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Research paper

Finite element modeling of energy absorbance in normal and disordered human ears

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ABSTRACT

The finite element (FE) model of the human ear has been developed to analyze the middle ear and cochlea function in relation to the ear structures. However, the energy absorbance or energy reflectance used in the research and clinical audiology test has not been reported in the FE model. The relationship between the middle ear structure and the energy absorbance (EA) needs to be identified using the FE model. In this study, a FE model of the human ear, including the ear canal, the middle ear and the spiral cochlea constructed from the histological sections of a human temporal bone, was used to calculate EA. The viscoelastic material properties were applied to the middle ear soft tissues. Three middle ear disorders were simulated in the FE model: otitis media, otosclerosis, and ossicular chain disarticulation. Multi-physics (acoustic, structure, and fluid) coupled analysis was conducted in the model. The FE model was first validated with the published experimental data on the middle ear input impedance and EA of the normal ear. The EA in three disordered ears was obtained from the model and compared with the published results measured in the clinics and the temporal bone experiments. The consistence of the model-derived EA with the published data demonstrates that the FE model is feasible to analyze EA. The effects of middle ear pressure, middle ear effusion, and mechanical properties of soft tissues on EA were estimated and discussed.

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1. Introduction

When sound pressure is presented in the ear canal, part of the acoustic energy is reflected by the tympanic membrane (TM) back to the canal, and the other part is absorbed by the middle ear. The energy reflectance (ER) represents the ratio of the acoustic energy, which is reflected while the energy absorbance (EA) represents the part absorbed. ER and EA have a simple relation that their sum is equal to one (Keefe and Feeney, 2009; Allen et al., 2005).

The ER, as an acoustic measurement, was first introduced by Stinson et al. (1982). Unlike the traditional acoustic impedance and admittance measurements, such as a single frequency (usually at 226 Hz) or the multiple-frequency tympanometry, the ER reaches high frequency over 2000 Hz at ambient pressure in the ear canal and is insensitive to the anatomic irregularities of the ear canal (Keefe and Feeney, 2009). Keefe et al. (1992) developed a rapid, noninvasive technique to measure the wideband ER in the human ear. Since then, ER and EA have become measurement tools in research and clinical audiology to differentiate the normal and diseased ears in children and adults (Keefe et al., 1993; Voss and Allen, 1994; Margolis et al., 1999; Feeney et al., 2003; Keefe and Simmons, 2003; Allen et al., 2005; Shahnaz and Bork, 2006, Shahnaz et al., 2009; Liu et al., 2008; Ellison et al., 2012). Since ER and EA have a simple interchangeability, only EA was used in the following context for consistency. Note that some EA cited in this study were converted from ER reported in the literature.

To date, the EA has been measured to characterize the human middle ear function in both normal and disordered conditions. The results reported in the literature show that there is a noticeable difference between the EA measured in the normal ear and the ears with pathologies, such as otitis media (Piskorski et al., 1999; Feeney et al., 2003; Allen et al., 2005; Ellison et al., 2012), ossicular chain disarticulation (Feeney et al., 2003, 2009), and perforation of the tympanic membrane (Feeney et al., 2003). The EA has the potential

Abbreviations: EA, energy absorbance; ER, energy reflectance; FE, finite element; IM, incudomalleolar; IS, incudostapedial; MEP, middle ear pressure; MEE, middle ear effusion; OM, otitis media; RWM, round window membrane; SAL, stapedial annular ligament; TB, temporal bone; TM, tympanic membrane; TMA, tympanic membrane annulus; TM-PF, tympanic membrane-pars flaccida; TM-PT, tympanic membrane-pars tensa.

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to be a standard objective test of middle ear function in clinical audiology.

The reason which prevents the EA being a standard audiology test is that the effect of middle ear disorders on EA is not completely understood and a simple criterion to differentiate the EA between the normal and disordered middle ears is not established. As the first step toward this objective, the relationship between the EA and all kinds of middle ear structural variations needs to be studied thoroughly. However, it is difficult to isolate and measure the effect of specific structural changes in pathological ears on the EA in patients because of the constriction to manipulate structures in patients, the broad inter-subjects variations, and the possible cross effect by multiple factors (e.g., the pressure, fluid, and morphological changes in otitis media ears).

As an alternate approach, a series of measurements were conducted on human cadaver temporal bones to study the change of EA between the normal and the abnormal ears, which were measured with a specific structural modification. Feeney et al. (2009) measured the EA on five cadaver ears with disarticulated ossicular chain. Voss et al. (2008, 2012) studied how the EA was affected by the measurement location, middle ear cavity volume, static pressure and fluid in the middle ear cavity, stapes fixation, ossicular chain disarticulation, and the TM perforation on the cadaver ears. However, the manipulations on the middle ear structure in the human temporal bone are limited, which may prevent a thorough study on EA relation to middle ear structural variations. Besides the experimental measurements on temporal bones, the circuit model was used by Voss et al. (2012) to simulate the specific middle ear disorders and to investigate their effects on EA. However, the circuit model cannot represent the real three-dimensional structural changes.

The finite element (FE) model of the human ear has been developed to study the middle ear and cochlea function in the normal and pathological ears in the past two decades (Zhao et al., 2009; Gan et al., 2004, 2007; Zhang and Gan, 2011). The FE model of the human ear was proved as a successful approach to simulate various middle ear disorders, such as the otitis media (Gan and Wang, 2007; Gan et al., 2011), TM perforation (Gan et al., 2009), and ossicular chain fixation or disarticulation (Huber et al., 2003; Koike et al., 2004). Compared with the lumped model (Feng and Gan, 2004) and the circuit models (Zwislocki, 1962; Shaw and Stinson, 1981; Kringlebotn, 1988; Voss et al., 2012), FE model has the intrinsic advantage of representing the real structure and coupling the multi-physics analysis in the ear. All kinds of the middle ear structural manipulations, including but not limited to the geometric alterations, mechanical properties changes, and middle ear effusion and pressure variations, can be simulated in the FE model. The FE model of the human ear should be feasible to study the relationship between the EA in the ear canal and the structural changes in the middle ear. However, to date there is no report in the literature using the FE model to simulate the EA in the human ear.

The goal of this study is to establish a method of analyzing EA using the FE model of the human ear, and to estimate the effects of middle ear structural variations in diseases on EA. In this study, a comprehensive FE model of the human ear, including the ear canal, middle ear, and spiral cochlea, was used to derive EA. The viscoelastic material properties were applied to the middle ear soft tissues. The middle ear input impedance and EA in the normal ear were derived from the model and validated with a comparison to the experimental or clinical measurements. Three middle ear disorders were created in the FE model to investigate the changes of EA in response to pathological conditions. The effect of the TM and the ossicular chain stiffness changes on EA was also estimated. This study is the first attempt to simulate the clinical audiology test using the FE model of the human ear. The results will help clinicians understand the relationship between the EA in the ear and the structural variations.

2. Methods

2.1. FE model of the human ear

A comprehensive FE model of the human ear consisting of the ear canal, middle ear, and spiral cochlea was reported by our group (Zhang and Gan, 2011; Gan et al., 2011). In brief, the model was created based on histological sections of a temporal bone (male, age 52, left ear). The ear canal had a length of 29.65 mm and an average cross-section area of 51.94 mm^2. The dimensions of the middle ear components of the model were listed in Gan and Wang (2007). The mass effect of the middle ear structures was defined by the density for each ear component. As listed in Table 1 of Gan and Wang (2007), the density of all middle ear soft tissues, including TM, was assumed as 1200 kg/m^3. The mass of malleus, incus and stapes was 30.01, 35.17 and 3.64 mg, respectively, calculated from the dimensions and density. The spiral cochlea with two and a half turns was connected to the stapes footplate at the oval window and to the middle ear cavity at the round window (Zhang and Gan, 2011). Fig. 1A shows the anterior-medial view of the model, and Fig. 1B shows the posterior-lateral view of the structures inside the middle ear cavity. Multi-physics (acoustic–fluid–solid) coupled analysis was conducted in the FE model using ANSYS (ANSYS Inc., Canonsburg, PA).

The soft tissues, including the TM pars flaccida (TM-PF), TM pars tensa (TM-PT), TM annulus (TMA), IM joint, IS joint, stapedial annular ligament (SAL), and round widow membrane (RWM), were assumed as viscoelastic materials in this study. The standard linear viscoelastic model (Fung, 1993) was used as the constitutive law for the tissues, and the relaxation modulus of the tissues is expressed as,

$$E(t) = E_0 + E_1 \exp\left(-\frac{t}{\tau_1}\right) \quad (1)$$

whereE_0, E_1 and τ_1 are viscoelastic parameters. The relaxation modulus $E(t)$ can be converted into the storage or elastic modulus $E'(f)$ and the damping factor $\eta(f)$ as the function of the frequency f:

Table 1
Viscoelastic parameters of the middle ear soft tissues in the normal condition and under different static pressures in the middle ear cavity. The abbreviations represent the middle ear soft tissues (TM-PF: tympanic membrane-pars flaccida; TM-PF: tympanic membrane-pars tensa; TMA: tympanic membrane annulus; IM joint: incudomalleolar joint; IS joint: incudostapedial joint; SAL: stapedial annular ligament; and RWM: round window membrane).

Soft tissues		TM-PF	TM-PT	TMA	IM joint	IS joint	SAL	RWM
Normal	E_0 (MPa)	7	25	0.2	60	0.4	2.0	1.0
	E_1 (MPa)	16	70	0.64	180	20	10.8	3.0
	τ_1 (μs)	25	25	28	20	20	24	30
−50 daPa	E_0 (MPa)	10.3	27.5	0.8	72	0.4	2.7	1.1
	E_1 (MPa)	23.5	77	2.6	216	20	14.7	3.3
	τ_1 (μs)	25	25	28	20	20	24	30
−100 daPa	E_0 (MPa)	23.2	48.6	2.7	90	0.5	4.8	1.4
	E_1 (MPa)	53	136.1	8.7	270	25	25.9	4.2
	τ_1 (μs)	25	25	28	20	20	24	30
−150 daPa	E_0 (MPa)	39	84.7	4.7	120	0.72	8.5	2
	E_1 (MPa)	89.1	237	14.9	360	36	45.9	6
	τ_1 (μs)	25	25	28	20	20	24	30
−200 daPa	E_0 (MPa)	62	133	7.3	176	1.06	14.3	3
	E_1 (MPa)	142	373	23.2	528	53	77.2	9
	τ_1 (μs)	25	25	28	20	20	24	30