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Review

# Finite element analysis of the middle ear transfer functions and related pathologies

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ABSTRACT

With developments in software and micro-measurement technology, a three-dimensional middle ear finite element (FE) model can now be more easily constructed to study sound transfer function. Many FE models of the middle ear have been constructed to date, and each has its own particular advantages and disadvantages. In this article, we review the latest developments and technologies in the field of the FE models of the middle ear, and the use of FE in the study of middle ear pathology. Proposals are made for future developments in the field of finite element analysis of middle ear transfer function.



**Contents**



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## 1. Introduction

The human middle ear consists of the eardrum (tympanic membrane (TM)), three ossicles (malleus, incus and stapes), ligaments and tendons, and the bony middle ear cavity. It works as a mechanical system and plays an important role in sound transmission. Sound collected in the air-filled external ear is transformed into mechanical vibrations of the eardrum and ossicular chain, and then into a travelling wave in the fluid-filled cochlea (inner ear). The middle ear functions as an impedance matching device between the low impedance of air and high impedance cochlear fluids. This is achieved naturally by the anatomy of the ear, mainly due to the difference in the areas of the tympanic membrane and the stapes footplate and, to a lesser extent, the lever action of the ossicular chain [1]. Therefore, the primary transfer function of the middle ear describes the efficiency with which sound energy is transferred from air to the fluids within the cochlea. Disruption to the middle ear structure will cause a reduction of the efficiency of the middle ear transfer function, resulting in a conductive hearing loss.

Common middle ear disorders which result in conductive hearing loss are, for example, (1) tympanic membrane perforation; (2) otitis media; (3) otosclerosis and (4) middle ear malformation. Middle ear disorders can usually be diagnosed by taking a medical history, together with carrying out a clinical assessment. Traditionally, some types of middle ear disorders due to structural abnormalities are investigated using X-ray or computed tomography (CT). This can provide information about the individual anatomy in cases such as malformation, trauma, inflammation or tumour. The radiographic findings not only support the clinical diagnosis but also determine the surgical approach. However, cross-sectional 2D CT images alone can only provide limited information about the complex anatomy of the middle ear and adjacent structures. Moreover, 2D CT scan images do not describe the dynamic characteristics of the middle ear.

Over the past 50 years or so, researchers have developed different middle ear models using a variety of bioengineering approaches for the purposes of simulating the anatomic structure of the middle ear, analyzing its dynamic behaviors, and therefore predicting the normal and pathological mechanics in the middle ear. These include early modeling works (e.g., the analogue circuit model [2,3], analytical model [4], multibody model [5]), as well as advanced finite element (FE) middle ear models (e.g., [6–13]). Each model has its own particular characteristics with certain advantages and disadvantages. For example, analogue circuit models are relative easy to construct and can be used for computational analysis in simple experiments [2]. However, the limitations of simple analogue circuit models are that they do not capture the complexities of real middle ear structures which contribute to the accuracy of simulating middle ear function. In contrast to the acoustic–mechanical approach, the FE method simulates the ear anatomy precisely and improves the geometric characteristics in the middle ear models. Moreover, middle ear transfer function can be simulated and analyzed by incorporating middle ear components with geometric parameters and mechanical properties. Therefore, the FE method is considered a powerful tool for the theoretical and numerical investigation of a dynamic middle ear system and related pathologies affecting the middle ear. However, there are still some challenges to create accurate FE human middle ear models because of the difficulties in obtaining important parameters from the microstructures of biological tissues in the middle ear system. The purpose of this paper is to review the advances and current development of the FE middle ear models, together with theoretical analysis of middle ear transfer function in the pathologic conditions. It will provide further insight into the middle ear dynamic mechanism in normal and pathological conditions, discuss the possibility of future clinical application of the FE middle ear model and areas of further development.

## 2. Search methods

A systematic literature search was conducted using The National Library of Medicine's search service – PubMed (website: http://www.ncbi.nlm.nih.gov/entrez/query.fcgi), with a combination of the subject headings 'Finite element model', 'Middle ear mechanics' and, 'Dynamic analysis'. In addition, we also manually searched reference lists in bioengineering textbooks and conference proceedings for FE models of the middle ear. Potentially relevant articles were identified for retrieval based on an assessment of the middle ear transfer function using FE model, parameters of the middle ear anatomic structure, simulations of common middle ear disorders and evaluation of otological surgery using FE model provided in titles and abstracts (when available) of citations. Full texts of all relevant citations were retrieved.

## 3. Overview

### *3.1. Early works on analogue circuit model of the middle ear*

The aim of middle ear modeling is to simulate the acoustic structure of the middle ear and its transfer function from the ear canal through the ossicles into the inner ear. Several early works on middle ear modeling were analogue electro-acoustical models developed on the basis of the principle of middle ear impedance [2,14,15]. For example, Zwislocki [2] established the electric analogue model of the middle ear, which specified the functions of various middle ear structures in a quantitative way. The numerical values used in the model were derived from impedance measurements on normal and pathological ears and anatomical data. The results showed that the changes in analogue parameters corresponding to certain anatomical changes in the middle ear had the same effect on the impedance characteristics as measured at the eardrum.

Furthermore, several other analogue models of the middle ear have also been developed based on the earlier ones (e.g., [3]). These models were successful in predicting the empirical experimental results and were widely acknowledged and applied to the ear pathological studies [16,17]. The advantage of the analogue models is to simplify the complex dynamic system with limited degrees of freedom so that it can be used as a theoretical basis for parameter evaluation and validation. However, because of their simplicity, analogue models do not provide an accurate simulation of the acoustic–mechanical responses of the middle ear which has complex geometric characteristics and various material properties.

### *3.2. Finite element analysis (FEA) and current development on FE modeling of the human middle ear*

FEA is a computer-based numerical technique for calculating the strength and behavior of structures. It has distinct advantages in