Prediction of a Mysticete Audiogram via Finite Element Analysis of the Middle Ear

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1 Introduction

The impact of anthropogenic sound on marine mammals is difficult to assess, especially for species without available audiograms. There are currently no audiograms for any species of mysticete because of their size and, in many cases, their endangerment status. Consequently, insight into the hearing range of all mysticete species comes from indirect sources such as vocalization recordings. In contrast to mysticetes, several odontocete species have published audiograms.

Both the middle ear and the cochlea play an important role in shaping the audiogram of any mammal. The transfer function of the middle ear shapes the low-frequency portions of an audiogram, whereas the high-frequency portion of the audiogram is shaped by the frequency place map of the cochlea (Rosowski 1994).

Biophysical models of the cetacean middle ear can be developed using finite element (FE) techniques. FE modeling has been successfully used to provide an understanding of how several terrestrial mammalian middle ear systems work. The advantage to using FE models is that they directly incorporate the geometry and material properties of the structures of interest. For this study, the middle ear of a mysticete species, *Balaenoptera acutorostrata* (minke whale), was modeled using FE methods. The same methods were used to develop a model for the *Tursiops truncatus* (bottlenose dolphin) middle ear, a control species that has a behaviorally derived audiogram to verify the modeling approach.

2 Model

A formalin-fixed *Balaenoptera acutorostrata* ear and a thawed *Tursiops truncatus* ear were scanned using computed tomography. The resulting stacks of images were segmented for structures of interest (malleus, incus, stapes, tympanic bone, incudostapedial joint, incudomalleolar joint, and annular ligament) using Amira (Mercury Computer Systems, Chelmsford, MA). The three-dimensional volume generated from the segmented slices was subsequently used for FE analysis (COMSOL, Stockholm, Sweden).

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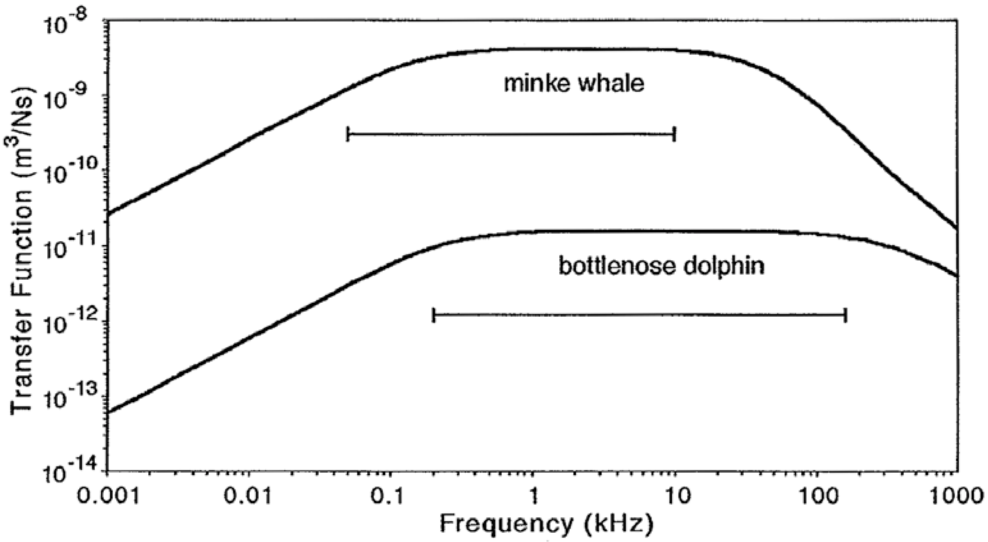

Fig. 1 Transfer functions for *Balaenoptera acutorostrata* and *Tursiops truncatus*. The solid lines under each curve represent the respective ranges of vocalization recordings (Gedamke et al. 2001; Ketten 1997)

Material properties were derived from a combination of literature and laboratory measurements and included density, Young's moduli, spring constants, cochlear damping, Rayleigh damping, and Poisson's ratio (Gan et al. 2004; Koike et al. 2002; Nummela et al. 1999).

An input force was applied to the malleus at the attachment point of the tympanic ligament. The model was fixed along the edge of the tympanic bone and the annular ligament to simulate the differential motion between the tympanic bone and the periotic bone. The soft tissues were modeled as springs and the cochlear input impedance was assumed to be resistive.

The models were calibrated using direct experimental measurements of middle ear stiffness (Miller et al. 2006).

3 Results

The model predicts that the passband for the middle ear (i.e., between the -3-dB cutoff frequencies) for *Balaenoptera acutorostrata* is between 100 Hz and 30 kHz (Fig. 1). Vocalizations for *Balaenoptera acutorostrata* occur at frequencies between 50 Hz and 9.4 kHz (Gedamke et al. 2001). In contrast, the FE model predicts the middle ear passband for *Tursiops truncatus* to be between 200 Hz and 300 kHz. The experimental audiogram for *Tursiops truncatus* (Johnson 1967) shows the range of best sensitivity of hearing to be between ~6 kHz and 140 kHz. Vocalizations occur at frequencies between 0.2 kHz and 150 kHz (Ketten 1997).

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