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MAIN ARTICLE

Three-dimensional temporal bone reconstruction from histological sections

N AHMAD[1], A WRIGHT[2]

[1]*Department of Otolaryngology-Head and Neck Surgery, James Cook University Hospital, Middlesbrough, UK, and* [2]*University College London Ear Institute, UK*

Abstract

Objective: To produce a high-resolution, three-dimensional temporal bone model from serial sections, using a personal computer.

Method: Digital images were acquired from histological sections of the temporal bone. Image registration, segmentation and three-dimensional volumetric reconstruction were performed using a personal computer. The model was assessed for anatomical accuracy and interactivity by otologists.

Results: An accurate, high-resolution, three-dimensional model of the temporal bone was produced, containing structures relevant to otological surgery. The facial nerve, labyrinth, internal carotid artery, jugular bulb and all of the ossicles were seen (including the stapes footplate), together with the internal and external auditory meati. Some projections also showed the chorda tympani nerve.

Conclusion: A high-resolution, three-dimensional computer model of the complete temporal bone was produced using a personal computer. Because of the increasing difficulty in procuring cadaveric bones, this model could be a useful adjunct for training.

Key words: Temporal Bone; Model; Computer Simulation; Computer-Assisted Three-Dimensional Imaging; Image Reconstruction; Training

Introduction

Understanding the anatomy of the temporal bone remains one of the most arduous and daunting challenges faced by the trainee otologist. The temporal bone is not only the densest bone in the body but is also one of the most complex structures found in otological surgery. Indeed, during their training, otologists aim to acquire the ability to mentally map, visualise and rotate, in complete three-dimensional (3D) perspective, all relevant structures and their inter-relationships. It can take hundreds of hours of painstaking dissection of numerous temporal bones to achieve this. The otological surgeon's task becomes even more challenging in the presence of anatomical variations, with or without associated compounding disease processes.

Teaching temporal bone anatomy

Much time and effort, and copious resources, are employed in teaching the surgical anatomy of the temporal bone. Teaching tools include illustrations, anatomical descriptions, histological sections, photographs, computed tomography (CT), magnetic resonance imaging (MRI), and even plastinated or sculpted models. In addition, hundreds of hours are spent observing experienced otologists performing procedures. These methods, combined with gaining experience in dissecting cadaveric temporal bones, are still considered the most effective means to fulfil training needs. However, a major problem is that training time in the operating theatre has become more limited in the UK since the 'Calmanisation' of specialist training. This problem is increasing with the ongoing Modernisation of Medical Careers and the European Working Time Directive reforms.

An even greater problem is the lack of cadaveric temporal bones available for dissection. There are a number of contributory factors. The UK Anatomy Act 1984 has made it more difficult to use temporal bones for surgical training because it only permits dissections for anatomical purposes. Furthermore, the supply is diminishing as medical schools phase out cadaver dissection as part of their curricula. In any case, such specimens are less than optimal for procedures involving dissection of soft tissues because fixation alters their handling characteristics. The best option is fresh frozen temporal bones obtained during post-mortem examinations (which fall under the

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provisions of the UK Human Tissue Act 2004). However, these are also becoming scarcer as the number of post-mortems being carried out dwindles.[1] Negative publicity concerning the use of organs removed at post-mortem without explicit consent has made it almost impossible to obtain an adequate number of temporal bone specimens.[2]

Although natural physical models of the temporal bone are considered the 'gold standard', their high costs and increasing difficulties in their procurement have led to a need to consider alternatives. Physical models have constraints other than lack of availability, such as the inability to 'rewind' the dissection if an error is made at an earlier stage of a simulated procedure.

Three-dimensional reconstruction in medicine

Useful 3D reconstructions require good resolution two-dimensional images and appropriate data processing methods. Stages in the reconstruction process include: (1) image acquisition and conversion to a format that can be manipulated; (2) segmentation of each image into regions of interest; (3) registration of the images to bring them into spatial alignment; (4) reconstruction to form 3D models; and (5) rendering of volumes and/or surface areas of the tissue layers in the 3D model to allow observer interaction.

Surface rendering using polygonal datasets to reconstruct the object as a shell allows the user to interact only with the surface generated by the volume. However, this method is inherently flawed when the interaction demands 'cutting'. The problem is overcome by constructing the temporal bone model using a series of layers (like Russian dolls), each slightly smaller than the adjacent outer layer and with slightly different surface features. These surfaces allow predominantly passive viewing (rotation, translation and zooming in). As the computer only has to deal with surfaces, as opposed to the entire volume, this approach requires much less processing power and is less time intensive. It was used in previous attempts to model the temporal bone by authors with access to less powerful computers.[3–5]

Volume rendering using 'voxels' (volume elements), the 3D equivalent of 'pixels' (picture elements), allows the user to interact with the entire volume of data, in much the same way as the surgeon does in the real world. Volume can be seen as a surface that can be removed (such as when a surgeon drills bone) to reveal underlying structures in a continuous fashion. We believe that this is a much better approach when using the model for surgical training. Volumetric data acquisition has a greater computational overhead (memory and processing time). Major difficulties in getting serial sections to 'line up' (registration) has forced authors to use lower resolution CT and MR data to generate temporal bone models.[6] Ideally, a model with the highest possible resolution would be based on histological sections and have the interactivity of 3D volume rendering.

Histological images for three-dimensional modelling

With CT data, there is poor resolution of soft tissues. Magnetic resonance imaging can be used to obtain cross-sectional images with better differentiation of soft tissues, but the resolution of MR images is again limited. Often anatomical structures within the temporal bone cannot be adequately resolved because of the ambiguous relationship between signal intensity and tissue composition, with partial volume averaging also contributing to the loss of resolution.

Many attempts at temporal bone reconstruction from CT and/or ultra-high-resolution MR data have found resolution to be the limiting factor. The visual and haptic displays for a 3D temporal bone reconstruction produced by Wiet *et al*.[6] were described as 'only as good as the resolution of the data used to produce such displays'. These authors highlighted a lack of visual detail, which is critical to simulation at higher magnification levels. Structures such as the long process of incus, the stapes crura and the footplate were not well resolved.[6] Furthermore, internal distortion within the finished MR image causes problems in constructing a good surgical model.

Although challenging and time consuming, the method of 3D histological reconstruction provides a level of spatial resolution and tissue demarcation not possible with other imaging techniques, such as CT or MRI. We believe this could serve as a reference standard for future models.

This study aimed to produce a high-resolution 3D volume rendered model of the complete temporal bone derived from histological sections using a personal computer (PC).

Materials and methods

Temporal bone preparation and sectioning

A complete series of histological sections of the right temporal bone from the Wright-Michaels Temporal Bone Collection of University College London was used for this study. The bone had been donated by an 84-year-old man who had died from pneumonia. He had a history of presbyacusis with moderate to severe sensorineural hearing loss (treated with hearing aids), but no other otological conditions.

The entire temporal bone specimen was decalcified and cut into 25 μm thick sections. All sections were stained with haematoxylin and eosin.

Image acquisition

A Canon EOS model 20D 8.2 megapixel single lens reflex digital camera with a 105 mm f2.8 macro lens (focal distance 0.34 m) was used. The camera was stabilised by fixation to a stand overlooking a light box. Photography of a grid showed no 'fisheye' distortion. Histological slides containing stained sections of the

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entire temporal bone were mounted onto the light box and photographed in a single session.

Image processing and registration

A 2.8 GHz Dell desktop computer with 1 GB random-access memory and a 256 MB graphics card was used. Adobe Photoshop image-processing software (San Jose, California, USA) was used to crop images to an optimal size, remove blemishes from the periphery of the section and, if necessary, alter the luminosity and contrast levels to facilitate delineation and segmentation of relevant structures.

Adobe Photoshop was used to process multiple layers within an image file, and each section was aligned to enable registration with the underlying section (Figures 1 and 2).

Image segmentation

Segmentation of all surgically relevant structures within the temporal bone was performed using histological atlases, as well as the authors' own knowledge and experience of otological procedures. Surgically relevant structures were highlighted on each slide.

Three-dimensional reconstruction and volume rendering

Alignment was reassessed prior to image stacking. The entire dataset was then processed using 3DView version 1.2 software (RMR Systems, East Anglia, UK). The 3D reconstructed model was then volume rendered in 3DView. The model was finally checked for anatomical accuracy and interactivity by practising otologists.

Results

An anatomically accurate, high-resolution, 3D, volume rendered computer model of the entire temporal bone was produced, containing many surgically relevant structures. The entire intratemporal course of the facial nerve, labyrinth, internal carotid artery, jugular bulb and all of the ossicles were seen, including the stapes footplate, the internal and external auditory meati, and the tympanic membrane. The chorda tympani nerve was seen in some projections. The resolution was sufficiently high that there was no significant loss of detail, even at higher magnifications (Figures 3–6).

Figure 5 shows a problem with manual segmentation. Although the nerve structures were highlighted in a different shade than their surrounding structures when segmented, some realism was lost at higher magnifications.

The model could be run satisfactorily on a PC with a 256 MB graphics card and 3DView software. There was a great deal of flexibility in the way that the model could be presented. For example, it was possible to 'computer drill' away all of the bone to reveal only the relevant soft structures. The resolution was sufficiently high to enable the internal anatomy of the cochlea to be seen. It was even possible to see cross-sections of the ampulla of the semicircular canal (Figure 6).

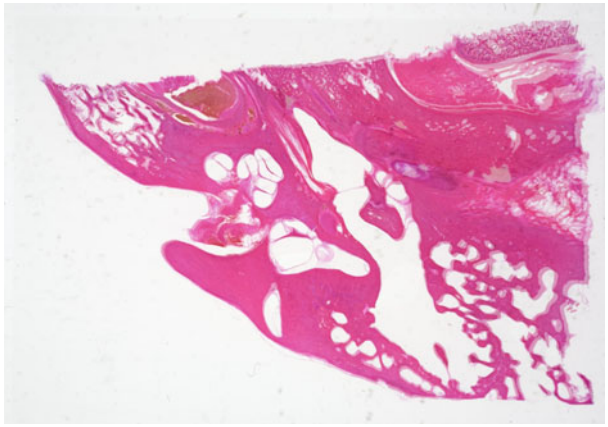


FIG. 2

Registered images of the same two adjacent sections shown in Figure 1, with the uppermost image shown at 50 per cent transparency.

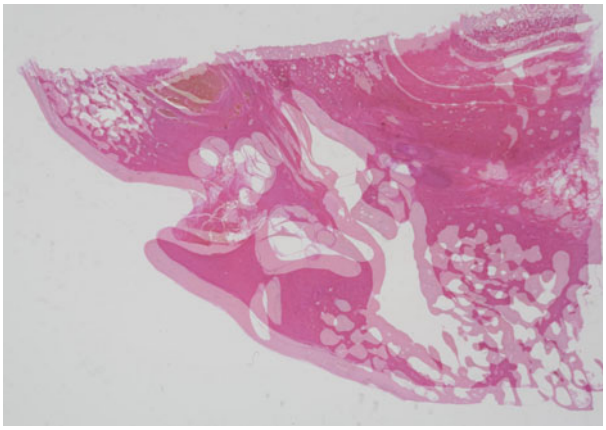


FIG. 1

Non-registered photomicrograph images prior to processing, with the uppermost image shown at 50 per cent transparency to allow registration.

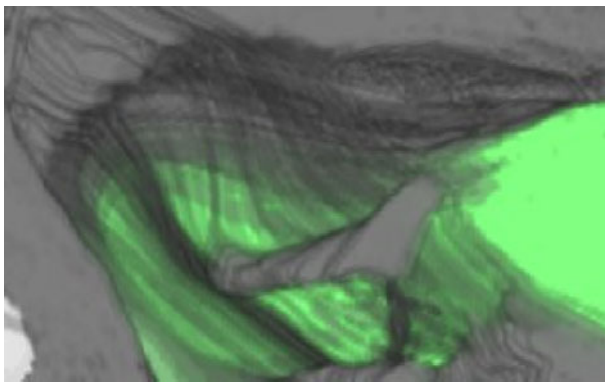


FIG. 3

Prepared image showing the handle of the malleus attached to the tympanic membrane. Note the fine detail of the translucent tympanic membrane.

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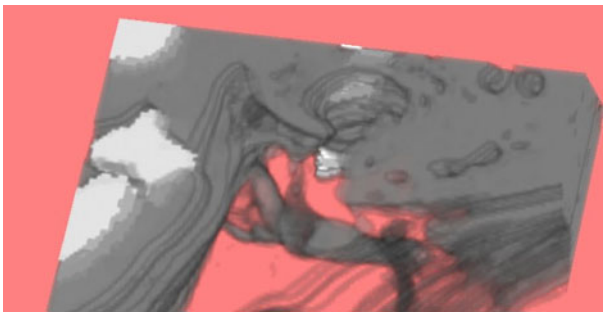


FIG. 4
Magnified prepared view showing the stapedius muscle extending from the pyramidal eminence to the head of the stapes.

It was also possible to create stereoscopic anaglyph projections to enhance the 3D realism of interacting with the model.

Discussion

This study aimed to investigate whether it was possible to produce a high-resolution, volume rendered 3D temporal bone reconstruction derived entirely from histological sections.

This question is pertinent because of the daunting technical and resource challenges involved. In the past, a balance had to be reached between interactivity and resolution as a result of limitations in computer processing power. An increase in detail or resolution of the dataset used to reconstruct the 3D model led to a reduction in interactivity. This problem is illustrated by surface rendered models which, despite providing a very detailed view of temporal bone anatomy, are severely limited in interactivity such that the observer can merely orientate the model.[5] Another problem with this type of model is that it does not incorporate the bony tissue that the otologist has to drill away. It is restricted to showing artificially coloured (and often smoothed) soft tissue structures. In this study, a model was produced that can be interacted with in real time. Furthermore, the structures have not been artificially coloured or smoothed, and they incorporate bone. A surface rendered model does not allow structures such as the compartments of the cochlea to be seen within the anatomical object. However, this can be achieved in the volume rendered model produced during this study.

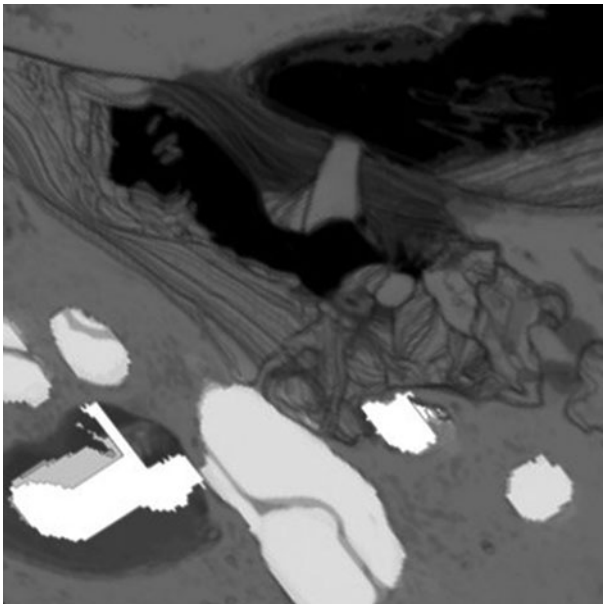


FIG. 5
Prepared view of the stapes superstructure (with footplate and incudostapedial joint). The facial nerve is in close proximity. Note the fine detail of the stapes, seen despite higher magnification.

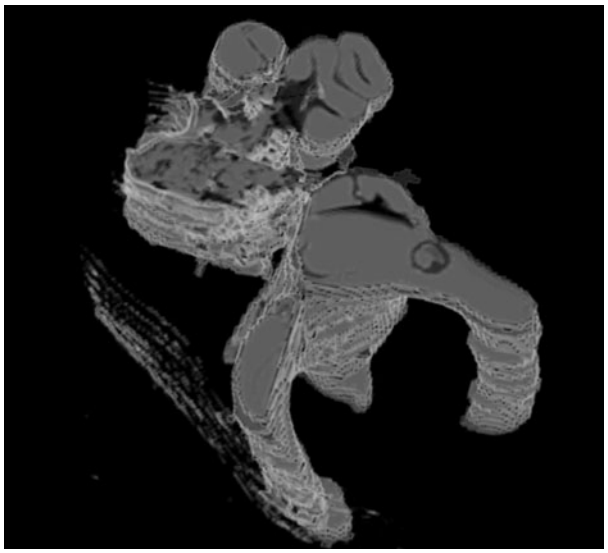


FIG. 6
Prepared view of part of the membranous labyrinth, showing the cochlea, the semicircular canals and the nerve tissue in the internal auditory meatus.

At the other end of the spectrum, there are models volume rendered from CT and MRI scans, which allow much greater interactivity (such as cutting away bone). However, the resolution of these models is inadequate for training otologists. In many cases, the semicircular canals look flattened, the stapes footplate cannot be seen and many soft tissue structures were omitted as a consequence of partial volume averaging.[6] Some studies have used volume rendering of only parts of the temporal bone, or have artificially enhanced the model; for example, those based on the Visible Human Project.[7–9] Sorensen *et al.* developed a significantly improved volume rendered model that demonstrated good interactivity with haptic feedback, with smoothing and colouring of structures.[10] However, this model was based on every fifth 25 μm thick section, resulting in significantly lower resolution than the model of the entire temporal bone presented in this paper. Furthermore, unlike our model, the stapes, incus and malleus were included only as surface rendered structures. Attempts in the previously published model to improve interactivity, by smoothing and colouring structures for example, detracted from its anatomical

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detail (by lowering resolution).[10] Rapid prototyping was employed in a recently published preliminary study. However, this was based on CT data, and, even after repeated alterations, there were some anatomical inaccuracies (e.g. no scutum).[11] A review of the literature reveals that the 3D model produced in this study is the world's highest resolution volume rendered temporal bone reconstruction derived from histological sections.

The model produced in this study has sufficiently high resolution to adequately show the stapes footplate, the semicircular canals as circular in cross section and the surgically relevant soft tissue structures. In addition, it is a highly interactive volume rendered model with the potential to become even more interactive with further improvements in software and hardware performance.

The fact that a desktop PC with an adequate graphics card can now be used to produce a volumetric 3D model shows the astonishing power of the PCs we all use routinely. With reductions in both the time available for higher surgical training and the supply of cadaveric temporal bones, it is necessary to prioritise the production of improved training models to enhance surgical training.

- **The temporal bone is a highly complex structure**
- **Both surgical training time and the supply of cadaveric bones are being reduced**
- **Computer-based temporal bone models can augment training**
- **Current models based on computed tomography and magnetic resonance imaging lack resolution**
- **We report a high-resolution three-dimensional temporal bone model based on histological sections**
- **This model has the highest resolution achieved so far**

There are areas in which the model produced in this study could be improved. For example, the surfaces over the volume could be 'smoothed' if appropriately compatible software was produced to more accurately simulate the surfaces of the temporal bone structure encountered during surgery. The incorporation of colouring and texture would improve the realism, which is crucial if a 3D model is to be useful for training. The development of cutting burr simulators with haptic and auditory feedback compatible with a high-resolution model based on real histological microanatomy, as opposed to that reconstructed from CT or MRI, would be extremely useful. However, such improvements in interactivity must not be obtained at the cost of anatomical detail, as occurred in previously published models.[6,10] We are optimistic that increasing computing power and graphics capability will lead to future improvements in terms of both resolution and interactivity of the models.

Worldwide temporal bone collections can provide a resource to generate a 'library' of all the surgical conditions that a trainee – and his or her trainer – is ever likely to encounter. All that is needed is collaboration, leadership and the appropriate resources.

Conclusion

This study demonstrates the feasibility of producing an anatomically accurate, 3D, volume rendered temporal bone reconstruction on a PC. Furthermore, this model has been derived entirely from histological sections, as opposed to CT or MR data, thus making it the world's highest resolution temporal bone reconstruction. With the increasing difficulty in procuring cadaveric bones, this model could be a useful adjunct for surgical training.

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Address for correspondence:
Mr Noweed Ahmad,
8 Stonebridge,
Darlington DL1 1PB, UK

Fax: 01325 288335
E-mail: dr_n_ahmad@yahoo.co.uk

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