

Finite element modeling of final placement and insertion depth of new cochlear implant electrode array embedded with nitinol shape memory alloy actuators

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Abstract

A new electrode array embedded with nitinol shape memory alloy actuator has been designed so that it can be located beneath the basilar membrane inside the cochlear scala tympani to effectively deliver neurotrophins (growth factors) into the cochlea. The electrode array is also expected to be inserted deeper into the cochlear middle turn to stimulate further auditory neurons compared to the Nucleus standard straight array. A finite element model has been developed to design and evaluate the new electrode array. Results from the model have shown that the new electrode array can be accurately positioned close to the desired final position.

Keywords: electrode array, finite element (FE), final placement, insertion depth, cochlear angle (θ).

1. Introduction

Cochlear implant has been invented to restore near-normal hearing to people suffering sensorineural deafness. A cochlear implant system involves an electrode array inserted into the scala tympani (the lower tubular space of the cochlea) to transmit electrical signals converted from external sound. The signals can stimulate the auditory neurons connected to the inner ear (cochlea) which provides hearing to the patients. The electrode array is also expected to be able to deliver neurotrophins (growth factors) into the scala tympani to regenerate the progressively lost auditory neurons caused by sensorineural deafness [1] and damage to the basilar membrane resulted from insertion of the array [2]. It is desirable to locate the electrode array close to 'central' position which is beneath the basilar

membrane inside the scala tympani (Fig. 1 – Position A) so that the neurotrophins delivered to the neurons close to the this cochlear structure are not wasted [3]. The electrode array is also expected to be inserted more deeply into the middle turn of the cochlea to stimulate further auditory nerve fibers [3].

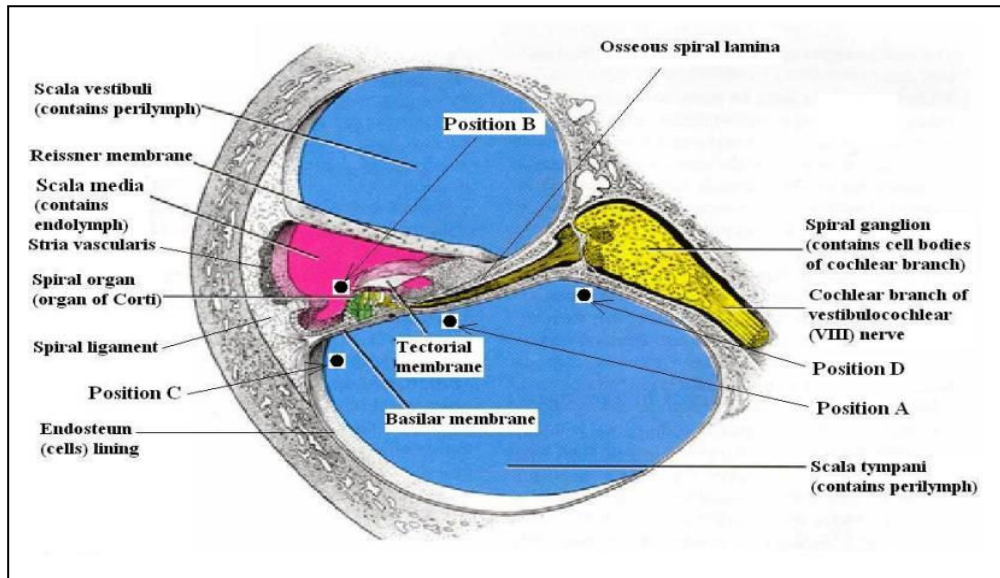


Fig. 1. Anatomy of the cross-section of cochlear pathways [4].

An electrode array embedded with a 6mm nitinol shape memory alloy actuator has been designed. The actuator was developed and has been proved to be biocompatible by Mineta et al. (2002) [5]. It has a ‘memorized’ pre-curved shape which can be straightened at room temperature. The ‘straight’ actuator is embedded close to the front end (2-8mm from the tip) of the Nucleus standard straight array (Fig. 2). Two ends of the actuators are connected with two platinum lead wires which extend to the rear end of the array. Heating up the actuator from room temperature to 37°C by using a small current generated by a battery connected to the lead wires at the rear end allows it to return to the ‘memorized’ shape which bends the electrode array to locate the front section at the desirable ‘central’ position.

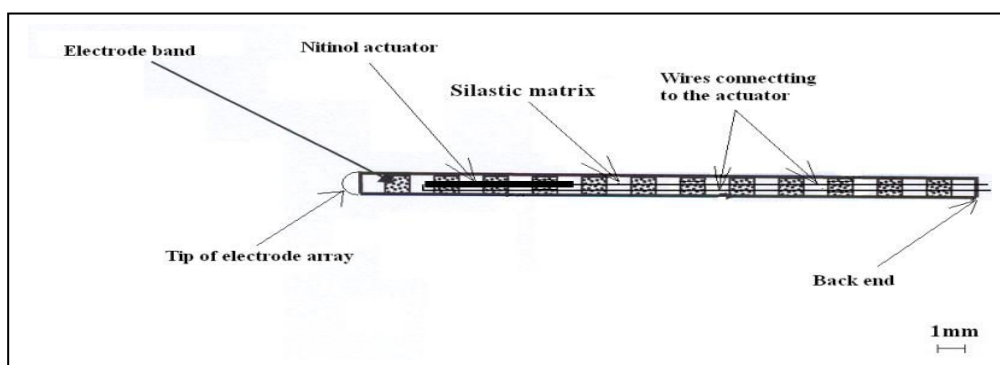


Fig. 2. Illustration of the electrode array embedded with a nitinol actuator and wires along the length.

It is difficult to use previous experimental models to study final placement and insertion depth of the new electrode array. The human temporal bone models [6,7] have low reproducibility and the silicone rubber scala tympani model [8] does not accurately represent material properties of the scala tympani. Further, the experimental methods [6-8] are labour-intensive, time consuming and costly.

This paper describes the use of finite element (FE) method to predict bending behaviour of the new electrode array embedded with nitinol actuators. The final position of the new electrode array is compared with those of existing arrays (the Nucleus standard straight and the Contour arrays) established in the literature. The design involves evaluation of a number of actuators along the length of the electrode array and their influence on final placement and insertion depth.

2. Methods

FE method was employed to predict bending behaviour and final position of the electrode array embedded with a nitinol actuator at 5mm from the tip (Fig. 2). The modeling was divided into two parts: (1) insertion of the electrode array into the scala tympani and (2) bending of the array activated by that of the nitinol actuator. In the first part of the model, displacement of 25mm and constrained rotation were applied at the back end of the electrode array while the scala tympani was fixed. Stiffness of the non-embedded segments was similar to that reported by Kha et al. (2004) [9] for the Nucleus standard straight array while that at the embedded segment was calculated using rule of mixture. The friction coefficient between the electrode array and the endosteum lining covering the interior wall of the scala tympani was similar to that reported by Kha and Chen (2005a) [10] for the Nucleus standard straight array. In the second part, force exerted by the actuator (due to its bending to the ‘memorized’ pre-curved shape) on the electrode array is calculated using Equation 1. Deflection (δ) of the segment of electrode array embedded with a nitinol bending actuator can be determined using Equation 2 [11]. Preprocessing of the model (construction of geometry, definition of mechanical properties and frictional conditions, boundary conditions and constraints) was undertaken using FEMAP. Non-linear static analysis was implemented using NE/NASTRAN 8.32 to solve for displacement/final placement of the electrode array (Equation 3). The solution methodology and algorithms are well established and have been described in detail [12]. Many increments (more than 100) and a large number of iterations (30) were used to ensure the convergence of each linear step (with convergence criteria for out-of-balance force of between 0.005-0.01). To ensure convergence in each incremental load step, stiffness scaling factor was chosen between 0.01 and 0.05.

$$F = \frac{3E_N I_N \delta_N}{L_N^3} \quad (1)$$

where

Young’s modulus of elasticity of the nitinol actuator: $E_N = 28\text{GPa}$ (martensite phase)

Moment of inertia of the nitinol actuator:

$$I_N = \frac{tw^3}{12} = \frac{0.035 \times 0.1^3}{12} = 2.92 \times 10^{-6} (\text{mm}^4) \text{ (t is thickness and w is width of}$$

the actuator)

Deflection of actuator: $\delta_N = 2.18\text{mm}$ [5]

Length of the actuator or embedded segment: $L_N = 6\text{mm}$

$$\delta = \frac{FL_N^3}{3E_{EA} I} \quad (2)$$

where

E_{EA} = average value of Young’s modulus of elasticity of the electrode array segment before embedment (MPa) [9].

I = moment of inertia of the embedded segment = $\pi d^4/64$ (mm^4); (d = diameter of the embedded segment = 0.45-0.7mm).

$$[K]\{\Delta D\} = \{\Delta R\} \quad (3)$$

where

K = global tangent stiffness matrix
 ΔD = global incremental displacement vector
 ΔR = global incremental load vector

The above procedures were repeated for other two electrode array models (one embedded with two actuators at 5 and 10mm from the tip and another embedded with three actuators at 5, 10 and 15mm from the tip) to study the effect of varying position and number of actuators on final placement of the array.

3. Results and discussion

Figures 3b-d shows positions of the three electrode array models after heating up the nitinol bending actuators. The electrode arrays were inserted up to $\theta = 315^\circ$ (Fig. 3a) which was similar to the final position of the Nucleus standard straight array reported by Chen, Clark and Jones (2003) [13]. At final placement, the front ends of the electrode arrays embedded with nitinol actuators were closer to the 'central' position of the scala tympani (Figs. 3b-d) compared to that of the Nucleus standard straight array (at the outer wall, similarly to the position in Fig. 3a). Final positions of these arrays were also more stable than that of the Contour array which was found to have significantly large variation [7, 14]. The new electrode arrays were also located slightly deeper into the middle turn of the cochlea (Figs. 3b-d) compared to the Nucleus standard straight array (Fig. 3a).

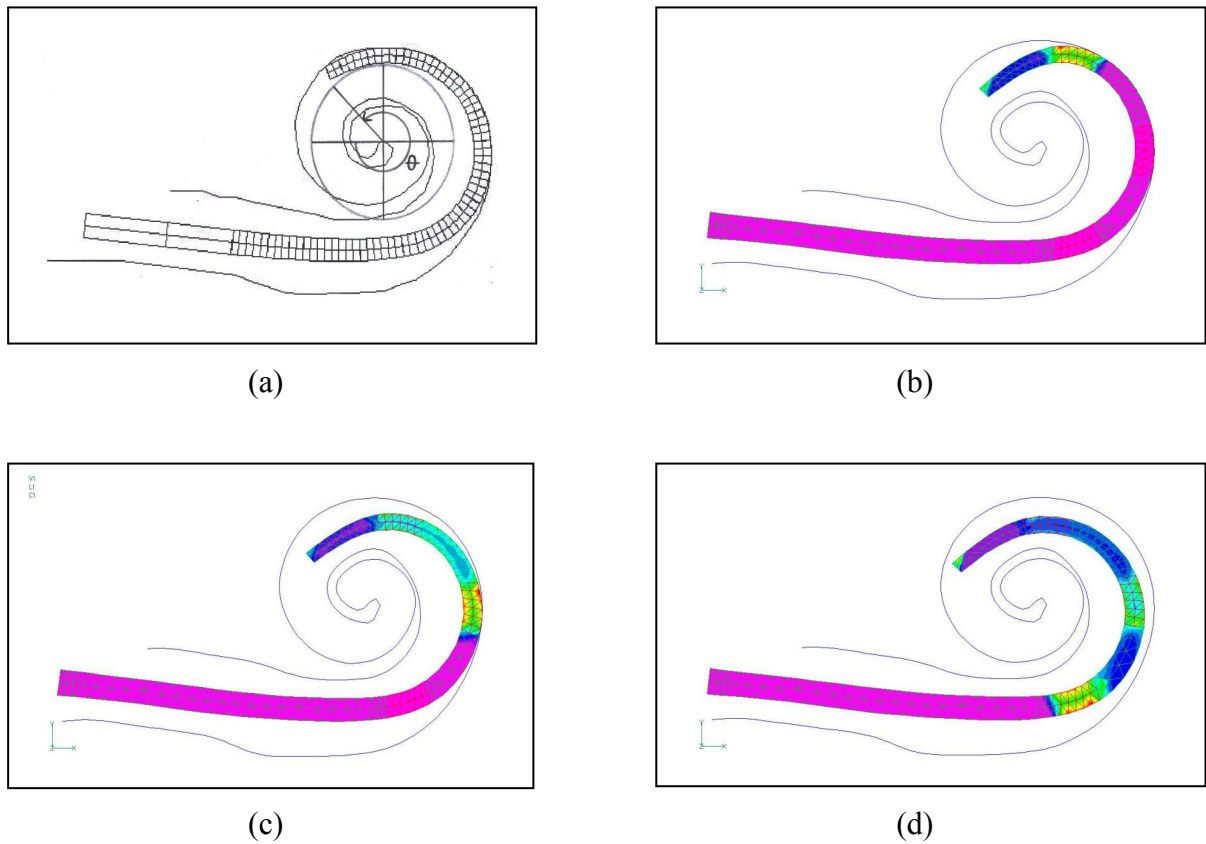


Fig. 3. Final placement of the electrode arrays (with variation in number of embedded actuators): (a) Before heating up the actuators, (b-d) Electrode arrays with one, two and three actuators, respectively (after heating).

The number of embedded actuators significantly influenced final position of the electrode array. The electrode array embedded with two actuators at 2-8 and 8-14mm from the tip has more bending at the front and the middle section. It is located more deeply into the middle turn (Fig. 3c) compared to that embedded with one actuator at the front section (Fig. 3b). Sections along the length of the electrode array embedded with three actuators at 2-8, 8-14 and 14-20mm from the tip (Fig. 3d) were also found to be located closest to the central position, compared to the other two arrays (Figs. 3b and 3c). The tip of the electrode array embedded with three actuators was also located most deeply inside the scala tympani (Fig. 3d) compared to the other two arrays (Figs. 3b and 3c).

4. Conclusions

In this study, a FE model has been constructed to predict final placement and insertion depth of the electrode array embedded with nitinol shape memory alloy actuator. Actuators have been used to locate the array closer to the 'central' position for delivery of neurotrophins into the cochlea compared to the Nucleus standard straight array.

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References

- [1] Richardson, R. T., Wise, A., O'Leary, S., Hardman, J., Casley, D. and Clark, G. M. (2004). "Tracing neurotrophin-3 diffusion and uptake in the guinea pig cochlea". *Hearing Research*, 198, 25-35.
- [2] Malgrange, B., Rigo, J.-M., Thomas, R., Van, d. W., Staecker, H., Moonen, G. and Lefebvre, P. (1999). "Growth factor therapy to the damaged inner ear: clinical prospects". *International Journal of Pediatric Otorhinolaryngology*, 49, 19-25.
- [3] Clark, G. M. and Wallace, G. (2004). "Bionic ears: their development and future advances using neurotrophins and inherently conducting polymers". *Applied Bionics and Biomechanics*, 1, 67-89.
- [4] Tortora, G. J. and Grabowski, R. S. (1993) "Principles of Anatomy and Physiology", 8th. Boston: Addison Wesley Longman, Inc.
- [5] Mineta, T., Mitsui, T., Watanabe, Y., Kobayashi, S., Haga, Y. and Esashi, M. (2002). "An active guide wire with shape memory alloy bending actuator fabricated by room temperature process". *Sensors and Actuators A*, 97-98, 632-637.
- [6] Shepherd, R. K., Clark, G. M., Pyman, B. C. and Webb, R. L. (1985). "Banded intracochlear electrode array: Evaluation of insertion trauma in human temporal bones". *Annals of Otolology, Rhinology & Laryngology*, 94, 55-59.
- [7] Tykocinski, M., Saunders, E., Cohen, L. T., Treaba, C., Briggs, R. J., Gibson, P., Clark, G. M. and Cowan, R. S. (2001). "The Contour electrode array: safety study and initial patient trials of a new perimodiolar design". *Otology Neurotology*, 22, 33-41.
- [8] Rebscher, S. J., Talbot, N., Bruszewski, W., Heilmann, M., Brasell, J. and Merzenich, M. M. (1996). "A transparent model of the human scala tympani cavity". *Neuroscience Methods*, 64, 105-114.

- [9] Kha, H. N., Chen, B. K., Clark, G. M. and Jones, R. (2004). "Stiffness properties for Nucleus standard straight and Contour electrode arrays". *Medical Engineering and Physics*, 26, 677-685.
- [10] Kha, H. N. and Chen, B. K. (2005a). "Determination of frictional conditions between electrode array and endosteum lining for use in cochlear implant models". *In press, Journal of Biomechanics*.
- [11] Gere, J. M. and Timoshenko, S. P. (1997) "Mechanics of Materials", Washington D. C.: International Thomson Publishing, PWS Publishing Company.
- [12] Noran Engineering Inc. (2002). "NE/Nastran Version 8.2 User's Manual".
- [13] Chen, B. K., Clark, G. M. and Jones, R. (2003). "Evaluation of trajectories and contact pressures for the straight nucleus cochlear implant electrode array - a two-dimensional application of finite element analysis". *Medical Engineering and Physics*, 25, 141-147.
- [14] Kha, H. N. and Chen, B. K. (2005b). "Prediction of curling behaviour and final placement of the Contour electrode array within the human cochlea using finite element analysis". In: Valafar, F., Valafar, H. and Arabnia, H. R. (Eds.), International Conference on Mathematics and Engineering Techniques in Medicine and Biological Sciences (METMBS'05), June 20-23, CSREA Press, 212-218.