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Research paper

Superior-semicircular-canal dehiscence: Effects of location, shape, and size on sound conduction

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A R T I C L E I N F O

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A B S T R A C T

The effects of a superior-semicircular-canal (SSC) dehiscence (SSCD) on hearing sensitivity via the air-conduction (AC) and bone-conduction (BC) pathways were investigated using a three-dimensional finite-element (FE) model of a human middle ear coupled to the inner ear. Dehiscences were modeled by removing a section of the outer bony wall of the SSC and applying a zero-pressure condition to the fluid surface thus exposed. At each frequency, the basilar-membrane velocity, v_{BM}, was separately calculated for AC and BC stimulation, under both pre- and post-dehiscence conditions. Hearing loss was calculated as the difference in the maximum magnitudes of v_{BM} between the pre- and post-dehiscence conditions representing a change in hearing threshold. In this study, BC excitations were simulated by applying rigid-body vibrations to the model along the directions of the (arbitrarily defined) x, y, and z axes of the model.

Simulation results are consistent with previous clinical measurements on patients with an SSCD and with results from earlier lumped-element electrical-circuit modeling studies, with the dehiscence decreasing the hearing threshold (i.e., increasing v_{BM}) by about 35 dB for BC excitation at low frequencies, while for AC excitation the dehiscence increases the hearing threshold (i.e., decreases v_{BM}) by about 15 dB. A new finding from this study is that the *initial width* (defined as the width of the edge of the dehiscence where the flow of the fluid-motion wave from the oval window meets it for the first time) on the vestibular side of the dehiscence has more of an effect on v_{BM} than the area of the dehiscence. Analyses of dehiscence effects using the FE model further predict that changing the direction of the BC excitation should have an effect on v_{BM}, with v_{BM} being about 20 dB lower due to BC excitation parallel to the longitudinal direction of the BM in the hook region (the x direction) as compared to excitations in other directions (y and z). BC excitation in the x direction and with a 'center' dehiscence located midway along the length of the SSC causes a reduction in the anti-symmetric component of the fluid pressure across the BM, as compared to the other directions of BC excitation, which results in a decrease in v_{BM} at high frequencies.

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1. Introduction

A semicircular-canal dehiscence (SCD) is characterized by a pathological opening in a small section of the bony wall of the semicircular canal (SC) of the inner ear. An SCD can be found in three different places according to different etiologies: the superior, lateral, and posterior SCs. Regardless of differences in SCD location, dehiscence patients have complained of similar symptoms such as vertigo, oscillopsia, and/or hearing loss (Minor et al., 1998; Chien et al., 2011).

Most previous studies have focused on superior-semicircular-canal (SSC) dehiscence (SSCD). Minor et al. (1998) first reported vertigo caused by an SSCD, and consequently many experiments have been performed to investigate vertigo (Minor, 2000; Cremer et al., 2000) and auditory symptoms due to an SSCD (Mikulec et al., 2004; Sohmer et al., 2004; Songer and Rosowski, 2005; Attias et al., 2011). Furthermore, SSCD effects on hearing thresholds were investigated theoretically using lumped-element electrical circuit models (Rosowski et al., 2004; Songer and Rosowski, 2007). The previous studies reached the consensus that a dehiscence acts

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Abbreviations: AC, air conduction; BC, bone conduction; BM, basilar membrane; FE, finite element; SC, semicircular canal; SCD, semicircular-canal dehiscence; SSC, superior-semicircular canal; SSCD, superior-semicircular-canal dehiscence

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as a *third window* in the inner ear that shunts a portion of the fluid motion away from the cochlea, with the first two such windows being the oval window and the round window, such that it acts as an additional pathway that alters the normal functioning of the SC. This shunting of the fluid motion away from the cochlea through the SCD increases the air-conducted (AC) threshold of hearing, which is well understood. But it also decreases the bone-conducted (BC) threshold, producing an improvement in BC hearing at low frequencies, which has not been well understood. Recently, the relationship between the hearing threshold and the dehiscence size (or location) has been studied in order to elucidate the mechanisms of SSCD syndrome and develop ways of screening patients for SSCD (Rajan et al., 2008; Songer and Rosowski, 2010; Niesten et al., 2012). Large air-bone gaps (ABGs) were shown to accompany SSCDs at low frequencies through animal experiments (fat sand rat and chinchilla).

The purpose of this study is to provide insight into the fundamental characteristics of SSCD syndrome under both AC and BC excitation. In order to do so, a 3-D finite-element (FE) human-ear model was used, consisting of the middle ear, cochlea, and SCs. For simplicity, the present model formulation is for passive mechanics and does not consider the active cochlear amplification mechanisms (e.g., Ren, 2005; Shera, 2007; Liu and Neely, 2010; Yoon et al., 2011). The basilar-membrane (BM) velocity was used to indicate hearing sensitivity, under the assumption that the BM velocity is inversely proportional to the hearing threshold. The model was used to investigate how hearing due to an SSCD varies at low and high frequencies resulting from variations in SSCD size, SSCD location, and the direction of BC stimulation. Furthermore, ABGs due to SSCDs were predicted at frequencies above 4 kHz, where experimental data do not yet exist.

2. Methods

In order to investigate the effects of SSCDs on hearing loss, a 3-D FE coiled-cochlea model with SCs was developed (Fig. 1). The FE model consists of the middle ear and cochlea, whose geometry was obtained by micro-computed tomography (μCT) scanning, and has the following mechanical characteristics: 1) inviscid cochlear fluid, 2) orthotropic elasticity in the BM, and 3) a complex speed of sound in the fluid and complex Young's modulus to incorporate damping. Details of the model are described elsewhere (Kim et al., 2011). In the current study, the geometry and boundary conditions of this FE model were modified to simulate the SSCD effects.

2.1. Modified model geometry

In this study, a dehiscence was modeled by making a hole in the SSC by removing a fraction of its bony elements. Clinically, SCDs have been shown to vary from 1 to 7 mm in length (mean: 3.64 mm, Chien et al., 2012) and they can be located anywhere along a given SC. The simulations were separated into two groups to better delineate the effects of SSCD size and location on the AC and BC thresholds.

2.1.1. Group I

A rectangular hole representing the SSCD was alternated between three different locations, indicated by '*top*', '*center*', and '*bottom*' in the rows of Fig. 2; and three different sizes, denoted as 'small', 'medium', and 'large' in the columns of Fig. 2. The areas of the three sizes were 0.78, 1.54, and 3.27 mm^2 respectively. The *top* and *bottom* locations represent the cases in which the SSCD is located, respectively, near the ampulla or near the common crus shared between the posterior canal and superior canal. The *center* hole is located midway between the ampulla and the common crus on the canal. Fig. 2 illustrates the nine combinations of SSCD location and size used in this study under *Group I*.

2.1.2. Group II

Additional factors that can have an effect on hearing besides the size and location of the dehiscence are the shape of the dehiscence and the distance between the oval window (OW) and the nearest opening location of the dehiscence. Five cases, shown in Fig. 3, were simulated to test the effects of these factors while keeping the location of the dehiscence fixed. The variables of interest in this simulation group, *Group II*, were the distance from the input window (i.e., from the OW) to the nearest point of the dehiscence, and the width of the dehiscence. The distance from the OW to the nearest point of the dehiscence was the same in all cases except for Case V, for which the distance was smaller. On the other hand, the area of the dehiscence was differentiated into three cases, which were smaller (i.e., Case I) or larger (i.e., Case III) than the cross-sectional area of the SC, or otherwise similar to the cross-sectional area of the SC (i.e., Cases II, IV, and V). Dehiscence widths were all the same except for Case IV, for which it was larger.

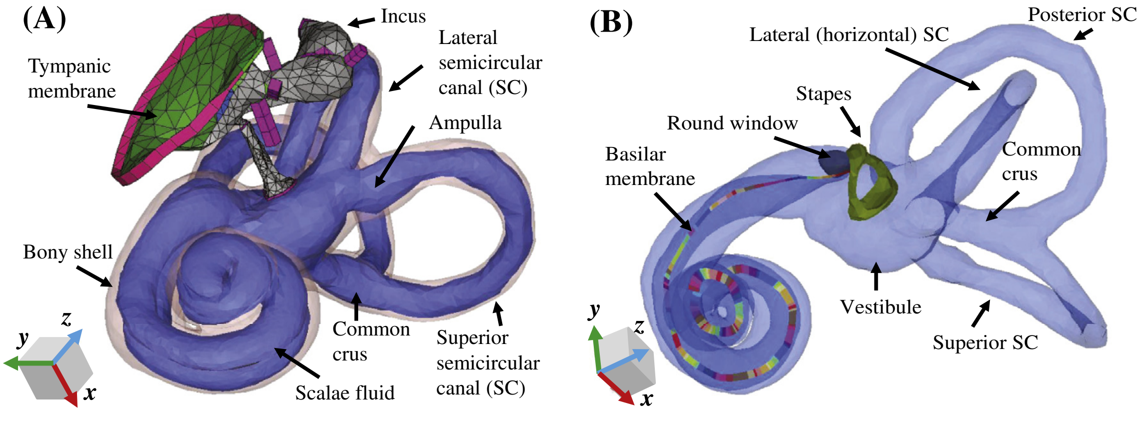

Fig. 1. A finite-element (FE) model of the human auditory periphery. (A) Middle-ear structures coupled to the inner ear are shown, with the bony shell of the inner ear represented by a transparent pink outline. (B) The scalae fluid of the inner ear is shown, including for each semicircular canal (SC), represented by a light-blue color, and the stapes, round window, and basilar membrane (BM) are highlighted. The different colors of the BM are used to differentiate individual sections, each of which has its own local coordinates and Young's modulus. The eardrum, malleus, and incus are masked in (B) for visualization purposes.