High-Resolution X-Ray Computed Tomographic 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 owing 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 computed tomographic (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 three-dimensional finite-element model that can simulate footplate motion.

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

Key words: annular ligament, finite-element model, footplate, stapes

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human stapes, seems to be an excellent alternative. FE modelling is a powerful and flexible computer-based approach to creating three-dimensional 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 first published an FE model of the cat eardrum. Considerable interest has continued in FE models of the middle ear.12

Our goal was to prepare a comprehensive model of the human footplate using microscopic x-ray computed tomography (micro-CT) and to compare the model with human histology data. Eventually, an 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 US Title 45 CFR 46, Section 110(b), paragraph (1). Human cadaveric temporal bones were dissected at the Royal Victoria Hospital Temporal Bone Laboratory. Under microscopic visualization, a 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 micro-CT 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 reimaging at 4 and 8 µm. We decided to use one of the 6 µm scans because 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.

FE Modelling

The FE 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. FE modelling has four stages: image segmentation, reconstruction, model generation, and simulation.

Image Segmentation

The software provided with the SkyScan scanner can produce three-dimensional 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 FE modelling. For that purpose, we used Fie (Fabrication d’imagerie extraordinaire), an interactive image-segmentation computer program developed 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. Tr3 is also a locally developed computer program that is used for triangulating three-dimensional 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 three-dimensional world. Triangulated models are generated by Tr3 in both VRML format (for interactive visualization) and SAP format (for FE simulation). This final step in modelling is the most exciting part, in which the model achieves a three-dimensional shape. Moreover, interaction, enlargement, rotation, and 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 anatomic 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 \textit{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.

\section*{Results}

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

A three-dimensional FE model of the footplate–oval window complex was created with \textit{Fie}. Strikingly, the footplate (Figure 2) resembled a footprint! Its anterior edge looks flattened, with a wide articulation with the oval window, whereas 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 histologic sections available in our laboratory that show analogous findings in different temporal bones (Figures 3 and 4).

Figure 5 shows a simulation result based on the model shown in Figure 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 that 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.

\section*{Discussion}

This study demonstrates that micro-CT and three-dimensional reconstruction of the stapes footplate and oval window are 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 an FE model, thus permitting us to begin simulating the complex motion of the stapes and footplate.

CT was first introduced over 30 years ago and has become a standard tool in many spheres of interest to otolaryngology. Currently, however, clinical CT is lim-
edited to a resolution that is insufficient to demonstrate pathology or even much of the normal anatomy of the footplate. Micro-CT, still relatively novel, is a research technique that is fast, requires no preparation and no reorientation, and does not heat the specimen. High-resolution micro-CT images have previously been published on blood vessels,14 teeth,15 and bone.16,17

Having obtained a very interesting view of the footplate–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 micro-CT, are generally comparable with what has been published before using conventional histology. Graham used electron microscopy to examine the articulating surface of the footplate and found it to vary considerably.18 In 1954, Bruner reported that the human annular ligament is wider and thinner at the anterior edge of the footplate than at the posterior edge.19 Anatomists generally have not, however, noted the “footprint” appearance of the footplate that appears so striking in our three-dimensional reconstructions. An exception is Eysell’s article, which was written in 1870 and clearly illustrates the same shape.20 He also noted that the annular ligament is not uniform around the footplate. Micro-CT 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 labour 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 (eg, von Békésy21 and Gyo and colleagues22) have identified a piston and hinge–like movement, whereas others, such as Vlaming and Feenstra,23 found only piston-like motions. Moreover, Heiland and colleagues 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.24 They did not observe hinge-like movements. Huber and colleagues made similar observations.25 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 FE models of the whole middle ear. With further refinements, the model will also be able to simulate pathologic conditions, such as otosclerosis, or various types of prostheses to choose the one that best mimics normal behaviour.

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References


