Journal of Biomechanics 40 (2007) 2796–2805

JOURNAL OF BIOMECHANICS

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3D finite element analyses of insertion of the Nucleus standard straight and the Contour electrode arrays into the human cochlea

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Accepted 16 January 2007

Abstract

Previous experimental studies of insertion of the Nucleus standard straight and the Contour arrays into the scala tympani have reported that the electrode arrays cause damage to various cochlear structures. However, the level of insertion-induced damage by these electrode arrays to cochlear structures (the spiral ligament, the basilar membrane and the osseous spiral lamina) has not been quantified. Although it has been suggested that rotation can overcome this resistance and prevent the basilar membrane from being pierced by the tip of the Nucleus standard straight array, there has not been any attempt to study the relationship between the rotation and the reduction of damage to the basilar membrane. In this study, 3D finite element analyses of insertions of the Nucleus standard straight array and the Contour array into the scala tympani have been undertaken. The perforation of the basilar membrane by the tip of the Nucleus standard straight array at the region of 11–14 mm from the round window appears to be compounded by the geometry of the spiral passage of the scala tympani. Anti-clockwise rotations between 25° and 90° applied at the basal end of the electrode array (for the right cochlea) were shown to significantly reduce the contact stresses exerted by the tip on the basilar membrane which support the practice of applying small rotation partway through insertion of electrode array to minimize damage to the basilar membrane. Although the Contour array (with its stylet intact) is stiffer than the Nucleus standard straight array, a slight withdrawal of the stylet from the Contour array before insertion was found to significantly reduce damage by the electrode array to the spiral ligament and the basilar membrane.

Keywords: Electrode array; Spiral ligament; Basilar membrane; Contact stress; Cochlear angle ($\theta_{cochlea}$)

1. Introduction

Clinical safety is an important subject for cochlear implants which have been invented to help severely-to-profoundly deaf people in restoring their hearing by converting sound into electrical impulses that are transmitted through an electrode array which is inserted into the scala tympani to stimulate auditory nerves (Clark, 2003). However, the insertion of an electrode array has been found to cause damage to different delicate cochlear structures such as the basilar membrane, the spiral ligament and the osseous spiral lamina (Shepherd et al., 1985; Tykocinski et al., 2001; Wardrop et al., 2005). It is desirable to thoroughly understand the nature of the insertion-induced damage by the electrode array to these cochlear structures and establish methods for reducing the damage.

Experimental studies using human temporal bones have been undertaken to understand the nature of damage to the spiral ligament, the basilar membrane and the osseous spiral lamina. In an experimental study using human temporal bones, Shepherd et al. (1985) reported that the tear of the spiral ligament caused by the Nucleus standard straight array typically occurred at 7–11 mm from the round window in five of the nine cochleae. The round window is an anatomical structure adjacent to the drilled opening into the scala tympani. Damage to the spiral

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0021-9290/$ - see front matter
doi:10.1016/j.jbiomech.2007.01.013

ligament by this type of electrode array was also observed at $\theta_{cochlea} \approx 180^{\circ}$ (or about 14 mm from the round window) in other experiments undertaken by Wardrop et al. (2005). The Contour array was also found to damage the spiral ligament at this region in separate experiments performed by Tykocinski et al. (2001). The Nucleus standard straight array was found to damage the basilar membrane at 14–15 mm from the round window in experiments undertaken by Shepherd et al. (1985). In another study, Wardrop et al. (2005) also observed the perforation of the basilar membrane caused by the tip of the Nucleus standard straight array at $\theta_{cochlea} \approx 180^{\circ}$. Franz and Clark (1987) suggested that rotation of this electrode array to overcome the resistance instead of persisting with the insertion can prevent the basilar membrane from being pierced. However, in that study there was not any attempt to investigate the extent of rotation required to reduce damage to the basilar membrane. Tykocinski et al. (2001) reported that damage by the Contour array to the basilar membrane was observed in two of the twelve cochleae in their experiments at $\theta_{cochlea} \approx 170^{\circ}$. The perforations of the basilar membrane in their study were observed to occur laterally, close to the junction of the basilar membrane and the spiral ligament. Damage by the Contour array to the basilar membrane at this region ($\theta_{cochlea} \approx 170$–$180^{\circ}$) was also reported by Wardrop et al. (2005). These experimental studies have also shown that damage to the osseous spiral lamina was an indirect result from damage to the basilar membrane.

Numerical models have been constructed to evaluate insertion of electrode array for cochlear implant. Previous models (Ketten et al., 1998; Yoo et al., 2000; Zakis and Witte, 2001; Lim et al., 2005) have generally assumed an idealized geometrical passage of the scala tympani with a uniform slope traced around the spiral axis. However, reconstruction of scala tympani using measurements obtained from the study by Cohen et al. (1996) (Fig. 1) showed that the rise in the cochlear spiral is not uniform but greater in the first 10 mm from the round window. The effects of geometrical variation in the spiral passage of the scala tympani have not been carefully evaluated but appear

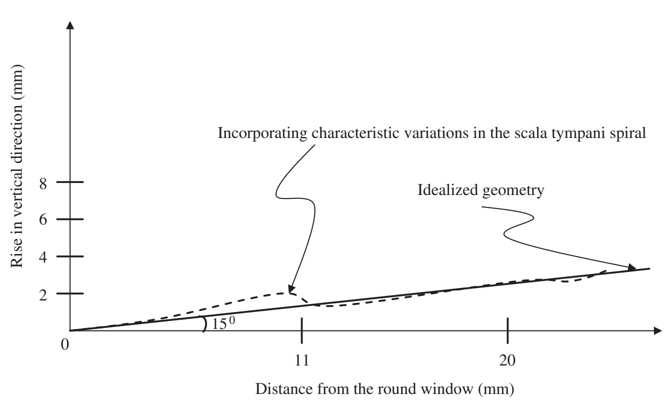

Fig. 1. Comparison of idealized slope of 15° versus actual measurements of position of (average) centroids of cross-sections of the scala tympani traced along the cochlear spiral obtained by Cohen et al. (1996).

to contribute to the resistance felt partway through the insertion of the electrode array as the tip of the array tends to be projected upwards and against the basilar membrane when the electrode array is inserted beyond 10 mm from the round window.

In this paper, 3D FE analyses of insertions of the Nucleus standard straight and the Contour arrays into two scala tympani models (with and without characteristic geometrical variations in its spiral passage) were undertaken. FE analysis is well established (Zienkiewicz, 1977) and has been used successfully to predict the stress–strain response of bodies under different boundary conditions such as external forces or applied loads. In this study, insertion trajectories of the electrode arrays were predicted. Contact stresses exerted by the tip of the electrode arrays on the spiral ligament and the basilar membrane were evaluated to assess the nature and severity of damage. Since previous studies (Shepherd et al., 1985; Tykocinski et al., 2001) have found that damage to the osseous spiral lamina was an indirect result of damage to the basilar membrane, the present 3D FE analysis will focus on evaluating contact stresses on the basilar membrane instead of those directly on the osseous spiral lamina. The effectiveness of applying a rotation to the Nucleus standard straight array part-way through the insertion in order to re-direct the tip of the array from the basilar membrane and reduce the likelihood of piercing of the basilar membrane was investigated using a 3D FE model. A modified insertion procedure for the Contour array with its stylet slightly withdrawn before insertion was modeled to assess the effects of a 'soft tip' on the contact stresses on these delicate structures in the cochlea.

2. Methods

Fig. 2a shows an idealized geometry of the scala tympani spiral and Fig. 2b shows a more realistic scala tympani with characteristic variations in the spiral passage (Fig. 2). The geometry of the realistic scala tympani model (Fig. 2b) was based on measurements of slides representing cross-sections along the 3D physical scala tympani molded with Silastic in experimental studies by Cohen et al. (1996) and reconstructed using SOLIDWORKS, a computer-aided-design (CAD) software. In the reconstruction, the scala tympani cross-sections were placed along the spiral of the scala tympani with corresponding cochlear length (distance from the round window) and lofted through by a surrounding surface. Geometry and dimensions of the physical scala tympani were exported from SOLIDWORKS as an Initial Graphics Exchange Specifications (IGES) file and then imported into FEMAP, a pre-processing software for NE/NASTRAN (FE package).

Each of the 3D FE models of the Nucleus standard straight and the Contour arrays was constructed using 900 triangular and rectangular elements. Each electrode array is 20 mm in length. The Nucleus standard straight array tapers from 0.7 mm at the rear section to 0.45 mm at the tip, while the Contour array also tapers but has larger diameters (from 0.8 to 0.5 mm, Kha et al., 2004). Patrick and MacFarlane (1987) undertook pioneering work to determine the stiffness of the Nucleus standard straight array. Subsequent studies by Kha et al. (2004) were performed to determine the lengthwise variation in the stiffness properties of both the Nucleus standard straight array and the Contour array. Young's modulus of elasticity of the Nucleus standard straight array increased from 182 MPa at the apical section to 491 MPa at the basal section while that of