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Finite Element Model of the Stapes-Inner Ear Interface

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Abstract

Since 1958, stapedotomy has been the method of choice for middle ear surgeons who operate on patients suffering from otosclerosis, especially stiffening of the interface between the stapes footplate of the middle ear and the oval window, which is a part of the cochlea of the inner ear. Later, many surgeons started to use the Schuknecht prosthesis, which consists of cartilage and is inserted into the complete opened oval window during stapedectomy. Our study shows that basilar membrane (BM) displacement is increased with an increasing stapes footplate area by a numerical simulation including the different geometries. An increase in the footplate area leads to an increase in BM displacement equivalent to 13 dB. Therefore, we recommend prostheses with areas as big as the normal stapes footplate area.

In the year 1958, a new surgical technique for the middle ear, i.e. stapedotomy, was introduced [1]. It was suggested to be used in patients who suffer from otosclerosis, which is a disease impeding the normally most efficient movement of the structures of the healthy ear. It is caused by fixation of formerly movable elastic or hinged connections of middle and inner ear structures. During the following years up to now, the surgeons who used stapedotomy developed a surgical procedure where a small hole is drilled into the stapes footplate and a small piston (0.6 mm in diameter) is placed into the hole. Although clinical studies show improvements of hearing results with pistons of a larger diameter (0.6 mm compared to 0.4 mm [2, 3]), ear surgeons prefer small prostheses either for practical reasons or because they are used to them (fig. 1).

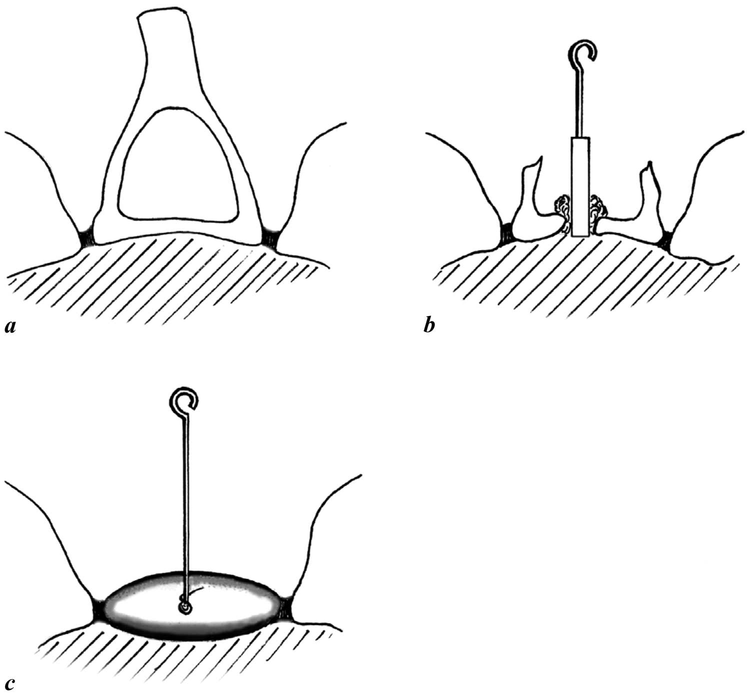

Fig. 1. ***a*** Normal. ***b*** Stapedotomy. ***c*** Stapedectomy.

Methods

To study the differences between a small piston and a prosthesis with an area similar to the area of a normal stapes footplate (3.6 mm^2), an existing finite element model of the cochlea was used and enlarged (fig. 2).

At first, an external pressure of 1 Pa [94 dB (SPL)] was applied to the small piston area of only 0.28 mm^2. Then, the same pressure was also applied to the large footplate area of 3.6 mm^2, as it was done in one of our former studies [4]. However, because this configuration is not realistic, neither for the healthy ear nor for any case of middle ear reconstruction, the loading (1 Pa) was applied to a newly suggested stapes prosthesis shown in figure 3.

In this case, the external pressure (1 Pa) was applied to the small area (0.28 mm^2) on top of the prosthesis, as it would be connected to the long process of the incus of the middle ear. At first, only one harmonic signal of frequency (f = 2,500 Hz) was used. Former studies had shown the maximum increase in basilar membrane (BM) displacement and therefore maximum improvement of hearing for this frequency.

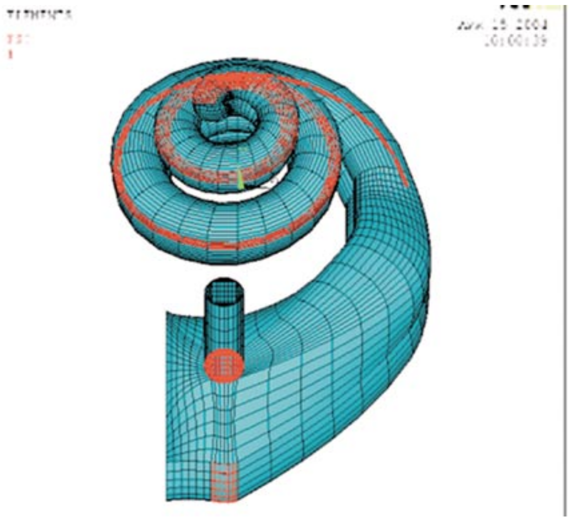

Fig. 2. Finite element model of the human cochlea with a small-area piston prosthesis.

Results

Figure 4 shows the BM displacement in the case of a small piston area such as that shown in figure 1. The maximum displacement occurs at approximately 12 mm from the base of the cochlea and reaches a (very small) maximum value of only 7.15 pm.

Figure 5 shows the BM displacement in the case of a large-area prosthesis such as that in figure 3. The maximum BM displacement increases to 0.0328 nm, which is equivalent to a gain of 13 dB compared to the small piston case. Another interesting fact is the basal shift of the maximum BM displacement in the cochlea (approx. 1 mm). We point out that the cochlear model is linear and basal shift has formerly been found in experiments with increased excitation levels at the eardrum.

Discussion

Our study shows the dependence of the BM displacement on the area of the stapes footplate by modelling the cochlea and numerical evaluation. At first, the examination was limited to one frequency (f = 2,500 Hz). The consequence of our results is the recommendation of stapes footplate prostheses which are as similar to the normal stapes footplate as possible. Of course, there are practical limitations to this, i.e. the prosthesis might be tilted during the insertion, and its unavoidable removal would cause a severe acoustic trauma to the patient.

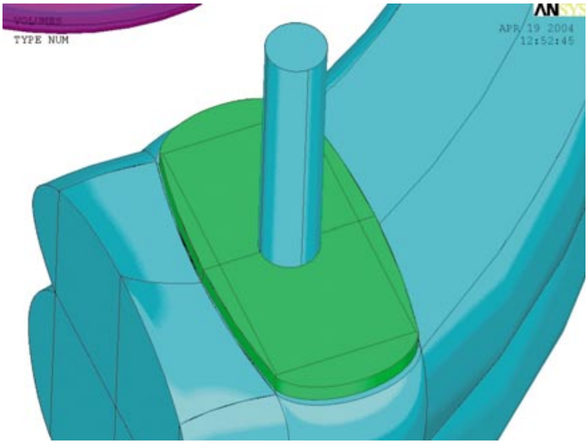

Fig. 3. Stapes prosthesis with a large footplate area.

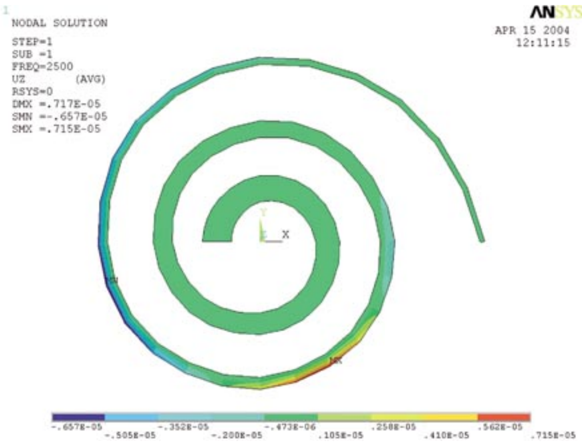

Fig. 4. BM displacement with a small-area (0.28 mm^2) piston.

An interesting result is the basal shift of the maximum BM displacement with increasing footplate area. Therefore, an enlargement of the stapes footplate is equivalent to an increase in the excitation level applied at the tympanic membrane, because this also leads to a basal shift of the maximum BM displacement. This was proven by direct measurements of BM displacement with the Mössbauer technique [6]. Another possibility to verify this result is by psychoacoustic examinations. These should not only verify the decrease in the pure-tone threshold level with increasing footplate areas, but might additionally show differing sensation of tone heights with varying size of the prostheses.

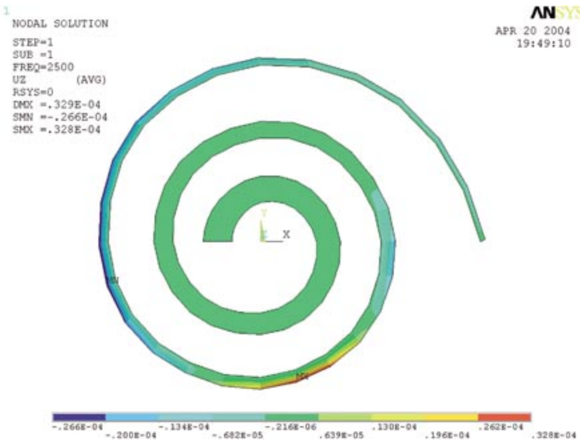

Fig. 5. BM displacement with a large-area (3.6 mm²) piston.

Further studies should include all parts of the middle ear, which were omitted in this study for simplification. These are the tympanic membrane, the three ossicles (malleus, incus, stapes), the three tendons of the malleus, the two tendons of the incus and two middle ear muscles (musculus tensor tympani and musculus stapedius). Of course, these studies should include the whole frequency spectrum of hearing and the nonlinear properties of the signal transmission of the middle ear.

References

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