FINITE-ELEMENT MODELLING OF THE NORMAL AND SURGICALLY REPAIRED CAT MIDDLE EAR

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INTRODUCTION

Discontinuity of the middle-ear ossicular chain results in conductive hearing loss. The most common type of ossicular discontinuity is caused by loss of the incudal long process; the second most common type is caused by loss of both the incudal long process and the stapes superstructure[1]. When the incudal long process alone is missing, a prosthesis (e.g., ossicular bone graft) can be fitted between the manubrium of the malleus and the head of the stapes; the resulting structure is called a malleus-stapes assembly (MSA). When both the incudal long process and the stapes superstructure are missing, a prosthesis can be fitted between the manubrium and the stapedial footplate; this structure is called a malleus-footplate assembly (MFA). The MSA and the MFA do not result in the complete elimination of hearing loss[7]. A quantitative understanding of the mechanics of the normal and surgically repaired middle ear should elucidate some of the reasons for this failure and would aid in the design of middle-ear prostheses.

This paper presents a finite-element model of the normal cat middle ear. The model was modified to investigate the effects of middle-ear surgery. The models are limited to low frequencies and sound pressure levels.

I. FINITE-ELEMENT MODELS

A. Normal Middle-Ear Model

Fig. 1 shows the normal middle-ear model which was developed by adding explicit representations of the stapedial footplate and cochlear load to an existing model of the cat eardrum[2]. The footplate is modelled as a thin plate with a thickened rim. Rigid plate elements are used to model the stapedial crura. The cochlear load acting upon the footplate is represented by in-plane and out-of-plane springs distributed around the periphery of the footplate. The malleus and incus are modelled as being effectively rigid with a fixed axis of rotation. The incudostapedial and incudomalleal joints are assumed to be rigid.

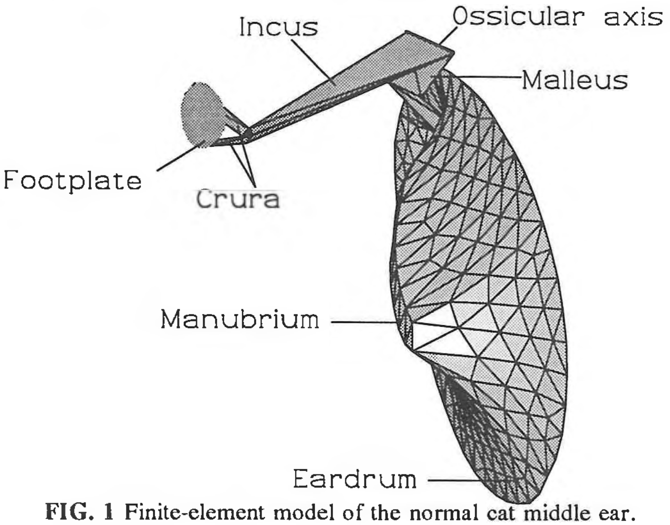


FIG. 1 Finite-element model of the normal cat middle ear.

B. MSA Model

It is assumed that the existing middle-ear structures being modelled have not been damaged by middle-ear disease or by the surgical procedure. Thus, the MSA model is identical to the normal middle-ear model except that the elements corresponding to the incus are replaced by a single brick element representing the prosthesis (shown in Fig. 2a).

C. MFA Model

As shown in Fig. 2b, the MFA model differs from the MSA model in that the crura are removed and the prosthesis makes direct contact with the footplate.

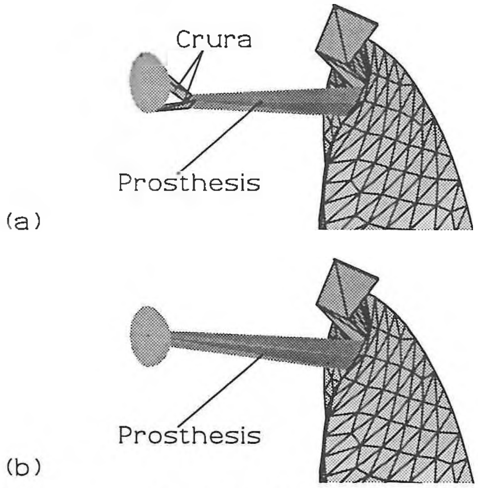


FIG. 2 Top portions of models of the surgically repaired cat middle ear. (a) MSA and (b) MFA.

II. RESULTS

A. Results for the Normal Middle-Ear Model

Displacement contours calculated for the eardrum in the normal middle-ear model are qualitatively similar to the low-frequency contours observed experimentally by Khanna[4]. The maximal displacement on the eardrum is 484 nm at 100 dB SPL and occurs in the posterior region of the pars tensa. Extrapolating the data of Tonndorf and Khanna[5] to 100 dB SPL gives a maximal drum displacement of 420 nm.

The umbo displacement calculated using the present model is 161 nm. The data of Tonndorf and Khanna[5] give an umbo displacement of 191 nm.

The out-of-plane component of footplate displacement at its centre provides an estimate of the volume displacement of the cochlear fluids. For the present model, the out-of-plane component has an amplitude of 93 nm. Guinan and Peake[3] measured the displacement of the footplate in anesthetized cats to be 85 nm which agrees well with the model.

B. Comparison of Normal, MSA and MFA Models

Fig. 3 shows the maximum eardrum displacement, the umbo displacement and the out-of-plane component of footplate displacement for the normal middle-ear, MSA and MFA models. The displacements for the normal middle-ear model and the MSA model with an intact ossicular axis are virtually identical. The displacement amplitudes for the MFA model with an intact ossicular axis are slightly larger than those of the normal middle-ear model; however, whereas the footplate in those models behaves as a rigid-body, that in the MFA model bulges as shown in Fig. 4. The displacement amplitudes of the MSA and MFA models increase when the ossicular axis is removed.

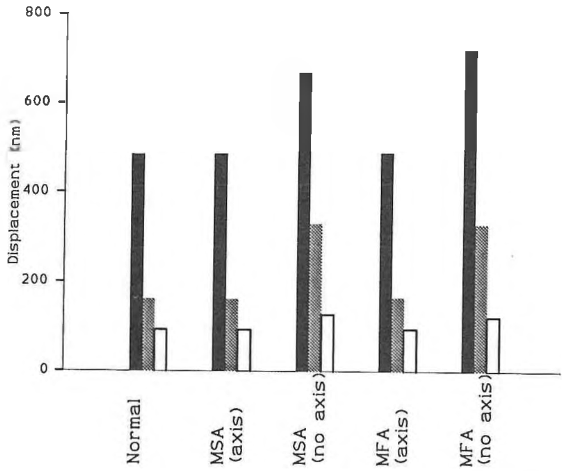
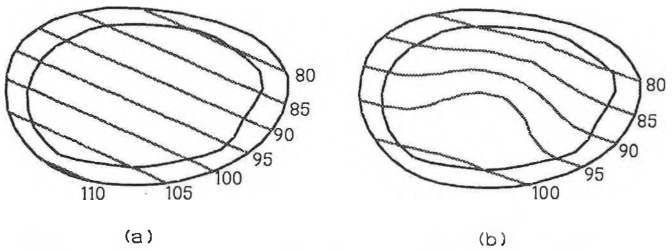


FIG. 3 Maximum eardrum (black), umbo (gray) and footplate (white) displacement amplitudes for the normal middle-ear, MSA and MFA models.



(a) (b)

FIG. 4 Contours for the out-of-plane component of footplate displacement for (a) normal middle-ear model and (b) MFA model. All displacements are in nanometres (nm).

C. Parameter Variations

Displacements of the footplate in the MFA model are very sensitive to the stiffness and thickness of the footplate and to the stiffness of the annular ligament. They are not sensitive to the Poisson's ratio of the footplate.

D. Prosthesis Location

In the MSA and in the MFA, it is possible to position the prosthesis at various locations along the manubrium. (In the above simulations, the prosthesis was placed at the upper end of the manubrium.) Moving the prosthesis down the manubrium does not significantly alter the mechanical behaviour of the footplate; this result is consistent with the experimental results of Tonndorf and Pastaci[6]. This behaviour is expected since the ossicular joints in the model are rigid causing the manubrium, prosthesis and footplate to act as a single rigid body.

If the joints between the prosthesis and the bones are made flexible, the footplate's mechanical behaviour will be affected by prosthesis location. For example, consider an extreme case where pin joints are assumed, but the prosthesis is still rigid; this situation can be modelled using a truss element for the prosthesis. Fig. 5 shows the out-of-plane component of footplate displacement at its centre for the MFA model without an ossicular axis as the truss element is positioned at various locations along the manubrium; also shown are results for inflexible joints (i.e., using a brick element). When the joints are flexible, the largest footplate displacements are obtained when the prosthesis is located close to the upper end of the manubrium.

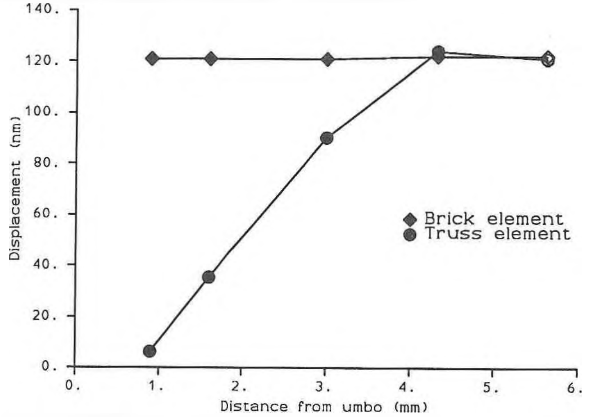


FIG. 5 Effect of prosthesis location (along the manubrium) on out-of-plane component of footplate displacement, in MFA model without ossicular axis.

III. CONCLUSIONS

The normal component of footplate displacement is virtually identical in the normal middle-ear model and the MSA model with an intact ossicular axis. For the MFA model, the mode of vibration of the footplate is somewhat different from that of the normal middle-ear model: direct contact between the prosthesis and the footplate results in bulging of the footplate.

In both the MSA and the MFA models, the position of the prosthesis along the manubrium does not affect the mode of vibration of the footplate as long as the joints between the prosthesis and the bones are rigid. When the joints are completely flexible, the largest footplate displacements occur when the prosthesis is closest to the upper end of the manubrium. More work is needed to characterize the rigidity of the joints.

REFERENCES

1. Austin, D.F. **(1971)**. "Ossicular reconstruction," *Arch. Otolaryngol.* **94**, 525-535.
2. Funnell, W.R.J, Decraemer, W.F., and Khanna, S.M. **(1987)**. "On the damped frequency response of a finite-element model of the cat eardrum," *J. Acoust. Soc. Am.* **81**, 1851-1859.
3. Guinan, J.J., Jr., and Peake, W.T. **(1967)**. "Middle-ear characteristics of anesthetized cats," *J. Acoust. Soc. Am.* **41**, 1237-1261.
4. Khanna, S.M. **(1970)**. *A Holographic Study of Tympanic Membrane Vibrations in Cats* (Ph.D. thesis, City University of New York, New York).
5. Tonndorf, J., and Khanna, S.M. **(1972)**. "The tympanic membrane as a part of the middle ear transformer," *Acta Otolaryng.* **71**, 177-180.
6. Tonndorf, J., and Pastaci, H. **(1986)**. "Middle ear sound transmission: A field of early interest to Merle Lawrence," *Am. J. Otolaryngol.* **7**, 120-129.
7. Vartiainen, E., and Nuutinin, J. **(1992)**. "Long-term hearing results of one-stage tympanoplasty for chronic otitis media," *Eur. Arch. Otorhinolaryngol.* **249**, 329-331.