High-resolution x-ray CT scanning of the human stapes footplate

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Abstract

Objectives:

The mechanical behaviour of the footplate and its annular ligament depends critically on their shape and orientation in the oval window, but accurate measurements have been difficult to make due to their small size. Our aims are to visualize the footplate at high resolution and understand its dynamics.

Methods:

The human cadaver stapes footplate was dissected and very high resolution x-ray CT scans, with voxel sizes from 4 to 8 µm, were performed. Locally developed software was used to reconstruct the images.

Results:

The data permit us to explore minor details of shape and orientation. The footplate looks like a footprint, and the annular ligament has variable thickness with a cleft (groove) in its anterior attachment to the oval window. The CT data also permit us to create a 3-D finite-element model which can simulate footplate motion.

Conclusions:

The results obtained lead to further understanding of the mechanical behaviour of the footplate and the annular ligament.

Author Keywords

Footplate, annular ligament, stapes, finite element model

Introduction

Revolutions in the field of imaging and computers facilitate and drive change in medicine. The technology now exists to image, at very high resolution, the human stapes and develop three-dimensional models. The stapes, the smallest bone in the body, has long been known to be important in the impedance matching properties of the middle ear [1]. The complex relationships and anatomy of the stapes and its articulation at the oval window remain the centre of intense study but many unanswered questions persist. Work based on animal[2-6] studies and serial human histological sections [7-9] has been previously reported. However, animal studies do not reflect the human situation closely since there are major differences with human anatomy and physiology. Histological study is expensive and time-consuming. Moreover, inaccuracies from decalcification, shrinkage, uneven slice thickness, poor staining, orientation and alignment of consecutive sections all complicate analysis of the information.

Therefore, other tools are needed to overcome these obstacles. Finite-element (FE) modelling together with very high-resolution CT of the human stapes seems to be an excellent alternative. Finite-element modelling is a powerful and flexible computer-based approach to creating 3-D models of complex objects, for the purposes of both visualization and simulation. It is capable of easily modelling complex structures, and irregular or inhomogeneous shapes. The model can then be used to simulate the detailed vibration modes, stress distributions and dynamic behaviour at any location in a system. Funnell and Laszlo[10-11] (1978) first published a finite-element model of the cat eardrum. Considerable interest has continued in finite-element models of the middle ear. [12]

Our goal was to prepare a comprehensive model of the human footplate using microscopic x-ray computed tomography (microCT) and to compare the model with human histology data. Eventually a FE model of this critical region could give a better understanding of the complex dynamics of the stapes footplate.

Materials and Methods

Our project was approved by the ethics committee of the McGill University Health Centre in accordance with Article 1.6 of the Canadian Tri-Council Policy on Ethical Conduct for Research involving Humans and U.S. Title 45 CFR 46, Section 110(b), paragraph (1). Human cadaveric temporal bones were dissected at the Royal Victoria Hospital Temporal Bone Lab. Under microscopic visualization simple mastoidectomy and hypotympanotomy were performed, the anterior bony wall of the external ear was drilled and the middle ear was explored from the middle cranial fossa. The intact footplate-oval window complex was harvested and trimmed to a maximum diameter of 19 mm to fit in the microCT scan container.

CT imaging

Three specimens underwent 6-µm very high-resolution CT scans using a SkyScan 1072 scanner. One specimen was then selected to go for re-imaging at 4 µm and 8 µm. The authors decided to use one of the 6-µm scans since they were done first and segmentation had started before the other data became available. No important differences were noticed between images at these different resolutions. The digital images were transformed into JPEG files for further computer manipulations.

Finite-element modelling

The finite-element method divides complex experimental domains into simple and small domains or elements. Each element is analyzed with its own equations, and the equations for all elements are then combined based on their connections to one another. This creates global system matrices which can be processed using standard computer algorithms[10-12] . Finite-element modelling has four stages: image segmentation, reconstruction, model generation and simulation**.**

Image segmentation

The software provided with the SkyScan scanner can produce 3-D renderings of the scanned structures, based on thresholding of the CT grey-level values, as is commonly done with clinical CT scanners. These renderings cannot, however, be used for finite-element modelling. For that purpose we used Fie[13] (*Fabrication d'imagerie extraordinaire*), a locally developed, interactive image-segmentation computer program by Dr. Funnell. The stapes footplate and oval-window images were segmented by manually marking points along the interesting outlines. This was done in all of the images containing the footplate and oval window.

Reconstruction

The structure outlines are maintained in text files suitable for subsequent surface triangulation using Tr3[13]. Tr3 is also a locally developed computer program, that is used for triangulating 3-D surfaces between serial-section contours. The file produced by Fie contains specifications for visualization and mechanical behaviour together with the basic geometry, so complete models can be generated in one operation. The Tr3 program creates triangles between outlines in consecutive images. Each triangle represents the anatomy and mechanical behaviour of a part of the footplate. The sizes of these triangles can be selected; the greater the number of triangles the better the resolution of the model. At a certain stage, however, the accuracy of the model is not improved markedly by a greater number of segments but it becomes more time- and power-consuming.

Model generation

VRML (Virtual Reality Mark-up Language) is a scene description language used to represent a 3-D world. Triangulated models are generated by Tr3 in both VRML format (for interactive visualization) and SAP[13] format (for finite-element simulation). This final step in modelling is the most exciting part, where the model achieves a 3-D shape. Moreover interaction, enlargement, rotation, flipping and observing the model from different angles are easy using any of several freely available VRML viewers.

Simulation

Using SAP, each tiny triangular element in the model can be assigned a stiffness as a function of its shape and orientation, and of its inherent material properties as specified in Fie. Thousands of equations are created by the computer and then combined into one matrix equation representing the complex anatomical and mechanical features of the footplate. That matrix is inverted using a standard algorithm to produce the triangle displacements in the x, y and z directions.

Eight nodes were distributed around the periphery of the footplate, and virtual springs were attached to them to represent the stiffness of the annular ligament. At each of the eight nodes, measurements were made representing the three dimensions of the annular ligament at that point. The measurements were made using maximum magnification in Fie, with each pixel visualized and counted. The spring-stiffness values were estimated based on those dimensions.

The simulated load applied to the footplate was a static (or, equivalently, low-frequency) force perpendicular to the plane of the footplate, applied at the location of the stapes head and transmitted to the footplate by two struts acting as simplified crura.

Results

Fig. 1 shows a 3-D rendering of the specimen scanned. This rendering, created using the SkyScan software, shows the overall configuration well but details are difficult to study.

A 3-D finite-element model of the footplate-oval-window complex was created with Fie. Strikingly, the footplate (Fig. 2) resembled a footprint! Its anterior edge looks flattened with a wide articulation with the oval window, while its posterior edge looks more or less like a heel.

Particularities of the annular ligament were apparent in the CT scans. Anteriorly, it was horizontally thicker and a cleft could be seen on the oval-window side. Posteriorly, the annular ligament was thinner. These findings were then compared and correlated with histological sections available in our lab that show analogous findings in different temporal bones (Figs. 3 and 4).

Fig. 5 shows a simulation result based on the model shown in Fig. 2, for a load applied as described above. The displacements of the footplate are shown by colour, with dark colours indicating small displacements and light colours indicating large displacements. This is a preliminary result which suggests the sorts of simulations that are possible. In this case the footplate appears to be rocking around an axis perpendicular to its long dimension.

Discussion

This study demonstrates that microCT and 3-D reconstruction of the stapes footplate and oval window is technically feasible and gives a view of the anatomy that correlates well with that obtained using traditional histology. However, in addition to simply depicting anatomy, the information obtained can be integrated into a finite-element model, thus permitting us to begin simulating the complex motion of the stapes and footplate.

Computed tomography (CT) was first introduced over thirty years ago and has become a standard tool in many spheres of interest to otolaryngology. Currently, however, clinical CT scanning is limited to a resolution that is insuffiencent to demonstrate pathology or even much of the normal anatomy of the footplate. MicroCT, still relatively novel, is a research technique that is fast, requires no preparation, no reorientation and does not heat the specimen. High-resolution microCT images have previously been published on blood vessels[14], teeth[15] and bone[16-17] .

Having obtained a very interesting view of the footplate and oval window complex we sought to assess how well it correlated with histology. We studied our own temporal-bone samples and searched the literature. We found that our results, obtained with microCT, are generally comparable with what has been published before using conventional histology. Graham[18] used electron microscopy to examine the articulating surface of the footplate and found it to vary considerably. In 1954, Bruner[19] et al, reported that the human annular ligament is wider and thinner at the anterior edge of the footplate than at the posterior edge. Anatomists generally have not, however, noted the “footprint” appearance of the footplate that appears so striking in our 3-D reconstructions. An exception is Eysell's[20] paper which was written in 1870 and clearly illustrates the same shape. He also noted that the annular ligament is not uniform around the footplate. MicroCT of this region appeared to give results that in some ways are as good as, if not better than, traditional histology – especially if one considers that it is far less time and labor intensive.

. How the stapes vibrates remains controversial. In part this is because the underlying anatomy remains incompletely studied. This is why we felt it important to study the annular ligament so closely. Histologically it is clear that the annular ligament varies in width, as does the space between the footplate and the labyrinthine bone. We felt it likely that this was important to stapes movement and needed to be considered in a model of the footplate. Experimental studies of the motion of the stapedial footplate (e.g. von Békésy (1960) [21] and Gyo (1987) [22] have identified a piston- and hinge-like movement whereas others such as Vlaming and Feenstra (1986) [23] found only piston-like motions. Moreover, Heiland et al.[24] reported vibration as a piston at low frequencies, up to 2.0 kHz, but more complex movements at higher frequencies because of an increase in anterior-posterior rocking motion. They did not observe hinge-like movements. Huber[25] et al made similar observations. The approach presented here shows promise of allowing us to model the mechanisms underlying the varying results found by these previous investigators. The model is still, however, at a preliminary stage of development. A more precise description of footplate mechanics will have to await more sophisticated finite-element models of the whole middle ear. With further refinements, the model will also be able to simulate pathological conditions such as otosclerosis, or various types of prostheses in order to choose the one which best mimics normal behaviour.

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Figures

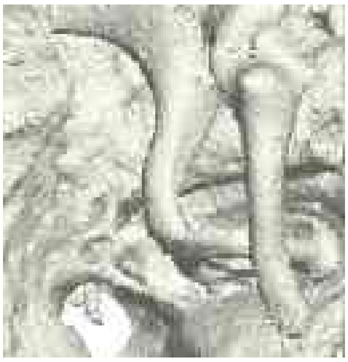

Figure 1: Reconstruction from 3-D microCT scan. Normal middle-ear ossicles: handle of malleus, long process of the incus and stapes footplate (Arrows).

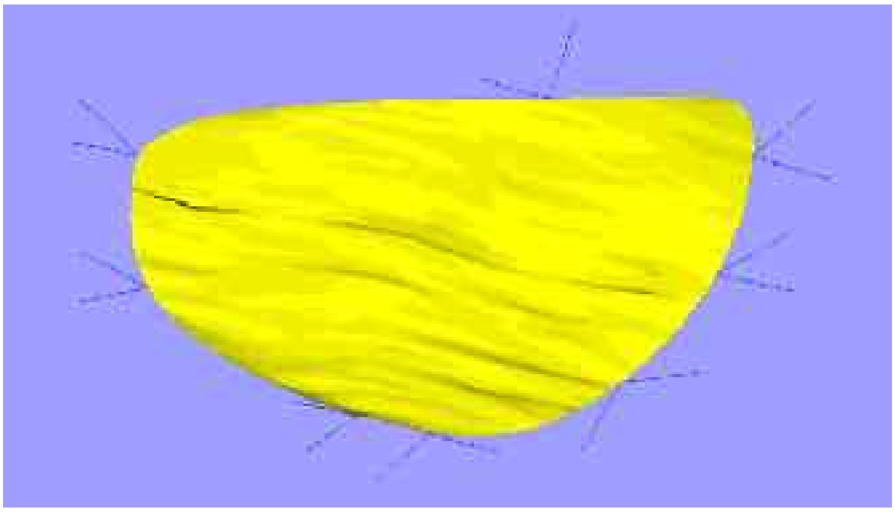

Figure 2: VRML picture of the right footplate as reconstructed from microCT scan using Fie

(Horizontal arrow toward spring and oblique arrow toward upper anterior corner of the right footplate).

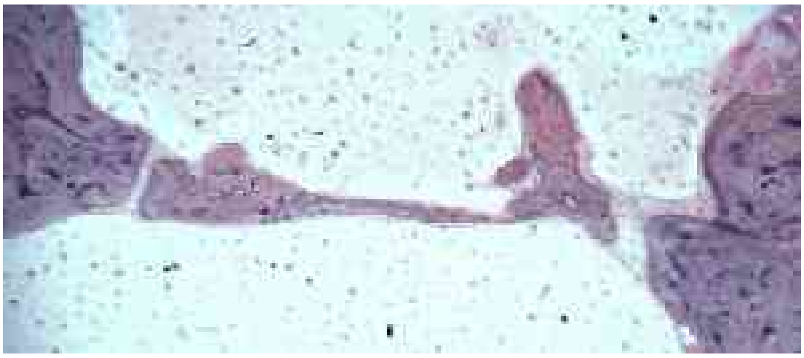

Figure 3: Histological section showing clear difference in the dimensions of the annular ligament between anterior (right) and posterior (left).

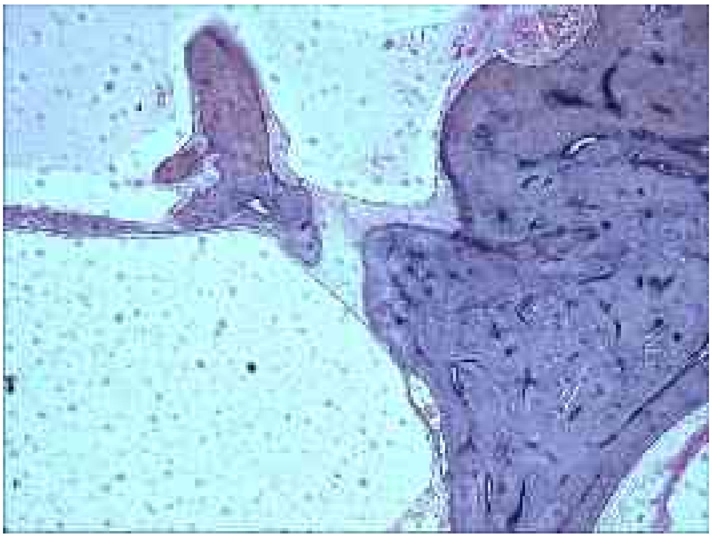

Figure 4: Histology cut showing a cleft in the anterior side of the right oval window.

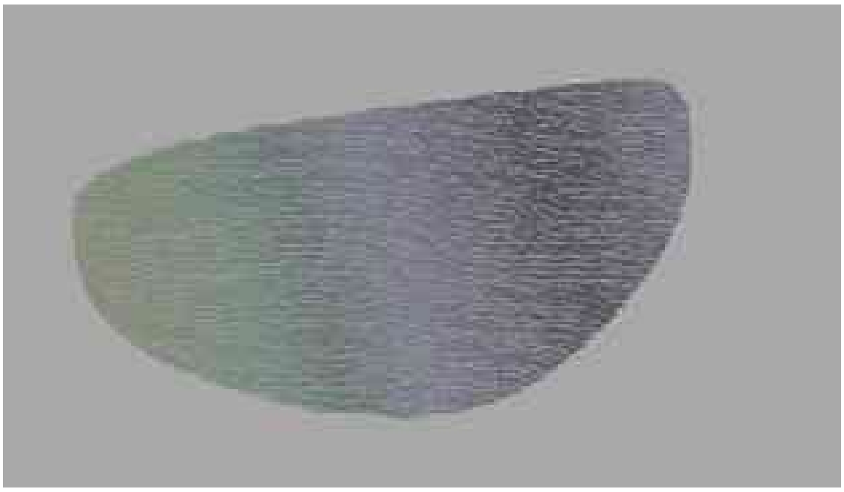

Figure5: The right footplate simulation. Left arrow posterior and right arrow anterior. Model displacements are indicated by colour: dark corresponds to small displacements, light corresponds to large displacements.