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Virtual reality modelling language: freely available cross-platform visualization technique for 3-D visualization of the inner ear

Paul Hans, B.Sc., M.B., Ch.B., Alan Jackson, Ph.D., F.R.C.R.*, James E. Gillespie, F.R.C.R.*, Richard T. Ramsden, F.R.C.S.

Abstract

This was a study of the use of virtual reality modelling language (VRML) for cross-platform interactive three-dimensional (3-D) visualization of high-resolution magnetic resonance (MR) images of the inner ear in the assessment of cochlear implant candidates.

A retrospective case review was made of cochlear implant candidates undergoing pre-operative high-resolution MR studies to determine their suitability for implantation. 3-D visualizations of MR scans of the inner ear structures were created using surface rendering and exported as portable VRML files.

Case studies are presented to illustrate different points of interest. VRML reconstructions aided the interpretation of two-dimensional (2-D) source images in a variety of inner ear abnormalities.

VRML is an internationally recognized standard for cross-platform 3-D visualization that creates a means of providing the implanting surgeon with a portable 3-D representation of the inner ear, aiding interpretation of the complex cross-sectional anatomy of these structures, and guiding selection of patients for implantation as well as implantation technique. The elucidation of the mechanisms behind inner ear malformations can also be aided by detailed imaging studies of the temporal bone, with VRML reconstructions providing an easily interpreted representation of deformities.

Key words: Internet, Imaging, Three-Dimensional; Magnetic Resonance Imaging; Cochlea; Cochlear Implantation

Introduction

Imaging is an important part of the pre-operative assessment for cochlear implant candidates.[1–3] Computed tomography (CT) is used to assess the temporal bone for any abnormalities which may complicate the surgical approach to the cochlea, such as the presence of a high jugular bulb, an abnormal course of the facial nerve, and patterns of pneumatization. It is also used to assess the cochlea for its ability to accommodate the electrode array by identifying congenital malformations and obliteration of the scala, which may contraindicate or require modification of the planned operation. CT has been shown to be accurate in predicting varying degrees of cochlear obliteration in 78–95 per cent of cases when compared to surgical findings.[4–8] However, if only cases of postmeningitic hearing loss are considered (26–37 per cent of cochlear implant candidates, causing 44 per cent of cochlear obliteration[8]) the accuracy of this imaging modality can drop to 53 per cent.[6] This may be due to the relative inability of CT to demonstrate the very small difference in attenuation between fluid and the fibrosis or poorly mineralized ossification that is often found after inner ear involvement in meningitis – ossification may be mistaken for fibrosis or even a patent cochlea in these cases.[9] Magnetic resonance imaging (MR), using high resolution heavily T2-weighted protocols to image the fluid spaces and soft tissues of the labyrinth has become increasingly popular in pre-operative assessment of this group of patients, as well as those with congenital malformations, in whom it is used to define the degree of cochlear dysplasia and to confirm the presence and size of the cochlear nerve.[1–3] Fibrosis and ossification can be seen as voids in the fluid signal within the cochlea, and differentiation between the scala tympani and scala vestibuli is possible. Demonstration of extensive obliteration of the scala tympani may direct the surgeon to the scala vestibuli.[9]

Interpreting cross-sectional images of the complex structures of the inner ear requires considerable experience and an intimate knowledge of the normal anatomy of the labyrinth. Thirty or more two

From the University Department of Otolaryngology Head and Neck Surgery, Manchester Royal Infirmary, Manchester, and Imaging Science*, Stopford Medical School, University of Manchester, Manchester, UK.
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dimensional (2-D) slices through the inner ear must be mentally reconstructed and compared with the viewer's internal model of normal 3-D anatomy. When pathological states exist, particularly severe congenital malformations and extensive ossification, the anatomy may be so different from the norm that the viewer's internal model becomes redundant. In these cases 3-D visualization of the labyrinth using maximum intensity projection (MIP)[10,11] or, more recently, surface[9,10] or volume rendering techniques[10–16] provides a useful reference for the interpretation of the cross-sectional images.

Unfortunately, software for 3-D visualization of medical data sets is expensive and is rarely available outside the radiology department. This produces a logistic limitation that restricts the application of 3-D reconstructions to the reporting radiologist. Hard copies or 2-D images of a 3-D reconstruction diminish the value of the technique whose major strength is the free, real time interactivity with the images. An alternative approach to this problem is the use of Virtual Reality Modelling Language (VRML, pronounced *vurmul*).[17] VRML supports the description of 3-D objects, which can then be interactively visualized using free and easily available software. Since the VRML language was developed as an Internet format these VRML viewers are in the form of 'plug ins' (program extensions) for commonly available Internet browsers such as Microsoft's Explorer and Netscape's Navigator. This has the further advantage that VRML is a true 'cross-platform' standard, which can be used in any operating system. In addition the VRML description files are small and easily transferred via e-mail or the web.

We propose the use of the VRML format to provide a standard for the viewing and reporting of cochlear abnormalities from MRI images. Adoption of this standard would allow free distribution of, and access to, interactive 3-D visualizations by all clinicians involved in the management of the patient. Equally importantly, the use of VRML renderings supports the development of case collections in electronic format, which could be used for teaching, reference and classification. This paper demonstrates the utility of VRML visualizations in a selection of cochlear implant candidates who underwent high resolution MR imaging as part of their pre-operative assessment.

Materials and methods

Data acquisition

Images were acquired on a 1.5 Tesla Philips Medical System ACS NT scanner (Phillips Medical Systems, Best, Holland). The petrous temporal bone was localized using T1-weighted images in the three cardinal planes, and the position of the inner ear was subsequently identified using a series of 3 mm coronal T2-weighted fast spin echo (FSE) images. All localization images were obtained with the use of a head coil. High resolution imaging of the inner ear was performed using a 3-inch diameter flexible circular surface coil positioned over the external auditory meatus using a flexible-arm coil holder. A series of T2-weighted FSE volume acquisitions were performed using the following parameters: TR 5000 msec, TE 330 msec, slice thickness 0.5 mm, field of view 130 mm^2, matrix 256×256. A review of the development of this protocol is given elsewhere.[11]

Data visualization

Images were exported in Digital Imaging and Communications in Medicine (DICOM) format to a recordable CD (CD-R) and subsequently imported to a standard desktop PC with an Intel Pentium III processor and 128 Mb RAM. Data visualization was performed using a software application developed locally (Endovascular Surgery Planner (ESP)) using the AVS/Express visualization software package (Advanced Visualization Systems Inc., Waltham, MA). Raw data was processed by cropping the imaging volume to include only that part containing the inner ear structures. Surface rendering using the marching cubes algorithm was then performed by interactive selection of threshold levels according to contours projected onto the 2-D image data. After the 3-D model was created, surface segmentation, using a recursive connectivity algorithm, was applied in order to remove any structures, such as fluid in the mastoid cells and CSF surrounding the petrous apex, that were impeding visualization of the inner ear. Each 3-D model was then exported as a VRML file.

VRML files were visualized using Cortona VRML client 4.0 beta 2 (ParallelGraphics, Dublin, Ireland (http://www.parallelgraphics.com)), which is a freely available add-on for Microsoft Internet Explorer and Netscape Navigator.

Results

Case 1

A 41-year-old Cantonese-speaking female, deaf in the right ear since a febrile illness aged eight. The hearing on the left side was apparently normal until six years prior to presentation. While in China she was administered an injection, which she thinks was for allergic rhinitis. Within six months of the injection her hearing had begun to deteriorate in the left ear, and after nine months she was totally deaf. Promotory stimulation on the left side showed a good dynamic range.

CT scan showed a normal right ear, but there was a suggestion of a narrowed basal turn on the left side. She therefore underwent MR scanning to further delineate the defect. 3-D reconstruction of the right ear (Figure 1) confirmed a normal appearing cochlea. The only abnormality in this ear is the presence of a slightly enlarged endolymphatic duct and sac. 3-D reconstruction of the left ear (Figure 2) demonstrates widespread loss of fluid signal from the vestibule, basal and middle turns of the cochlea.

Despite the imaging findings, as the left side had a shorter duration of hearing loss, a drill-out procedure with split electrode insertion was performed.

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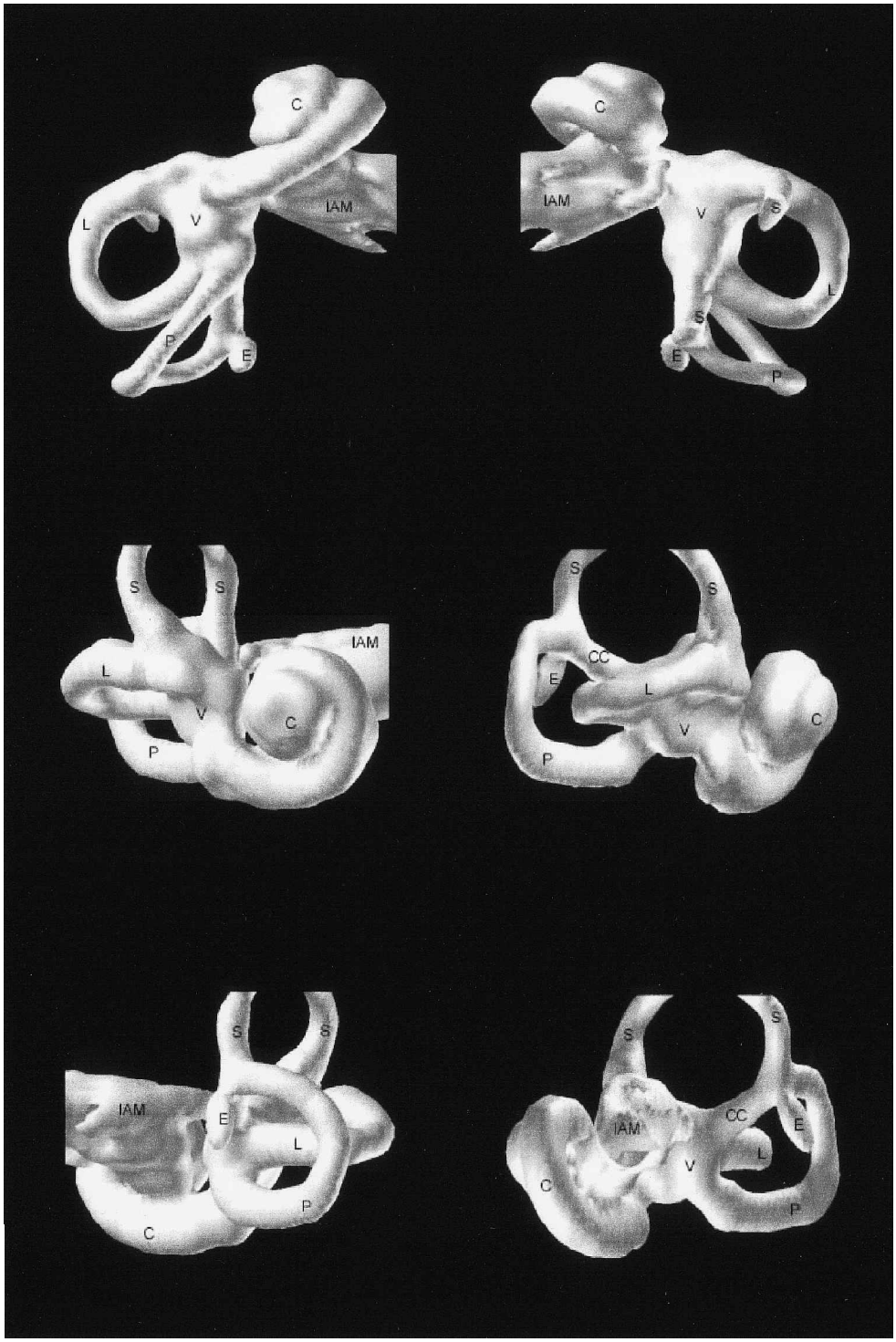


FIG. 1

Case 1, 3-D reconstruction of MR scan of right ear. The images are 2-D representations of a 3-D VRML rendering. Six views: inferior, superior, anterior, lateral, posterior and medial. This is an example of normal anatomy, except for a slightly enlarged endolymphatic duct and sac. Of over 60 patients imaged since 1996 only four others had visible endolymphatic ducts and sacs on MR imaging – these were all massively dilated, unlike this case.
C = cochlea; V = vestibule, S = superior semicircular canal; P = posterior semicircular canal; CC = common crus; L = lateral canal; E = endolymphatic duct and sac; IAM = internal auditory meatus.

Case 2

A 14-month-old male had contracted group B streptococcal meningitis aged three weeks. His parents immediately noticed a hearing loss, which was confirmed on evoked response audiometry. A trial of hearing aids failed, but apart from the hearing loss his development was normal.

A high resolution MR scan was initially reported by an experienced neuroradiologist with a special interest in temporal bone imaging as an essentially

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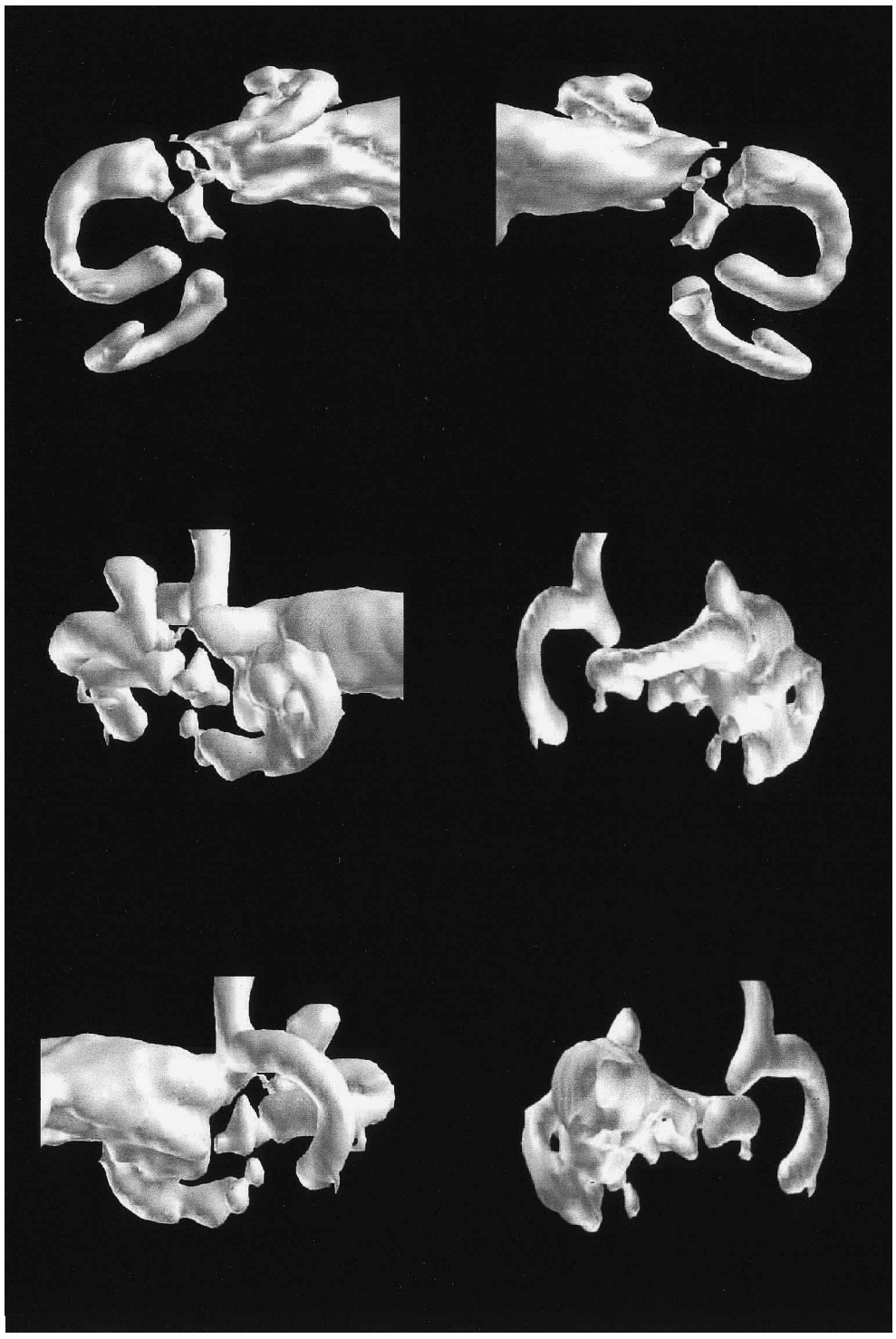


FIG. 2

Case 1, 3-D reconstruction of MR scan of left ear. The images are 2-D representations of a 3-D VRML rendering. Mirror images are presented here to aid interpretation by comparison with the normal anatomy shown by Figure 1. Widespread obliteration of the vestibule and cochlea can be seen. The superior semicircular canal is not fully included in the scan volume, resulting in the sharp attenuation of the medial limb. The lateral limb's attenuation is due to obliteration and shows a rounded end.

normal right cochlea, with slight narrowing of the basal turn on the left side.

He was therefore implanted on the right side with Nucleus CI 24k. A full insertion was achieved with two supporting bands out. However, a 3-D reconstruction which was created post-operatively reveals a loss of fluid signal from the middle and apical turns on the right side probably due to fibrosis or ossification, which, if it had extended any further into the basal turn may have lead to an incomplete insertion (Figure 3).

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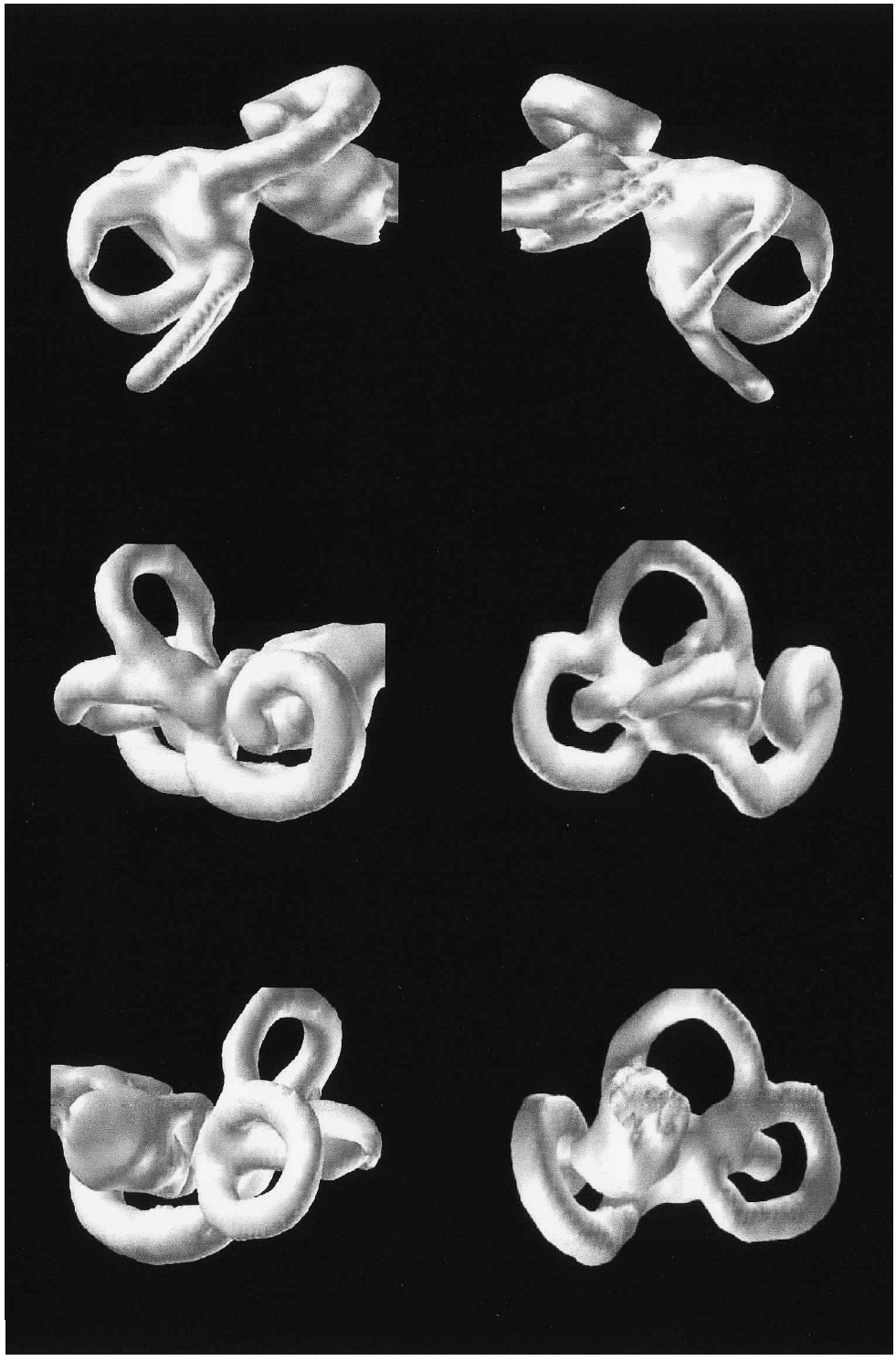


FIG. 3

Case 2, 3-D reconstruction of MR scan of right ear. The images are 2-D representation of a 3-D VRML rendering. Complete loss of fluid signal from middle and apical turns can be seen. In addition, the lateral semicircular canal appears to have a focal loss of signal.

Case 3

This was a 16-year-old female, self referred from Sri Lanka for assessment of congenital progressive hearing loss and consideration for cochlear implantation. On examination she was noted to have Duane syndrome affecting the right eye. Duane syndrome is a congenital eye movement disorder characterized by uni- or bilateral limitation of abduction and/or adduction, retraction of the globe on adduction associated with a narrowing of the palpebral fissure and occasionally upshoot or downshoot of the eye. Neuropathologic, neuroradiologic and neurophysiologic studies have all been cited in support of the hypothesis that the syndrome is a result of congenital absence of the VIth (abducens) nerve. No other abnormalities were detected on physical examina-

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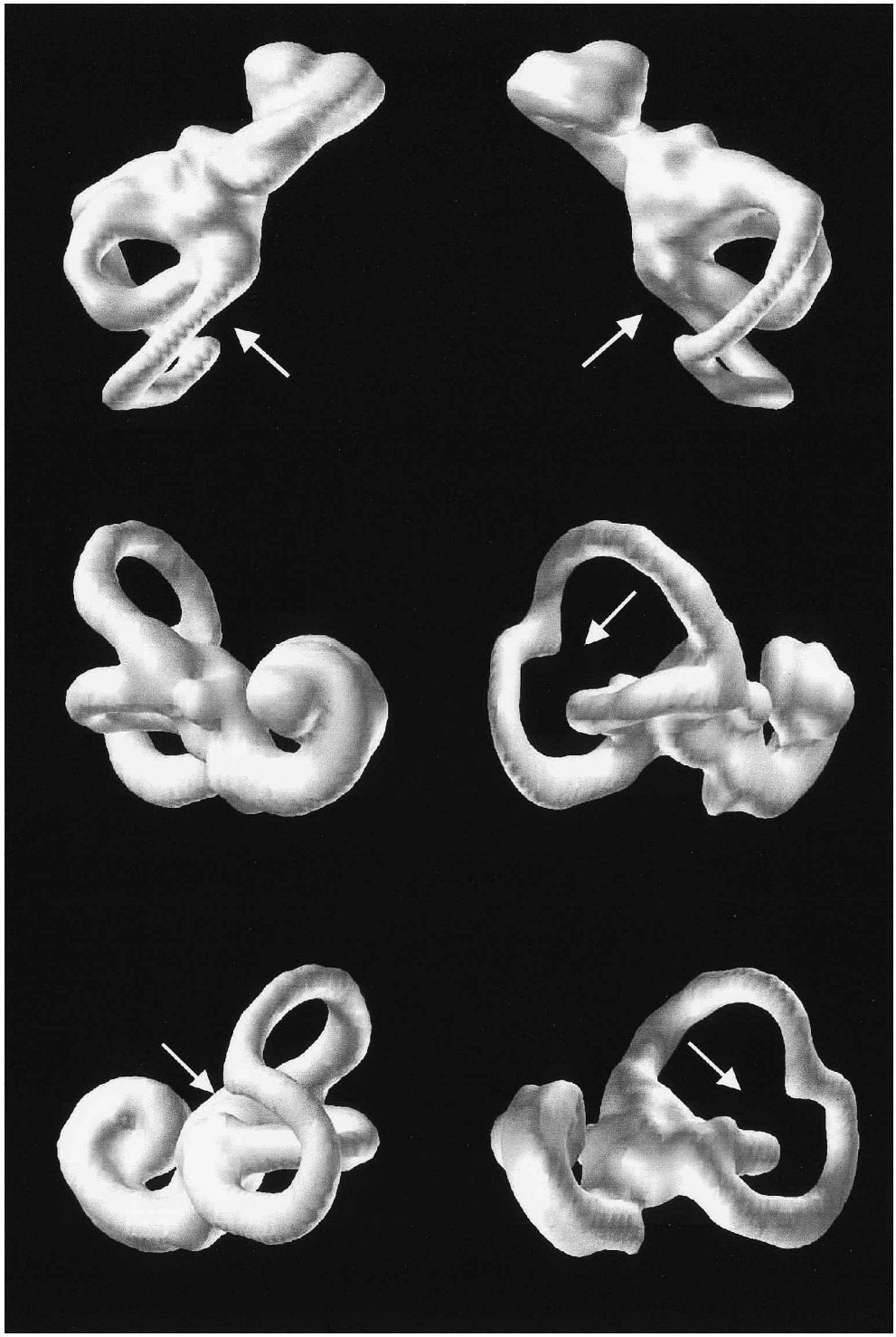


FIG. 4

Case 3, 3-D reconstruction of MR scan of right ear. The images are 2-D representations of a 3-D VRML rendering. Dysplastic cochlea, vestibule and lateral semicircular canal are seen. There is a complete loss of fluid signal from the common crus (arrow). The internal auditory meatus has been removed from this visualization using surface segmentation.

tion. Pure tone audiometry revealed moderate bilateral sensorineural hearing loss. She was fitted with hearing aids.

A CT scan suggested bilateral dysplasia of the cochlea, vestibule and lateral semicircular canal. High resolution MR scanning was performed to further define the congenital abnormalities. In addition to those abnormalities seen on CT scanning, 3-D visualization of the MR scan vividly demonstrated the loss of fluid signal from the common crus bilaterally (Figure 4). This was not immediately apparent to the experienced neuroradiologist who first interpreted the 2-D MR data. Once they had viewed the 3-D reconstruction however, the abnormality was easily identified on the 2-D images.

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Discussion

Until the introduction of high resolution 3-D FSE and constructive interference in the steady state (CISS) sequences, it was suggested that MR imaging did not have a role to play in the routine pre-operative assessment of cochlear implant candidates. MR is now more and more widely used for this purpose both as an adjunct to CT scanning and in some institutions as a replacement for CT scanning as the first line imaging modality.[1] Its advantages over CT include better depiction of intracochlear fibrosis and neo-ossification, demonstration of the presence of the cochlear nerve, a prerequisite to successful implantation, and the ability to image the central auditory pathways. Westerhof *et al.*[18] recently reported on their experiences of the evaluation of children with sensorineural hearing loss using CT and MR. They found MR and CT to be equally effective in detecting inner ear malformations, but in nine of the 21 patients studied a rudimentary or absent vestibulocochlear nerve was detected only by MR, with important implications for cochlear implant surgery. Casselman *et al.*[19] have also recently reviewed the assessment of congenital malformations of the inner ear using CT and MR, showing that MR provides additional detail to CT in the depiction of subtle abnormalities of the interscalar septae. This review utilized 3-D visualizations to demonstrate the abnormalities detected. Klingebiel *et al.*[14] provide a more detailed account of 3-D visualization of congenital malformations using 3-D CISS and volume-rendered reconstructions and conclude that radiological assessment with 3-D visualization of such complex labyrinthine pathologies can be performed in a routine imaging setting.

While MR is obviously superior to CT in many aspects, there are limitations to its usefulness as the sole imaging modality in the pre-operative assessment of implant candidates due to its relative inability to demonstrate much of the surrounding temporal bone anatomy routinely imaged with CT, abnormalities of which may complicate the surgical approach. It has therefore been suggested that a combination of MR and CT imaging provides the best pre-operative information. However, while more pre-operative information is available by utilizing both CT and MR, practical considerations can limit the application of this combination in some cases. For example, many institutions will not have a CT and MR scanner in close proximity to each other, increasing the risks associated with the transfer of small children who require general anaesthetic in order to undergo imaging. The Utah University group recommend 3-D FSE as a single modality for routine imaging in cochlear implant candidates – the majority of which will have normal surrounding temporal bone anatomy. Only in cases that demonstrate a congenital abnormality of the inner ear on MR do they perform a CT scan in order to detect any associated bony congenital abnormality such as that of the course of the facial nerve (found in 16 per cent of cases with a congenital abnormality of the inner ear).[1]

Acquired abnormalities

We have previously reported on the use of high resolution MR imaging combined with 3-D visualization to demonstrate obliteration limited to the scala tympani, which directed the implanting surgeon to a scala vestibuli insertion. Another case involved a normal-looking inner ear on CT scanning that was subsequently shown to return no fluid signal from any part of the inner ear on MR scanning, presumably representing fibrosis or ossification.[9] The first two cases in the current report describe further patterns of obliteration with different aetiologies that impact on the implanting surgeon's choice of insertion technique and device type. *Case 2* resulted from group b streptococcus meningitis. The pattern of obliteration would suggest that the spread of infection from the meninges occurred through the IAM, compared with a probable route of spread along the cochlear aqueduct for cases with obliteration limited to the scala tympani (as seen in the left ear of the same child). This child had a full insertion in the right ear after this was reported as normal on initial review of the 2-D films. A post-operative reconstruction, however, showed that the apical and middle turns were obliterated. Had the obliteration spread any further proximally, and not been identified preoperatively, an incomplete insertion may well have resulted. In this case the left ear may have been selected for implantation since the degree of narrowing of the basal turn was minimal and distal to this short segment the cochlea was fully patent. *Case 1* has no history of meningitis and no immediately identifiable cause of the very different pattern of obliteration seen. In this case the choice of which ear to implant was made by the duration of hearing loss in each ear but the imaging findings helped the implanting surgeon to select the appropriate device type and insertion technique pre-operatively.

Congenital abnormalities

In addition to acquired changes, 3-D visualization is useful in the interpretation of MR scans of congenital malformations. Jackler *et al.*[20] proposed a classification for congenital malformations of the inner ear based on embryogenesis, which was elegantly illustrated by diagrams of polytomographic examinations. The improvement in imaging techniques since Jackler's original article allows even greater insight into the relationship between embryogenesis and congenital malformations. The posterior semicircular canal is routinely visualized, more accurate measurements are possible, and in the case of MR scanning, no radiation exposure is necessary. Their hope that the 'accurate differential diagnosis of these disorders will permit a more reliable assessment of prognosis, a more precise description of hereditary patterns and a more tailored therapeutic approach' has been realized, with imaging findings in malformations impacting on decisions regarding cochlear implantation, lifestyle advice regarding head injury avoidance in large vestibular aqueduct syndrome, and genetic counselling in selected abnormalities.

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Case 3 provides an excellent example of the value of these new imaging and visualization techniques in the investigation of the mechanisms behind congenital malformations. This 16-year-old girl presented with a bilateral sensorineural hearing loss. On examination she was noted to have Duane syndrome, but no other congenital abnormalities were found. CT suggested mildly dysplastic cochleas, and she underwent MR scanning to further delineate the malformation. 3-D reconstructions demonstrate the mild dysplasia of both cochleas, and bilateral loss of fluid signal from the common crus becomes immediately apparent. Duane syndrome is an isolated finding in 70 per cent of cases, but the remainder are associated with other congenital malformations, which can affect skeletal, neural, ocular and otologic structures, as well as syndromes which involve the ear, including Wildervanck syndrome and Goldenhar syndrome. Both genetic and environmental factors are likely to be responsible for the aberrant development of the abducens nerve between three to eight weeks gestation, with the extraocular abnormalities also occurring during this time.[21] The malformation seen in the common crus of both ears in this case does not appear to correspond to any arrest in development that would fit with Jackler's classification. The superior semicircular canal is the first of the canals to develop at day 36, finishing on day 44. Its development overlaps with that of the posterior semicircular canal, with which it shares the common crus, which starts at day 42, finishing on day 47. If this malformation was due to arrest the lateral semicircular canals would be expected to be severely malformed as their development only begins on day 44; in this case only a mild dysplasia is seen. Manfre *et al.*[22] reported a case of Goldenhar syndrome with a unilateral absence of the common crus, but without Duane syndrome. They postulated that focal haemorrhages around the inner ear seen during embryogenesis in animal models of Goldenhar syndrome are responsible for the abnormal re-absorption of the neuroectodermal tissue of the common crus.

The increasing availability and continuing improvement in imaging technology means that more abnormalities are likely to be detected and characterized in future, leading to revisions in current classifications, especially as the molecular basis for the various malformations are elucidated

- **Imaging is essential in the pre-operative assessment of cochlear implant candidates**
- **The resulting series of cross-sectional images through the complex anatomy of the temporal bone can be difficult to interpret in the presence of significant pathology**
- **3-D visualization aids interpretation of the cross-sectional data in these cases**
- **3-D visualization software can be expensive and impractical to use in a routine clinical setting**
- **Virtual Reality Modelling Language provides an inexpensive, freely available means of providing clinicians with an easy to use portable 3-D visualization of the inner ear that can be viewed interactively across standard computing platforms**

VRML

The use of 3-D visualization techniques is becoming increasingly routine in many areas of medical imaging. The petrous bone is particularly suited to the use of 3-D visualization methods since it contains small complex structures which are difficult to appreciate from 2-D data sets. Unfortunately, the software necessary for this type of visualization is not readily available outside the radiology department. This restricts other clinicians' access to the 3-D visualization and effectively prevents them from experiencing the benefits inherent in real-time interaction with a 3-D model. VRML is a well-recognized and well-established standard for the representation of three-dimensional objects, which has previously been applied in otolaryngology, including temporal bone reconstruction[23] and haptic palpation of head and neck lumps.[24] Originally designed for use on the World Wide Web it describes the surface morphology of the structures being studied in a compact and easily transferable file format. Using the VRML file format a typical cochlear rendering such as the one that is shown here has a file size between 100 and 150 kB. This means that the 3-D model can be easily transferred by e-mail or by the World Wide Web. More importantly, the VRML standard is sufficiently well established that many free VRML viewing software packages are available. These are generally free or at a very low cost and most commonly acted as plug-ins for existing Web browsers such as Microsoft's Internet Explorer and Netscape's navigator. Versions of these browsers are available for all current operating systems including UNIX, Linux, Windows and MacOs so that the VRML file format is truly cross platform. The implications of this are that 3-D interactive images can be viewed by anybody with access to an Internet browser on even a low powered personal computer. For data sets the size of a cochlea the interaction with the 3-D model is effectively real-time on any current computing platform. The 3-D models can easily be attached to electronic reports and could be stored in electronic patient records. Equally important the VRML format provides a basis for archival collections of material for teaching and research, which can easily be made universally available via the Web for minimal cost. Many institutions hold a collection of temporal bone histology or radiology, and publish reports on their findings within such collections. However, in the case of rare malformations they may only hold one of each type. The Internet, online journals and VRML provide the opportunity for collaboration between such geographically separate groups with, for example, the creation of a virtual database of inner ear malformations accessible for reference from anywhere around the world. The traditional role of the

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journal may be modified by its expansion onto the Internet, by acting as host to such collections.

The VRML format does however have some minor disadvantages. Firstly, many visualization platforms do not currently have the ability to export images in VRML format although this can easily be remedied by the manufacturers if demand is sufficient. The second disadvantage is that the 3-D model in the VRML format does not retain much of the original information in the source images. The 3-D rendering which is produced uses isosurfaces selected by the initial operator and these cannot be changed once the model has been rendered into the VRML format. In practice we have found it not to be a major disadvantage and the selection of standardized isosurface levels for the VRML rendering is straightforward. In cases where the original operator identifies features which can only be appreciated with the use of alternative isosurface levels then it is simple to generate two or more VRML models to represent the findings.

Conclusion

VRML is an internationally recognized standard for cross-platform 3-D visualization that creates a means of providing the implanting surgeon with a portable 3-D representation of the inner ear, aiding interpretation of the complex cross-sectional anatomy of these structures, guiding selection of patients for implantation as well as the implantation technique used. The elucidation of the mechanisms behind inner ear malformations can also be aided by detailed imaging studies of the temporal bone, with VRML reconstructions providing an easily interpreted representation of deformities that can be shared among researchers around the world using the internet.

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Address for correspondence:
Professor Richard T. Ramsden,
University Department of Otolaryngology Head and Neck Surgery,
Manchester Royal Infirmary,
Oxford Road,
Manchester M13 9WL, UK.

Fax: +161 276 5003

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