# Modelling The Mechanics Of The Coupling Between The Incus And Stapes In The Middle Ear

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## 1. INTRODUCTION

The middle ear contains of a chain of three small bones or ossicles (Figure 1): the malleus, the incus and the stapes. Between the long process of the incus and the lenticular process is a tiny bony bridge (pedicle). Although many studies have been done on the mechanics of the ossicles, little is currently known about the function and mechanical behaviour of the pedicle. Therefore, a simple finite-element model which includes the pedicle and the incudostapedial joint was created and used for a preliminary analysis of the mechanics of the coupling between the incus and the stapes.
The model consists of the end of the long process of the incus, the pedicle, the lenticular plate, the joint gap, the joint capsule, and the head of the stapes. The shape and dimensions of the model were based on histological sections of a cat middle ear. Possible values for the Young's moduli of the joint, joint capsule and pedicle were tested under simple static loading conditions to investigate the interaction between the pedicle and the joint.

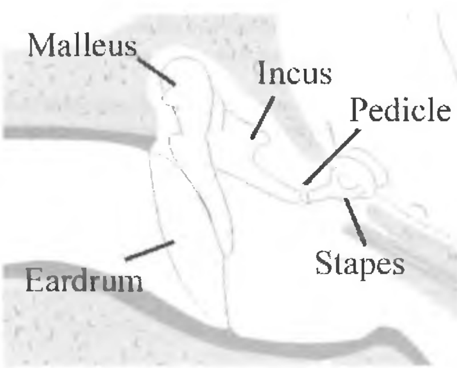



**Figure 1: The human middle ear**

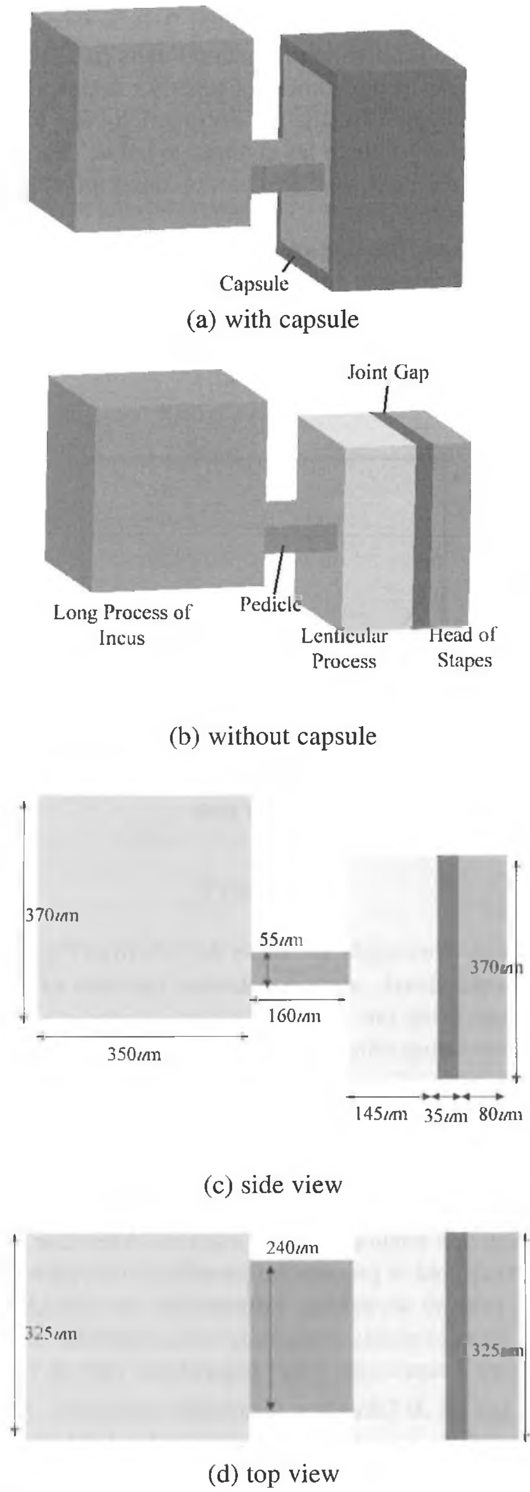



**Figure 2: Shape and dimensions of the finite-element model**

## 2. FINITE-ELEMENT MODEL

### 2.1 Model Geometry

The simple representation of the pedicle and the incudostapedial joint was constructed with several hexahedra as shown in Figure 2(a) and (b). The dimensions of each structure were carefully approximated from the histological sections of a cat middle ear, and are shown in Figure 2(c) and (d). Figure 3 shows two histological sections from different cats. Practically, it is very difficult to keep the tiny pedicle or the incudostapedial joint intact in histological sections.

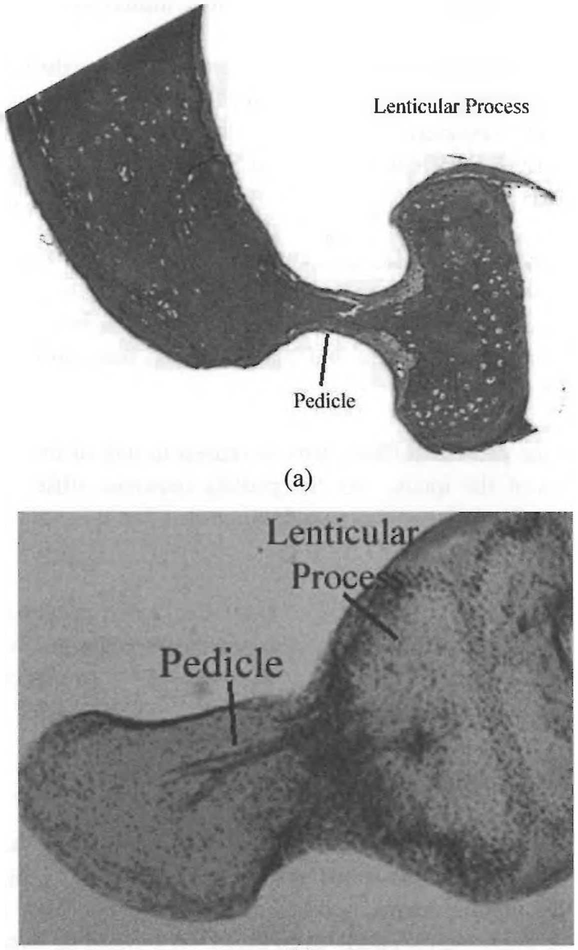



**Figure 3: Part of the histological sections of cat middle ear with pedicle in (a) side view; (b) top view.**

## 2.2 Material Properties

The material properties of the model are assumed to be linearly elastic, uniform (i.e., the same in all locations) and isotropic (i.e., the same in all directions). Viscoelastic properties of the biological materials will be ignored in this model for simplicity. The linearity assumption is generally true for small strains under normal hearing conditions.

The material stiffness is expressed as a Young's modulus. Poisson's ratio has been taken to be 0.3.

### Pedicle

Evidence from the serial histological sections of the pedicle suggests that it is most likely to be a continuation of bone from the long process of the incus to the lenticular plate. The estimates for Young's modulus for bone may vary from 1 G to 20 G, depending on the nature of the bone, the direction of measurement, and the part of the bone. In this model, a stiffness modulus of 5 GPa is adopted for the pedicle, as measured from small bone specimens directly beneath joint cartilage (Mente and Lewis, 1994).

### Joint Gap

The incudostapedial joint is a synovial joint, in which the load is transferred from a cartilage layer on one bone to a cartilage layer on the other bone, either through direct contact, through a thin film of synovial fluid between the layers, or by a mixture of both.

As shown in Figure 2(b), the contacting region in the incudostapedial joint is modelled by a 35-μm-thick articular cartilage. This is based on the assumption that the two articulating surfaces are (at least partially) in direct contact during acoustic vibration. A stiffness modulus of 10 MPa is a fair estimate for cartilage in healthy joint (Elices, 2000), and is adopted for the joint gap in the model.

### Capsule

Another key structure in the model is the incudostapedial joint capsule that completely encloses the joint. Figure 2(a) shows that the joint capsule is modelled by introducing an extra 30-μm-thick outer layer surrounding the joint model. To be consistent with the real anatomy of the synovial capsule as observed in the histological sections, only the two ends of the capsule are attached to the bone.

The outer layers of the capsule consist of dense fibrous connective tissue and capsule ligament, which dominate the capsule mechanical properties. Therefore it is possible to apply the value of Young's modulus for capsule ligament to the capsule directly. In this model, a rough estimate of 50 MPa is used as the Young's modulus of the capsule.

### Others

The long process of the incus is given a Young's modulus of 12 GPa, corresponding to stiff compact bone. The lenticular process and the head of the stapes may regarded as composite materials, mainly consisting of calcified cartilage ($E \approx 0.32$ GPa) and subchondral bone ($E \approx 5$ GPa) (Mente and Lewis, 1994). Hence an intermediate value of 1 GPa is used as the Young's modulus for the two structures.

## 2.3 Meshing Considerations

One important question that needs to be addressed in finite-element modelling is how many elements are enough for accurate simulation results while keeping reasonable computational time. In the 3-D tetrahedral representation of the model, most of the major substructures, such as the pedicle and the joint contact region, were first tested in simple convergence tests that involved both compressive and shearing loads. Then an optimal resolution was decided upon for each substructure. In the model presented here, a discrepancy of 15-30% between the simulation results and the analytical results is considered to be within the "acceptable" range based on the rationale that 15-30% is relatively small compared with the uncertainties of the Young's moduli of each substructure.

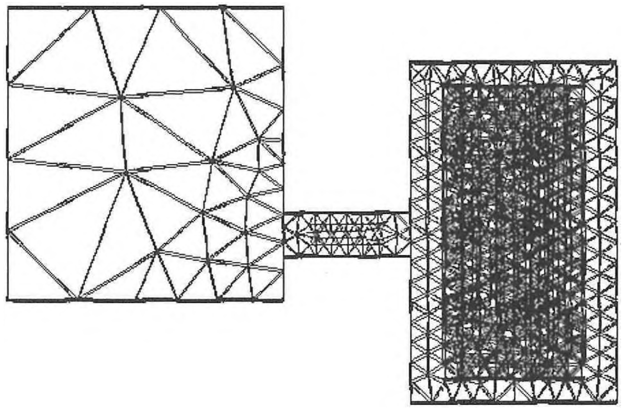


**Figure 4: Side view of the model**

Another way of reducing the number of elements is to use longer and thinner tetrahedral elements. However, the quality of the mesh will be affected, as the tetrahedral elements should ideally be equilateral for the best simulation results. A poorly meshed model is very likely to reduce the accuracy of the finite-element simulation results. Hence it is important not to over-stretch the elements. Generally, reducing the quality of the mesh can be accomplished by changing the settings in the mesh generation programme or by stretching the geometry of the model after the mesh generation.

## 3. RESULTS

The simulated load was a uniform static pressure applied on the long process of the incus. A few simulation results are shown in Figure 5. As the displacements of the ossicles are on the order of nm, the simulated deformations presented here were scaled up so that the displacements can be seen.

One way to evaluate the results is to compare the relative contributions of the pedicle and incudostapedial joint to the displacements of the long process of the incus. If there is a significant bending of the pedicle while the incudostapedial joint appears to be relatively rigid, then it suggests that the presence of the pedicle has an effect on the mechanics of the ossicles.

Since the values for the Young's moduli are uncertain, we have explored a range of possible values. In Figure 5(a) the Young's modulus of each substructure in the model was set to the value given in Section 2. In this case, there is a comparatively large bending at the pedicle.

In (b) the Young's modulus of the joint gap was reduced from 10 MPa to 5 MPa, and the result is similar to (a).

In (c) the Young's modulus of the capsule was reduced to 20 MPa, which is the value used for the eardrum in a previous model (Funnell, 1978). Again, lowering the stiffness of the capsule does not make much difference to the results compared with (a).

In (d) the Young's moduli of the joint gap and the capsule were both reduced, to values of 5 MPa and 20 MPa respectively. As the joint becomes more flexible, there is more deformation at the joint and relatively less bending of the pedicle.

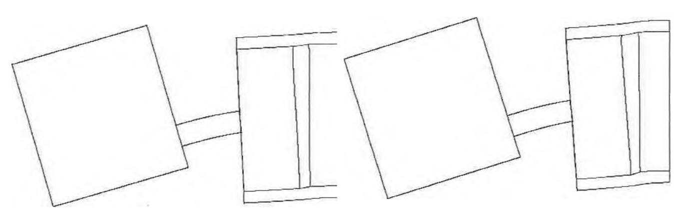
In (e) the pedicle stiffness was increased to that of the long process of the incus. As the pedicle becomes stiffer, the degree of bending at the pedicle decreases but it is still significant in this case.

In (f) the Young's modulus of the pedicle was reduced to 3 GPa, which is the value estimated for subchondral bone specimens from a human tibia (Murray, 1984). In this case the pedicle bending becomes quite large.

## 4. DISCUSSION

The results presented here suggest that load transmission from the incus to the stapes is affected by both the pedicle and the incudostapedial joint. For this model, at least, the pedicle bends significantly even though it is made of bone.

Due to the similarity of the cat and human middle ears, the model and the simulation results presented here can serve as a guide for the modelling and mechanics of the human middle ear. Validation of the results could be accomplished by making experimental measurements on the pedicle and the incudostapedial joint in a preparation with, for example, a disarticulated incus and a fixated stapes. The present model can be incorporated into a complete middle-ear model in order to provide more insight into the significance of the pedicle in hearing.



(a) *p*=5 G; *j*=10 M; *c*=50 M (b) *p*=5 G; *j*=5 M; *c*=50 M