Finite element modelling of insertion of electrode array into the cochlear scala tympani with lubricant

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Abstract

The cochlear implants consisting of electrode arrays for electrically stimulating the auditory nerve fibres have been developed to restore hearing for profoundly deaf people. The insertion of a straight electrode array into the spiral cochlear scala tympani has unfortunately been found to damage delicate structures within the inner ear such as the spiral ligament and the basilar membrane. Although a number of studies suggested the use of lubricant for 'smooth' insertion, little attempt has been made to quantitatively study the effect of lubricant on the damage by the electrode array to the cochlear structures. In this study, a mathematical model using the finite element method was developed to predict the trajectories of the Nucleus standard straight electrode array during insertion into the scala tympani and associated contact stresses exerted by the array on the cochlear structures. Results from the model have shown that the use of a lubricant such as glycerine reduces the contact stresses exerted by the tip of the array on the spiral ligament from 0.31 to 0.2 MPa, whereas the contact stresses on the basilar membrane reduce from 0.075 MPa (without lubricant) to 0.025 MPa (with lubricant). The results suggest that the use of a lubricant is clinically important for minimising the likelihood of damage by the electrode array to the cochlear structures.

Keywords: contact stresses, finite element, spiral ligament, basilar membrane, scala tympani.

Introduction

Although the cochlear implants were successfully developed to restore near-to-normal hearing for deaf people, the implantation has been found to damage the delicate cochlear structures. In each implant system, a microphone (located above the external ear) picks up sound which is sent to a microprocessor and then converted to electrical currents travelling through a straight electrode array (consisting of platinum wires embedded in Silastic matrix) inserted into the scala tympani (the lower tubular space of the cochlea). The currents stimulate the auditory nerve fibres within the cochlea (Clark, 2003). As the cochlea has a spiral shape, the electrode array largely bends and slides against the outer wall of the scala tympani during insertion, which has a great potential for damaging cochlear structures (Fig. 1). Results from previous experimental studies, in which electrode arrays were inserted into cochleae harvested from temporal bones, have shown that the electrode arrays usually tore the spiral ligament located along the outer wall and eventually pierced the basilar membrane at the upper surface of the scala tympani (Shepherd et al., 1985; Tykocinski et al., 2001; Wardrop et al., 2005).

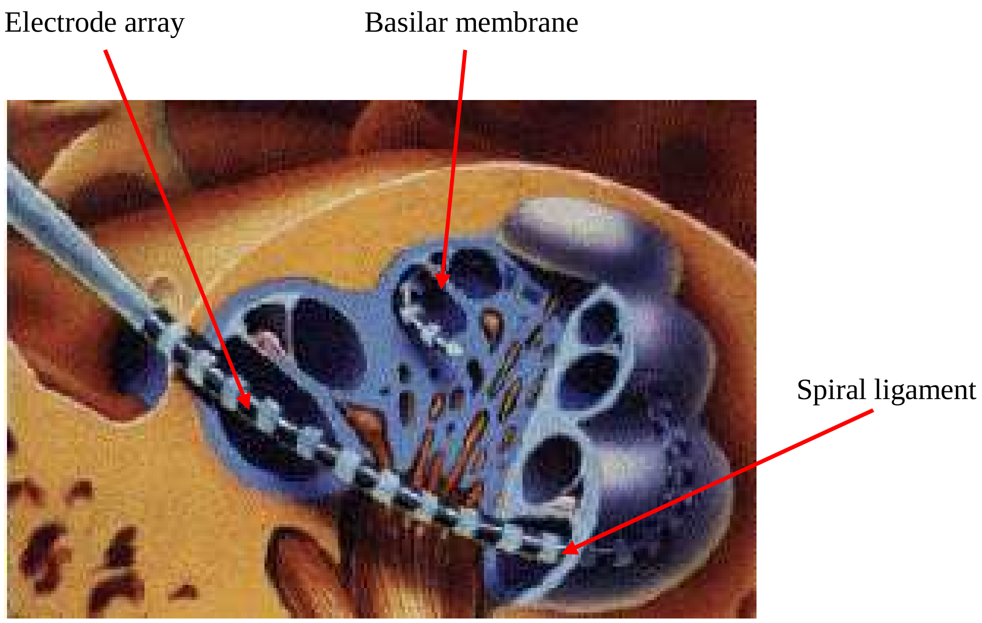


Figure 1. Insertion of an electrode array into the cochlear scala tympani (Chen et al., 2003).

A number of studies have suggested the use of lubricants for reducing the damage by the electrode array to the cochlear structures. Biocompatible lubricants such as glycerine and hyaluronic acid (Healon) are often used to coat the electrode array with a thin layer to reduce friction between the array and the endosteum lining covering the interior walls of the scala tympani (Lehnhardt, 1993; Roland et al., 1995; Tykocinski et al., 2001; Laszig et al., 2002; Clark, 2003; Wardrop et al., 2005). The electrode arrays in these experiments were reported to be ‘smoothly’ inserted into the scala tympani; however, there has not been any attempt to quantitatively study how the use of these lubricants could reduce the damage to the spiral ligament and the basilar membrane.

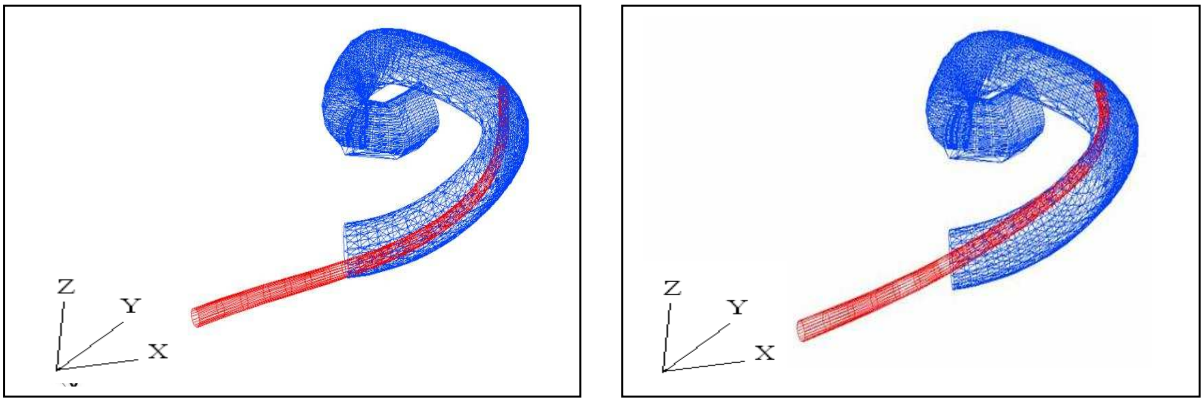
In this study, a mathematical model using the finite element method was developed to predict the contact stresses exerted by the electrode array on the outer wall and the upper surface of the scala tympani during insertion into the cochlea. The model was used for studying the effect of lubricants such as glycerine on the reduction of damage by the tip of the electrode array to the spiral ligament and the basilar membrane.

Methods

A finite element model was developed to simulate the insertion of the electrode array into the scala tympani. The scala tympani model was constructed using the polar coordinates of the cochlear pathway (Cohen et al., 1996) and the cochlear gradient of 15^0 (Chen, Clark and Jones, 2003). The electrode array model was created using dimensions of the prototypes provided by the manufacturer. The array was 20 mm in length and tapered from 0.7 mm at the rear section to 0.45 mm at the tip. 1993 elements were used for meshing the scala tympani and the electrode array. The Young’s modulus of elasticity of the array, which increased from 180 MPa at the rear section to 490 MPa at the front section (Kha et al., 2004), was incorporated into the model. Surface-to-surface contact algorithm was employed to model the sliding of the electrode array (‘slave’ surface) against the scala tympani (‘master’ surface), in which the friction coefficient of 0.19 was used for the case of no lubricant and as glycerine was used as a lubricant, the coefficient of 0.12 (Kha et al., 2006) was incorporated into the model. Enforced displacements were prescribed at nodes of the basal end of the electrode array, whereas the nodes on the scala tympani were fixed. The finite element code NE/Nastran (Noran Engineering) was used for implementing the non-linear static analysis (the Newton-Raphson method) with more than 100 increments and 30 iterations to ensure convergence for each linear step.

Results and discussion

Figure 2 shows bending behaviour of the electrode array during insertion into the scala tympani. The electrode array without lubricated glycerine (Fig. 2a) was found to experience significantly less bending at the front section (due to more friction between the tip of the array and the endosteum lining), compared to that with the use of lubricant (Fig. 2b). The result is consistent with observations from the previous experimental studies in which the electrode array appeared to be more 'smoothly' inserted into the scala tympani and experience less resistance, compared with that without a lubricant (Shepherd et al., 1985; Lehnhardt, 1993; Roland et al., 1995; Laszig et al., 2002).



(a) (b)

Fig. 2. Predicted bending behaviour of the electrode array: (a) without lubricant and (b) with lubricant.

The finite element model was used to predict contact stresses exerted by the tip of the electrode array on the outer wall of the scala tympani which were indicative of the damage to the spiral ligament (Fig. 3). The stresses in the non-lubricated condition were ~0.1 and ~0.31 MPa when the tip was at 9-10 mm and 12-13 mm from the round window (the entry for insertion into the scala tympani), respectively. These stresses were higher than those exerted by the tip of the array on the outer wall in the lubricated insertion (~0.07 and ~0.2 MPa, respectively). Without lubrication, the tip of the electrode array exerted relatively high contact stresses (up to ~0.17 MPa) on the outer wall beyond 13 mm from the round window compared to those in the lubricated insertion (up to ~0.07 MPa). Therefore, there is a greater risk of damaging the spiral ligament without the use of lubricant.

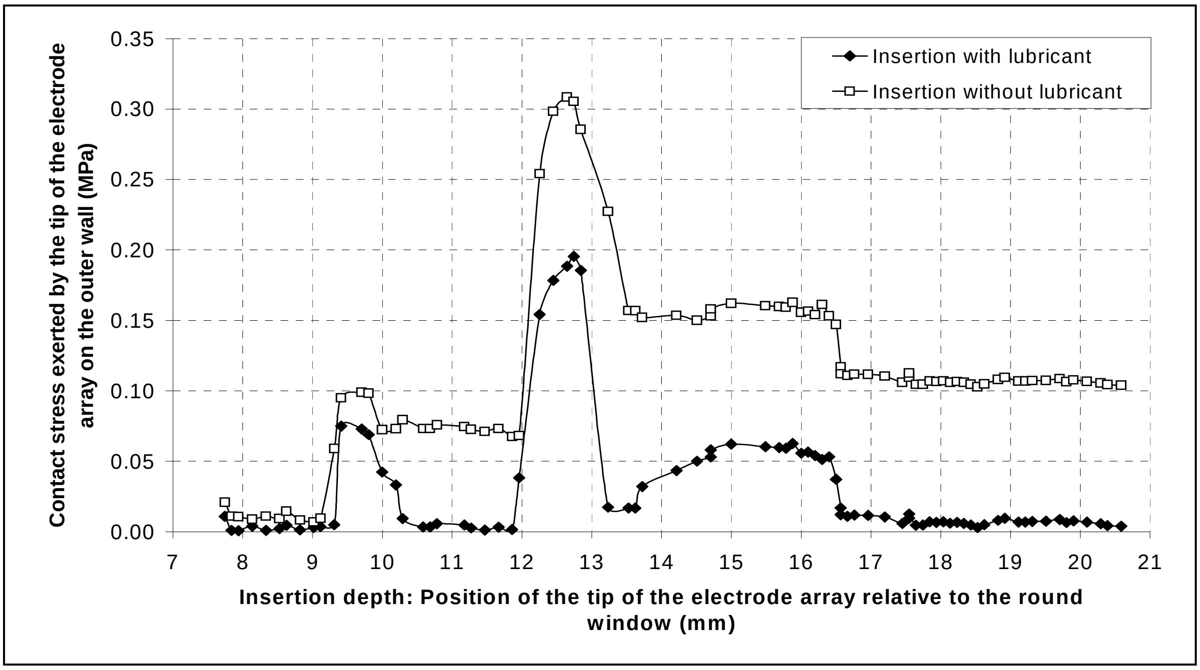


Fig. 3. Contact stresses exerted by the tip of the electrode array on the outer wall of the scala tympani in the lubricated and the non-lubricated insertions.

The model was also used for predicting the effect of a lubricant on the damage by the electrode array to the basilar membrane (Fig. 4). The contact stresses exerted the tip of the array on the upper wall of the scala tympani were relatively high (~0.05-0.075 MPa) without lubrication, compared to those with lubrication (~0.02-0.04 MPa). The basilar membrane is thus more likely to be damaged by the electrode array in a non-lubricated condition.

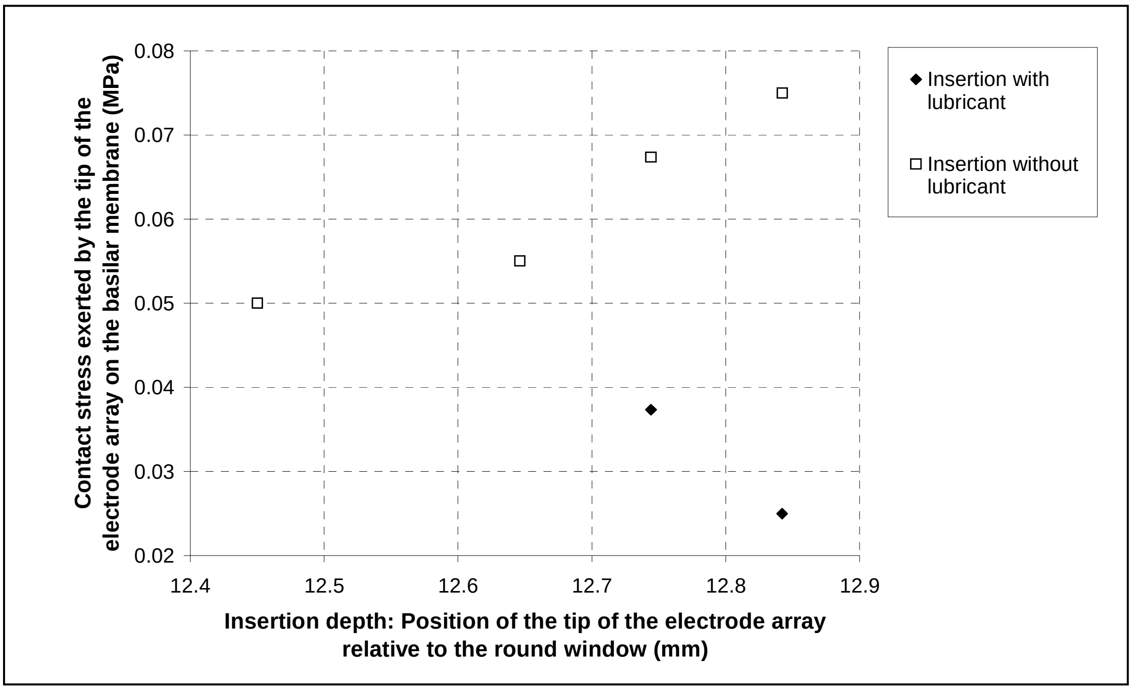


Fig. 4. The contact stresses exerted by the tip of the electrode array on the basilar membrane in the non-lubricated and the lubricated insertions.

Conclusions

In this study, a mathematical model of insertion of electrode array into the human cochlear scala tympani using the finite element method has been developed to study the effect of lubricant on the damage by the array to the spiral ligament and the basilar membrane. The use of glycerine has been found to significantly reduce the contact stresses exerted by the tip of the array on these cochlear structures. The results have quantitatively confirmed the importance of using lubricant for reducing damage by the electrode array to the cochlea.

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