“Biomechanics of ossiculoplasty”

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Biographies

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Abstract

Many different designs of prostheses are available for middle ear surgery. Clinical comparisons of such prostheses are often difficult because of the large number of variables involved in the clinical outcome; including the skill of the surgeon or patient variability. In an attempt to compare the performance of four different middle ear implants (Kurz Bell-Tubingen, Kurz Aerial-Tubingen, Xomed no.0362, Xomed no. 0321), a finite element model of the middle ear before and after ossiculoplasty was developed, based on a micro CT scan of the ossicles. The response of each prosthesis was different and could be related in part to the design of the prosthesis or its location within the middle ear. This study shows how finite element modelling might be used in optimizing the design of new middle ear prostheses.

Introduction

The world of material science has provided the Otologist with a wide array of biomaterials for middle ear reconstruction. Throughout the '70's and '80's many different materials were used in an attempt to improve the results of middle ear reconstruction and in particular ossiculoplasty. Ultimately, it became apparent that the main problem in terms of biofunctionality rested with an incomplete understanding of the biomechanics of the middle ear itself and how any given prosthesis performed. The knowledge of middle ear mechanics had remained relatively static or constant over many years until the advent of techniques such as laser-Doppler vibrometry, analog models and finite element analysis.

Finite element analysis is a technique used by mathematicians and engineers to study complex systems based on the geometry and material properties of the components. The technique involves dividing the geometry, into a series of simple blocks called "elements". The relationship between any load applied to such an element and the resulting deformation of that element is dependant on the stiffness of the element, which is expressed in matrix form. A 'global stiffness matrix' representing the entire system can then be developed when the stiffness matrix of the individual elements is assembled[1]. The accuracy of a finite element model depends partially on how the geometry of the model is defined. Developments in micro CT and MRI scanning have enabled highly accurate models of biological systems to be developed. The advantage of such computational models is that they can be updated on a regular basis, as further information becomes available in the field.

To fully appreciate the biomechanics of ossiculoplasty, one most first have a basic understanding of middle ear mechanics. The middle ear is often referred to as an impedance matching system, allowing sound waves that pass through the low impedance medium of air to stimulate the high impedance fluids of the inner ear. For such impedance-matching to occur, the pressure that acts at the tympanic membrane must be substantially increased at the inner ear. Conventional teaching suggests that this pressure gain is achieved via two mechanisms:

(i) The tympanic membrane area ratio. Since the area of the tympanic membrane is approximately 20 times greater in area than the oval window, a similar pressure magnification is theoretically possible. However experimental studies[2] have shown that all regions of the tympanic membrane do not always vibrate in phase (i.e. in the same direction), hence reducing the pressure magnification at the oval window.

(ii) The ossicular lever ratio. It has long been assumed that the ossicles rotate about an axis. Due to rotation about such an axis it is believed that the ossicles provide a mechanical leverage. Dahmann[3] calculated this axis to run from the anterior ligament of the malleus to posterior ligament of the incus. Dahmann defined the effective lever ratio of the ossicles as the ratio of the displacement amplitude of the umbo to the displacement amplitude of the stapes, calculated to have a value of 1.3 : 1. In recent years the concept of a fixed axis of rotation has come under scrutiny. Decraemer and Khanna[4] have shown that the orientation of the axis of rotation varies with frequency, implying that the magnitude of any ossicular lever ratio would also vary with frequency. In fact

Gyo et al.[5] have shown experimentally that indeed the effective lever ratio does vary with frequency.

So while the function of the middle ear may seem obvious, it is suggested that the exact mechanism is still not fully understood. Therefore improving our knowledge of middle ear biomechanics can only help in our efforts to design the optimal middle ear implant.

Materials and Methods

An anatomically-accurate finite element model of the ossicles was developed based on a micro CT scan of the ossicles and an MRI scan of the ear canal and tympanic membrane, see Fig. 1. The model was partially validated previously[6] by comparing results obtained from the finite element model to laser-Doppler vibrometry studies. This model can now be used to compare the performance of various middle ear prostheses to the normal ear. Four different prostheses were modeled. In the case of a partial ossiculoplasty the incus is replaced in the finite element model with a Kurz Bell-Tubingen PORP and an Xomed PORP (Ref: 0362). For modelling a total ossiculoplasty both the incus and stapes are removed from the finite element model and replaced with a Kurz Aerial-Tubingen TORP and a Xomed TORP (Ref: 0321). In the models of both Kurz prostheses a piece of cartilage is placed between the prosthesis and the manubrium.

In cases when the angle between the manubrium and the stapes is large (>45 degrees), it has been hypothesized by Goode et al.[7] that a posterosuperior tympanic membrane location for the prosthesis would result in superior sound transmission as opposed to an umbo or near umbo location. To test this idea a finite element model of the middle ear with a large angle between manubruim and stapes has also been developed.

Results and Discussion

It is predicted that reconstruction with a Kurz PORP results in a greater umbo vibration than reconstruction with the Xomed PORP, see Fig. 2(a). However, considering the footplate vibration, it is predicted that both prostheses produce a response similar to that of the normal middle ear, see Fig. 2(b), with a fall off in performance at higher frequencies. The dip in response observed with the Kurz PORP at around 1700 Hz is attributed to a tilting of the prosthesis during resonance, and highlights the importance of a stable prosthesis fixation for optimal sound transfer. The piece of cartilage placed between manubruim and prosthesis could be influencing the tilting of the prosthesis.

Larger variations in umbo and footplate vibration are predicted in the case of a total ossiculoplasty. The Xomed TORP consists of a titanium link that makes the prosthesis very flexible. This design feature reduces the stiffness of the prosthesis, and is responsible for the large fluctuations observed in the plots of umbo and footplate vibration, see Fig. 2 (a) and (b), highlighting that the stiffness of a prosthesis has an important role in its performance, as reported by Ferris and Prendergast[8]. Such a flexible prosthesis may not be required if another suitable location for a prosthesis can be found on the tympanic membrane. In a finite element model with a large angle between the manubruim of the malleus and the incus, the prosthesis is placed beneath the tympanic membrane, in a posteo-superior location, instead of under the manubrium of the malleus. Predictions from this study predict that in fact the magnitude of stapedial footplate vibration obtained by placing the prosthesis onto the tympanic membrane is similar to that obtained by placing the prosthesis under the manubrium, see Fig.3.

Conclusions

This study has shown that different prostheses produce differing vibrational responses. Clinically however if an implant is biocompatible and mechanically stable it usually produces an improvement in the patients hearing. This raises the possibility that the inner ear may be quite "forgiving" in terms of the sound or motion that is presented to it and that a certain amount of "unscrambling" is performed by the inner ear. What is certain though is that no implant fully restores a patients hearing to normal levels. In the future the finite element model will be used to try to optimize prosthesis design in relation to both geometrical design and material of manufacture.

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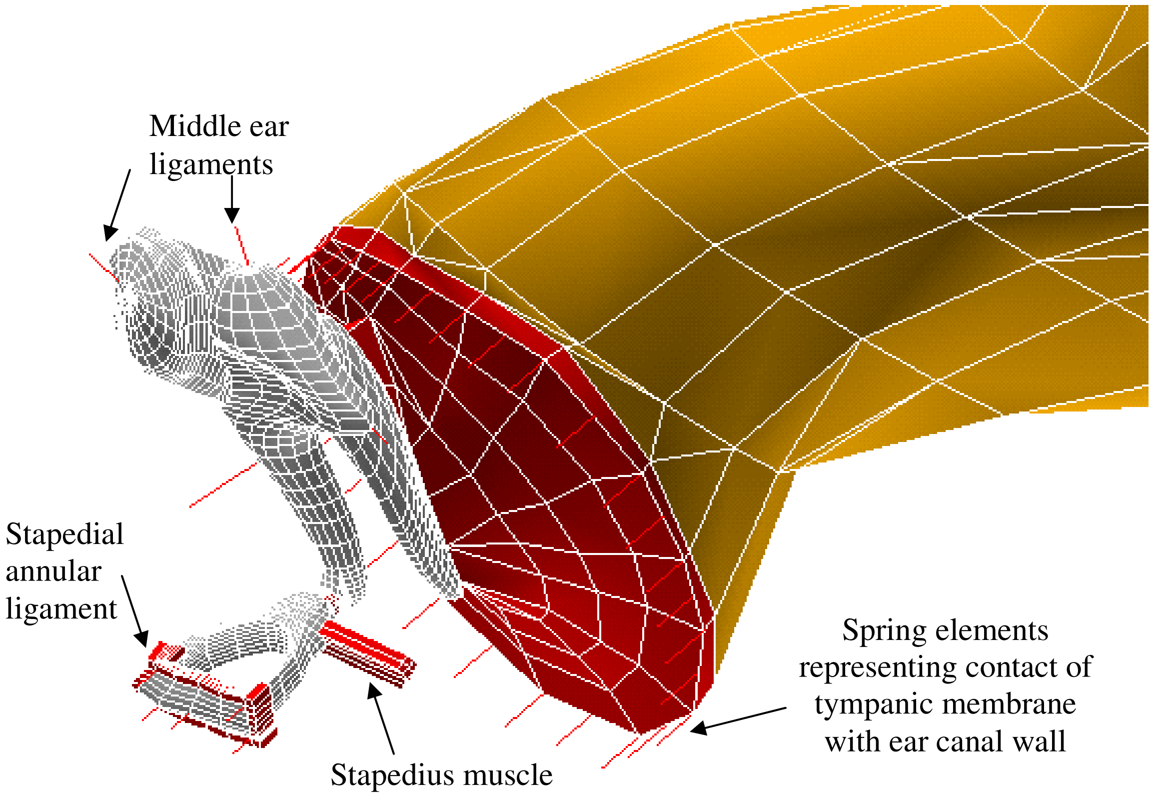

Fig. 1. The finite element model of the outer and middle ear. The ear canal is only partially shown.

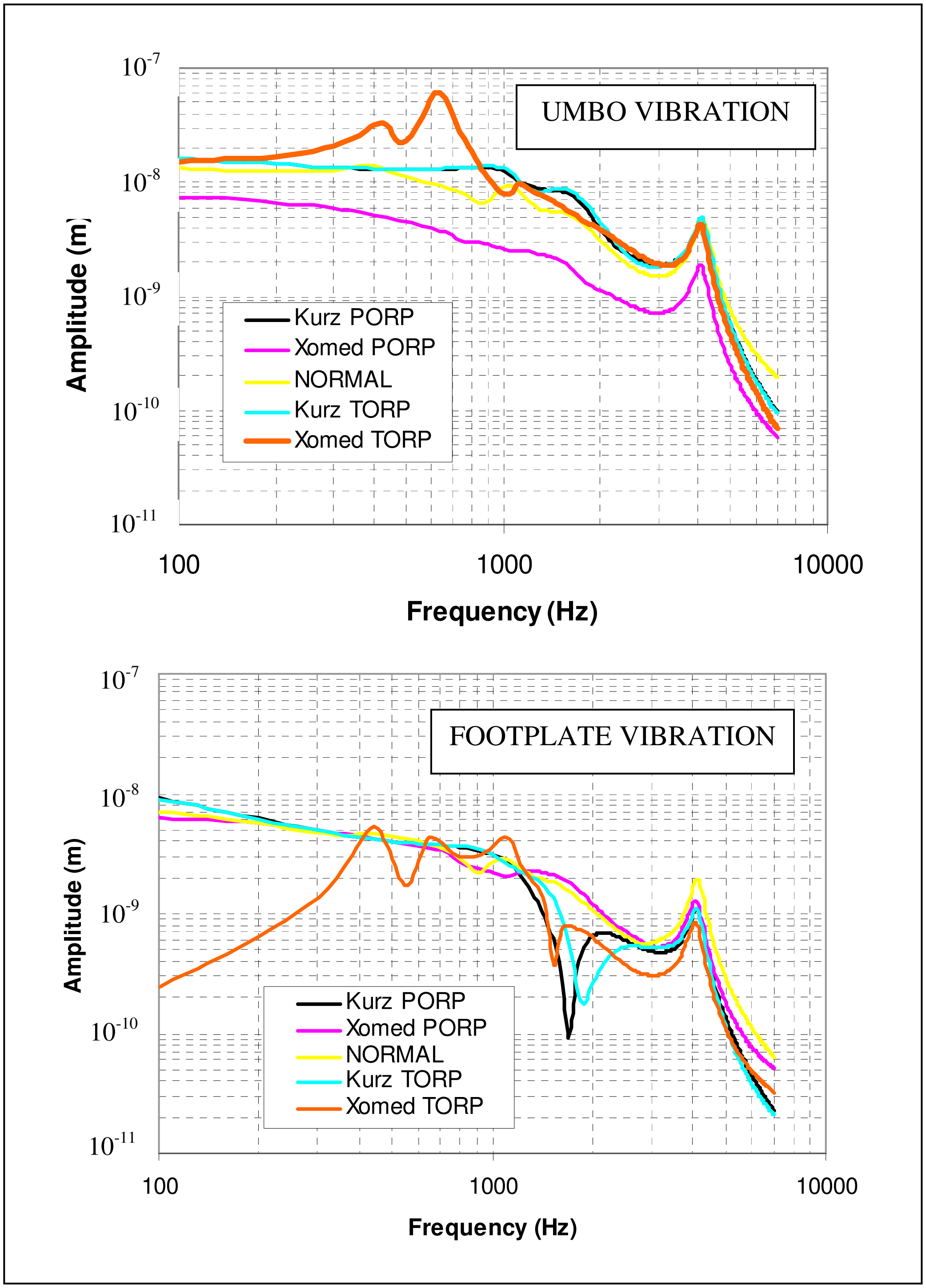

Fig. 2. Amplitude of umbo displacement and footplate displacement vs. frequency for the normal middle ear, the middle ear reconstructed with an Xomed PORP and TORP and the middle ear reconstructed with a Kurz PORP and TORP.

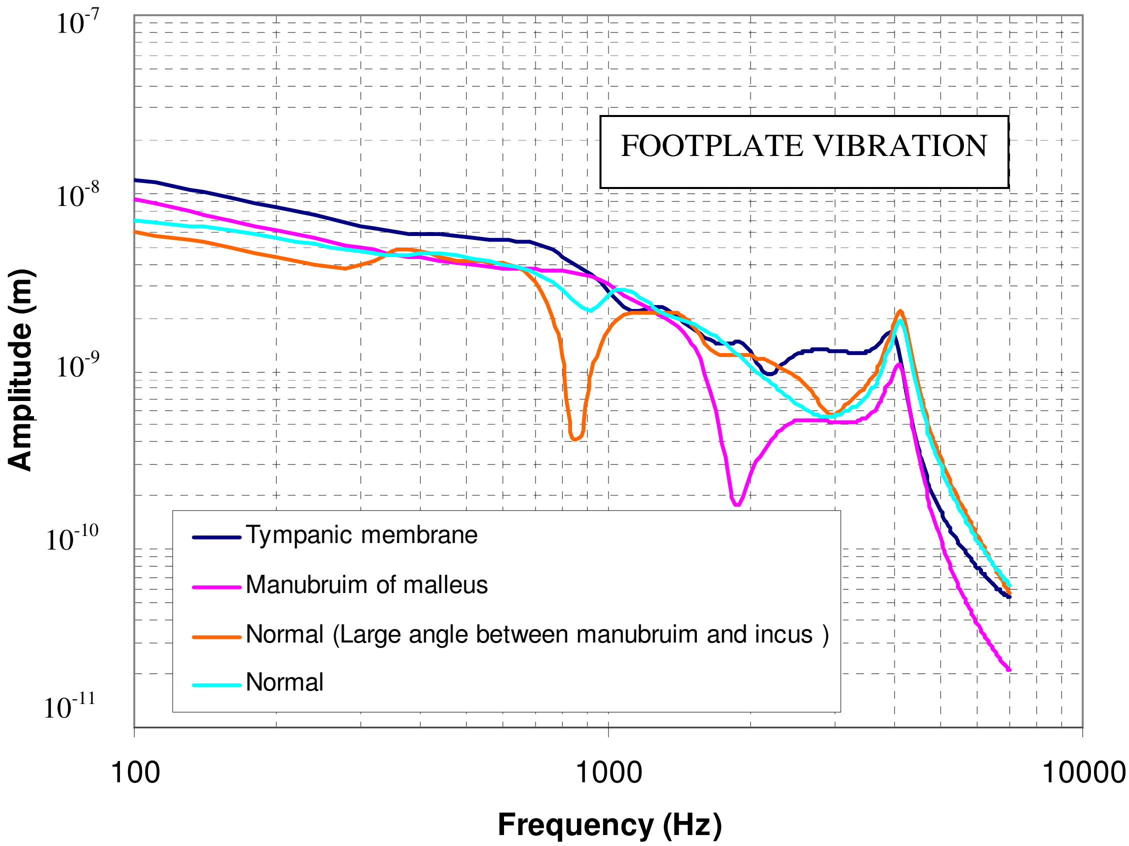

Fig. 3. A comparison of stapedial footplate vibration for the middle ear reconstructed with an Xomed TORP placed on the manubruim of the malleus and placed on the tympanic membrane.

Multiple Choice Questions

Which of the following questions are true:

1. Vibration of the umbo and stapes generally decrease with frequency in the healthy human ear.
2. Prosthesis stiffness does not have an effect on middle-ear vibration.
3. Under the manubruim of the malleus is the only location for a prosthesis to satisfactorily reconstruct the middle ear.
4. The pressure increase at the oval window is due primarily to the difference in area between the tympanic membrane and the oval window.

Answers:

1. True. There is a relatively flat response below 1kHz, decreasing above this frequency.
2. False. As seen in the case of the Xomed TORP, the stiffness has a very significant effect on the vibrational response of a prosthesis.
3. False. In cases when the angle between the manubruim and the incus is large, placing the prosthesis under the tympanic membrane is predicted to produce a satisfactory reconstruction.
4. True. The area of the tympanic membrane is 20 times that of the oval window, resulting in a 20-fold increase in the pressure at the oval window.