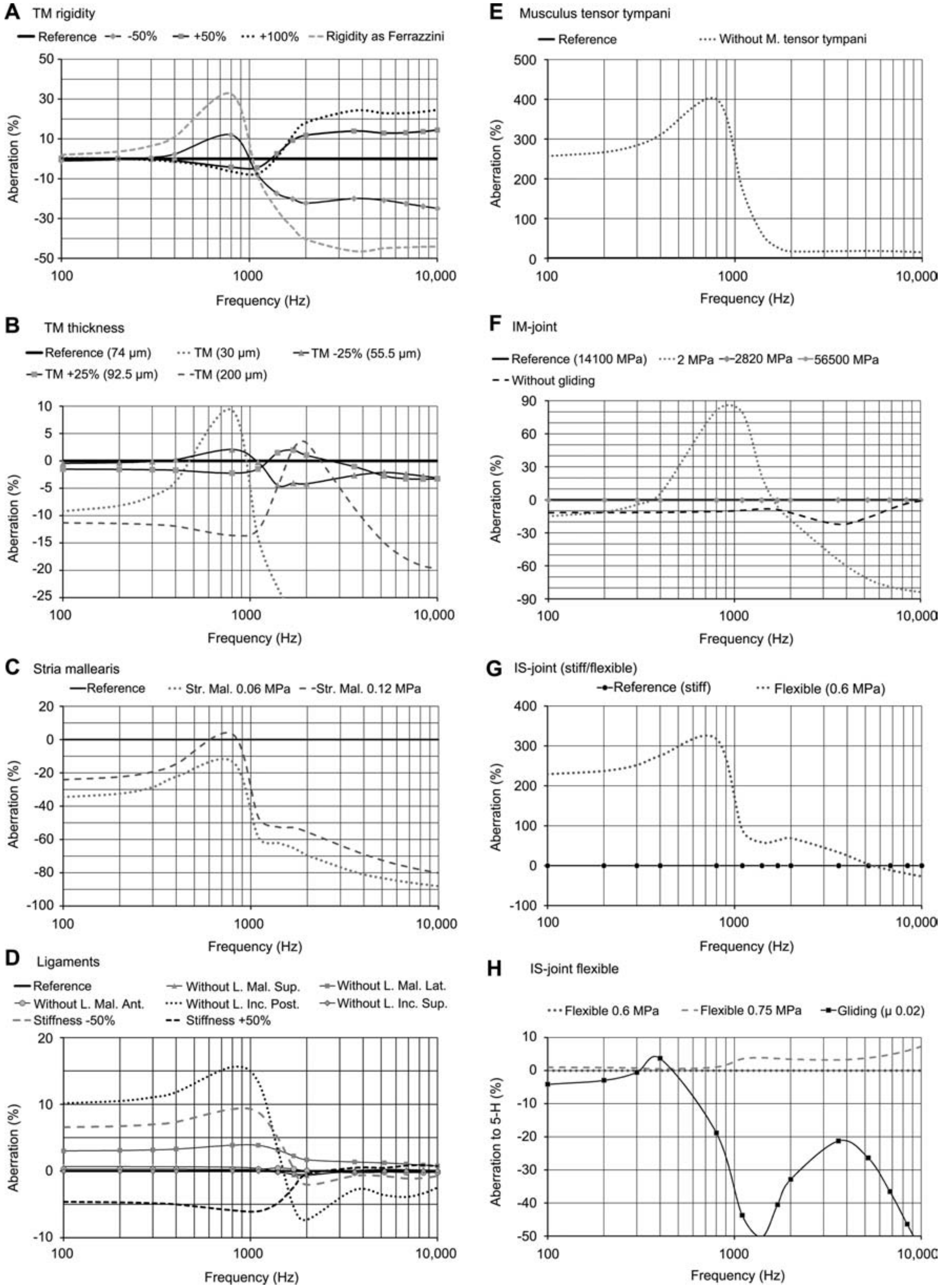

Figure 5 Survey of the parameters showing the most important influence, as discussed in detail.

The tympanic membrane (TM) was varied in rigidity (A) and thickness (B). The Stria mallerias was varied in Young's modulus (C). The ligaments of the middle ear, namely the L. mallei superior, lateral and anterior as well as the L. incudis posterior and superior were varied in stiffness or removed from the system individually (D). The Musculus tensor tympani was removed from the system (E). Gliding within the IM joint, as considered in the reference model, was blocked and its stiffness was varied, respectively (F). The IS joint, simulated as stiff in the OTO-µ model, was replaced by a flexible bonding (G) and its stiffness was varied and replaced by gliding (H).

of friction of $\mu = 0.02$. Only the latter variation showed significant influence (Figure 5H).

Survey of all parameters To evaluate and compare all parameters, their influence was classified according to the scheme of evaluation, displayed in Table 2, distinguishing between negligible (<5%), medium (5–10%), important (10–25%) and crucial (>25%) influence. The results of all variations depending on the frequency are listed in Table 1.

Discussion

By varying 24 parameters it was possible to distinguish between those with negligible and those with important influence on the FEm. This will allow focusing on the most influencing parameters in future studies. It is important to point out that only one parameter was varied. If two parameters with minor influences are changed simultaneously, their effect might not only be cumulated but mutually reinforcing, resulting in a crucial influence on the TF. Only by further research can it be pointed out if the variation of several parameters is independent or interwoven. The dimensions of the model (area of the TM, lever of ossicles) can be considered to be moderate according to the literature [2, 7, 22, 28]. In a similar study, Koike et al. [24] investigated the influence of the size of the middle ear structures as well as the stiffness of the ligaments. The results are comparable, Koike et al. showed that the effect of variation of the size of TM and ossicles influences the TF dependent on the frequency in differing extent. Koike et al. also indicated that the influence of the material properties of the ligaments is significantly large compared with the effect of difference in size. Hence, not varying the dimensions of the model is an allowed simplification of this parameter study.

Tympanic membrane

Further investigations on the anatomy of the TM appear to be very useful because the anisotropic structure and material properties dominate the vibration characteristics. This result emphasizes the work of Daphalapurkar et al. [4] and Cheng et al. [3] who analyzed the anisotropic nature of the TM in detail. The thickness did not appear to be very important, showing negligible influence in a wide range (~50–100 μm). However, the contact between TM and manubrium should be investigated more thoroughly. High resolution computer tomography (μCT) with enhanced resolution (voxel size <1 μm) could contribute to elucidate the mechanical behavior during the perception of sound.

Ligaments

The ligaments supplemented to the basic model feature a simplified rod-shaped structure with dimensions taken from the literature [2, 28, 29] to ascertain reproducibility. This neglects the fact that the stiffness of the ligaments might change over their length not only as a result of altering material properties [24] but also because of variations in geometry. Nevertheless, as the results concerning the ligaments are in agreement with the findings of others, this simplification seems to be reasonable. With the exception of the L. incudis posterior, removal of each ligament only showed minor influence within the model presented. When evaluating the results of Gan et al. [10] according to the scheme presented in Table 2, these results are congruent. Furthermore the influence of each ligament is different and just one ligament showed major influence. However, contrary to Gan et al. [10], who assumes the L. mallei superior to be showing the biggest influence, within the model presented the L. incudis posterior was found to be the most important influence. This could be as a result of differences within the geometries used by Gan et al. and for the model presented. To recapitulate, it can be assumed that an influence of the ligaments can only be observed at frequencies below 1.5 kHz as assumed by Gan et al. [10] and Hüttenbrink [17].

Musculus tensor tympani

The displacement of the stapes footplate increases significantly when removing the M. tensor tympani but only for frequencies below ~1.5 kHz. Gan et al. [10] and Hüttenbrink [17] report the same influence but in a more moderate extent. Nevertheless, it could be confirmed that for simulations on the acoustical behavior of the middle ear, this muscle cannot be neglected. Further analysis on the three-dimensional movements of the ossicles in this model might clarify if the muscle ascertains the functionality of the joints as proposed by Hüttenbrink [18] and Probst et al. [28].

IM joint

Its function could not be explained entirely using this simplified model of the IM joint. The fact that varying its stiffness only showed minor influence could indicate that this joint is less important for transmission of sound at a physiological level but rather compensates extreme SPLs and lateral displacement of the TM owing to changes in atmospheric air pressure. This statement is in agreement with the results of Hüttenbrink [16], Goldenberg and Grant [13] and Hudde [14]. The issue whether the joint can be considered stiff at frequencies up to 1 kHz as assumed by Goldenberg and Grant [13] and Offergeld et al. [27] or flexible as observed by Nakajima et al. [26], Decraemer and Khanna [5] and Willi et al. [32, 33] could not be clarified. A further examination of its anatomy would probably help to gain knowledge about the function of the IM joint. Measurements using very high resolution μCT could lead to more sophisticated FEMs to enhance comprehension of this structure.

IS joint

The influence of the IS joint was shown to be as crucial as the influence of the IM joint. Hence, it should be thoroughly analyzed as its bigger abutter. The simulation of a flexible bonding versus a gliding articulation of stapes and incus yielded significantly differing results. As gliding halves the quality of sound transfer in the region of 1 kHz, it was assumed that a rather stiff flexible bonding within the model represents reality in an improved manner. Probably the IS joint, similar to the IM joint, rather compensates lateral displacements of the TM caused by changes in static air pressure than influencing the transmission of sound. The same conclusions are drawn by Funnell et al. [9], Javia and Ruckenstein [20] and Nakajima et al. [26] in their experimental measurements. Hüttenbrink [16, 19] observed the same functionality and underlines the protective function of the IS joint, shielding atmospheric peak pressure. Further investigations of its built-up as proposed for the TM or IM joint might elucidate an underlying mechanism.

Conclusion

Despite the great effort over the past decades, many aspects of the functionality of the middle ear could not be clarified in a fulfilling manner. FEM is a very well suited method to enhance knowledge on structures that often can hardly be approached in an experimental way. Nevertheless, the input parameters have to be determined in an improved way, including material properties and geometry at high resolution, particularly for the topography of articular surfaces, structure of joint spaces and the bonding between ossicles to the TM and cochlea. It would also be useful to further test geometries in combination with the same material properties for simulations. It can be expected that material properties vary far less than anatomy does among different individuals. Hence, a set of good selected material properties should lead to congruent results in simulation regardless of the geometric set used. Presumably thus the range suggested for material properties could be confined.

Acknowledgements

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Appendix

Appendix 1 Material properties used.

Ossicles	
Youngs's modulus	14 100 MPa
Poisson ratio	0.3
β (Rayleigh)	1 e–4 s
Density	Malleus: 2250, 4530, 3700 kg/m^3; incus: 2360, 2360, 5080 kg/m^3; stapes: 2230 kg/m^3
Ligaments: (1) L. m. superior; (2) L. m. lateralis; (3) L. m. anterius; (4) L. i. posterior; (5) L. i. superior	
Youngs's modulus	(1) 4.9; (2) 6.7; (3) 21; (4) 52; (5) 4.9 MPa
Poisson ratio	0.3
β (Rayleigh)	1 e–4 s
Density	1200 kg/m^3
Muscles: (1) M. tensor tympani; (2) M. stapedius	
Youngs's modulus	(1) 70; (2) 52 MPa
Poisson ratio	0.3
β (Rayleigh)	1 e–4 s
Density	1200 kg/m^3
Thickness	(1) 0.53; (2) 0.43 mm
Tympanic membrane: (1) pars tensa; (2) pars flaccida; (3) annulus fibrocartilagineus	
Youngs's modulus	(1) E_{radial} 35 MPa; $E_{tangential}$ 20 MPa; $E_{vertical}$ 20 MPa; shear modulus Grφ: 13.5 MPa Gφz; 7.7 MPa Gφz 7.7 Mpa; (2) 10 MPa; (3) 0.6 MPa
Poisson	0.3
β (Rayleigh)	1 e–4 s
Density	1200 kg/m^3
Thickness	(1–2) 74 μm; (3) 200 μm
IM (1) und IS (2) joint	
Youngs's modulus	(1) 14 100 MPa; (2) 0.6 MPa
Poisson ratio	0.3
β (Rayleigh)	1 e–4s
Density	(1) 3200 kg/m^3; (2) 1200 kg/m^3
Inner ear	
Ligamentum anulare	25 spring damping elements; spring constant 40 N/m; damping 0.02 Ns/m
Contact stapes, footplate, cochlea fluid	5 spring damping elements; spring constant 40 N/m; damping 0.02 Ns/m
Fixing fluid cochlea	5 spring damping elements; spring constant 40 N/m; damping 0.02 Ns/m
Fluid cochlea	Cube with 25.5 mg

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