The Journal of Laryngology and Otology
April 1996, Vol. **110**, pp. 322–327

Intra-operative image guidance in otolaryngology – The use of the ISG viewing wand

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Abstract

The ISG viewing wand is an intra-operative guidance system with a proprioceptive robotic-like jointed arm. It provides surgeons with almost instantaneously reconstructed computer-generated CT or MRI images in two or three dimensions and can correlate any point within the operative field to its corresponding locus on the reformatted scan images. In addition to having been used in over 400 neurosurgical patients in Bristol, 14 patients with skull-base, cerebello-pontine angle or temporal bone lesions have also undergone wand-guided resections. The wand has proved to be particularly useful in pre-operative planning, allowing minimally-invasive incisions, providing per-operative navigation, identifying the relationship and proximity of important anatomical structures and in assessing the extent of lesion resection. We illustrate the advantages of intra-operative image-guidance by discussing four cases. The potential applications of this form of imaging technology to other otolaryngological procedures are discussed.

Key words: Image processing, computer assisted; Stereotaxic techniques; Temporal bone; Cholesteatoma; Glomus jugulare tumour; Chordoma.

Introduction

Otolaryngology, like other surgical specialities, has benefited from recent improvements in imaging techniques. In particular, the availability of high quality, computerised tomography (CT) and magnetic resonance imaging (MRI) has revolutionized clinical practice. Advances in computer technology have enabled radiologists to reconstruct 3D scan images from 2D data and the role of 3D imaging is now well recognized in otolaryngology (Davis *et al.*, 1991; Friedman *et al.*, 1993). The potential intra-operative advantages of 3D reconstructions are still limited by several factors, however. Small operative fields may lack anatomical landmarks that would aid orientation with respect to the computer-generated images and small anatomical cues which would usually assist correlation may have been distorted or even destroyed by the pathology itself.

In neurosurgery, to maximize intra-operative accuracy, the location and biopsy of intra-cranial

TABLE I
WAND-ASSISTED OTOLARYNGOLOGICAL PROCEDURES

Case	Age	Side	Procedure	Diagnosis
1	34	R	Mastoidectomy	Glomus tumour
2	66	N/A	Trans-sphenoidal excision	Clivus chordoma
3	35	L	Petrosectomy	Cholesteatoma
4	25	L	Sub-occipital craniectomy	Recurrent glomus tumour
5	27	R	Sub-temporal craniotomy	Clivus chondrosarcoma
6	35	R	Sub-occipital craniectomy	Recurrent acoustic neuroma
7	66	R	Sub-occipital craniectomy	Clivus meningioma
8	37	L	Sub-occipital craniectomy	CPA meningioma
9	71	R	Petrosectomy	Secondary squamous carcinoma
10	46	R	Petrosectomy	Cholesteatoma
11	63	R	Sub-occipital craniectomy	CPA dermoid
12	28	R	Sub-occipital craniotomy	Recurrent clivus chondrosarcoma
13	71	R	Sub-occipital craniectomy	Acoustic neuroma
14	52	L	Sub-occipital craniectomy	Acoustic neuroma

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Presented in part to the Royal Society of Medicine, Section of Otology, 3 March 1995.
Accepted for publication: 9 January 1996.

lesions has traditionally been performed using stereotactic frame systems (Galloway *et al.*, 1991; Sandeman *et al.*, 1994). Such frames, however, are not versatile, restrict access to certain areas of the skull and do not provide 'real-time' intra-operative information.

In recent years, major developments in parallel processing technology have allowed some of these obstacles to be overcome. It is now possible to identify a specific point within the operative field with a probe and have its exact position shown instantly on a high resolution 2D or 3D computer-generated image (Zinreich *et al.*, 1991).

A system utilizing this technology has been used in over 400 neurosurgical cases in Bristol since June 1992. It has also been used in 14 neuro-otological and skull-base procedures (Table I). We describe its technical applications and illustrate, with case histories, the potential advantages that image-guided surgery can offer the otolaryngologist.

Materials

The 'viewing wand' is a system, created by ISG Technologies (Mississauga, Ontario, Canada) which links reconstructed computer images (formatted by an ISG Allegro computer from pre-operative CT or MRI data) to a position-sensing robotic-like articulated arm (built by FARO Medical Technologies, Lake Mary, Florida, USA). The arm has six joints, allowing unrestricted movement of any instrument fixed to its distal end. Its base is rigidly attached to a standard three-pin Mayfield headrest (Figure 1). Each joint contains a potentiometer, enabling the computer to calculate the exact spatial position of the instrument's tip, relative to the base, at any given time.

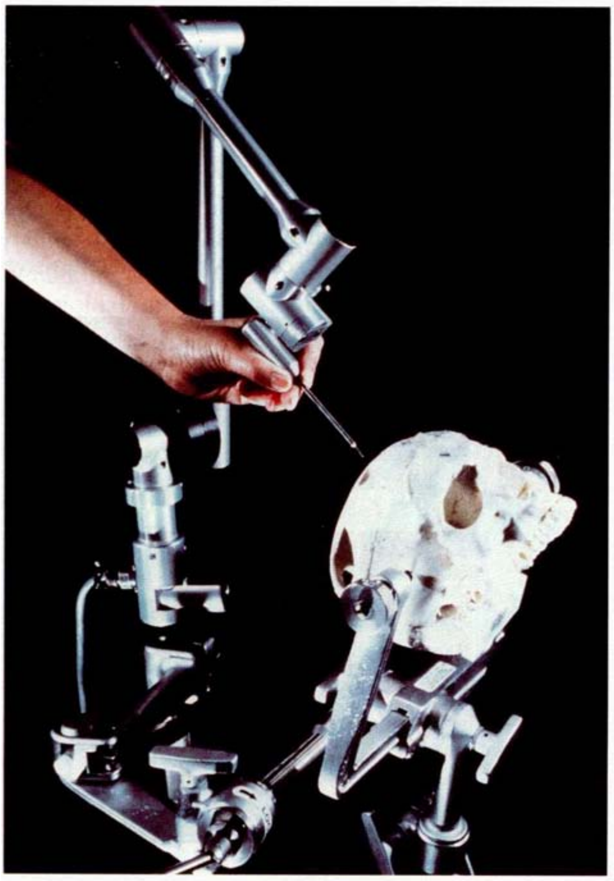

FIG. 1
The ISG viewing wand with a demonstration skull held in a standard Mayfield headrest.

The Allegro can provide almost instantaneous 3D reconstructions or reformatted 2D images in any plane required. This information is then linked to the proprioceptive signals from the arm, enabling the position of the pointer tip to be automatically marked on each computer-generated image (Zinreich *et al.*, 1991; Zinreich *et al.*, 1993; Sandeman *et al.*, 1994).

With the patient anaesthetized and their head fixed in the headrest, the system can be calibrated by several methods. For practical purposes, we have used a protocol utilizing five recognizable surface landmarks (e.g. nasion, inner canthi, tragus) then up to 30 random surface skin points linked to a contour-matching algorithm to further refine the registration (Sandeman *et al.*, 1994). The tip of the wand and arm is placed precisely on the relevant anatomical landmark and using a cursor, each location is manually correlated to an identical point on a 3D reconstruction of the patient's skin on the computer screen. The more numerous random skin surface points are automatically correlated to the image by the computer to refine its perception of the head's orientation and position relative to the fixed arm base. The whole registration process takes an average of 22 minutes (D. R. Sandeman, unpublished data).

After registration is completed, the system allows the surgeon to visualize the position of the probe in exact relationship to surrounding structures and surface anatomy. Wherever the probe is placed, its position can be shown on the screen in triplanar form (saggital, coronal and axial) or on a 3D reconstruction. Important anatomical landmarks (e.g. the internal carotid artery) can also be highlighted with relative ease.

The equipment is run on an industry standard Hewlett Packard computer (HP710) using Image Applications Platform software (IAP) developed by ISG for image processing. The 3D reconstruction of the patient's skin surface is carried out using the ISG Allegro software run directly on a UNIX platform of a Sun workstation with additional accelerator boards constructed by ISG. The Allegro/Sun equipment constitutes a sophisticated independent image processing workstation which is housed permanently in the radiology department. Data transfer between the Allegro and the wand occurs via an 'Ethernet' link between the radiology department and the operating theatre.

Case reports

Case 1

A 34-year-old woman with a mild right-sided sensorineural hearing loss secondary to childhood meningitis presented with a four-year history of

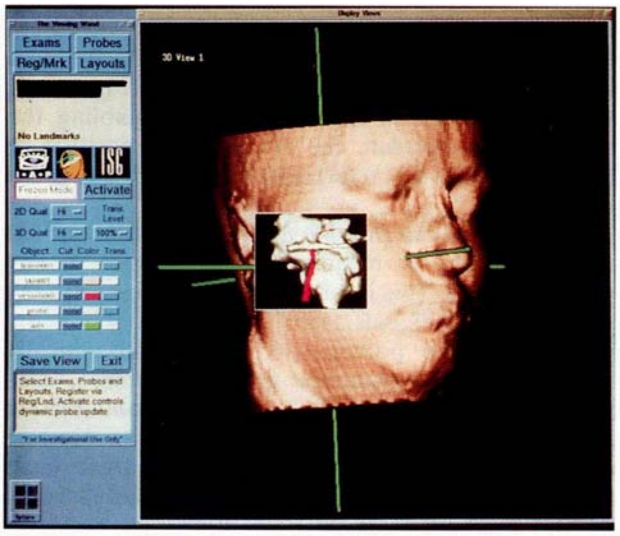

FIG. 2

A 3D reconstruction of right glomus jugulare tumour with the internal carotid artery shown in red.

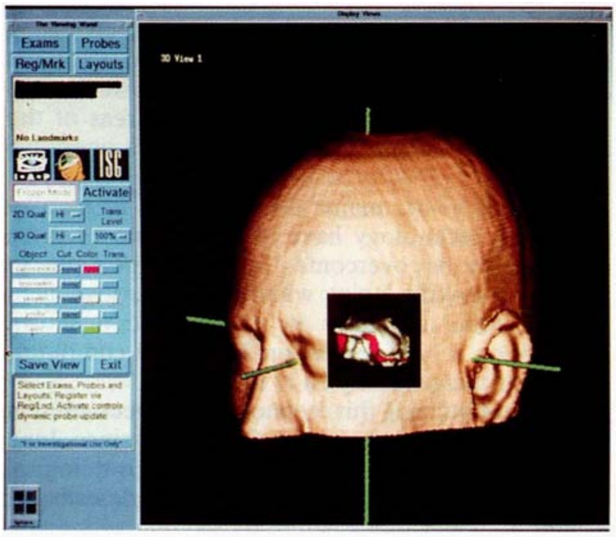

FIG. 4

3D reconstruction of clivus chordoma showing both internal arteries in red.

deterioration of hearing in the same ear. She had experienced several recent attacks of otitis media and a middle ear effusion was visible on otoscopy. An audiogram revealed the presence of a mixed conductive and sensorineural hearing loss. At exploratory tympanotomy, a glomus jugulare paraganglioma was confirmed within the middle ear. An MRI scan showed the lesion to be Fisch Class C_3D_2 (Valavanis and Fisch, 1989) replacing most of the right petrous temporal bone, extending to the cerebello-pontine angle, encasing the internal carotid artery and totally occluding the internal jugular vein. With the aid of 3D wand images (Figure 2), a two-stage procedure was planned. By a trans-cochlear approach, the extra-dural tumour was resected under image-guidance, with sacrifice of the facial nerve. The wand safely allowed an extensive resection of the lesion (Figure 3) and she was re-admitted eight months later for the planned second-stage resection of the residual intra-dural portion of the tumour with facial nerve cable grafting. At follow-up six months later a repeat MRI scan revealed no evidence of residual tumour.

Case 2

A 66-year-old gentleman had experienced diplopia for two years and presented only after noticing some facial numbness and mild left-sided tinnitus. On examination, he was noted to have a depressed corneal reflex, in addition to oculomotor and abducent nerve palsies on the left. There was no evidence of any significant vestibulocochlear impairment bilaterally. An MRI scan revealed an extensive

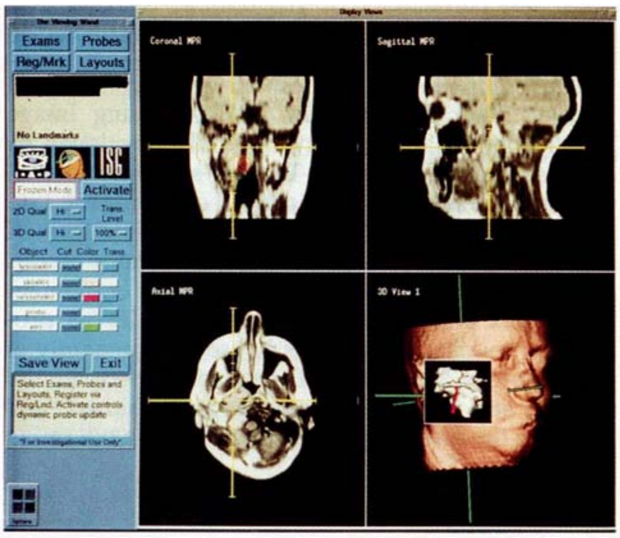

FIG. 3

Intra-operative tri-planar view of right glomus jugulare tumour. Centre of cross-wire indicates position of wand tip. Internal carotid artery seen passing vertically through lesion (red cursor).

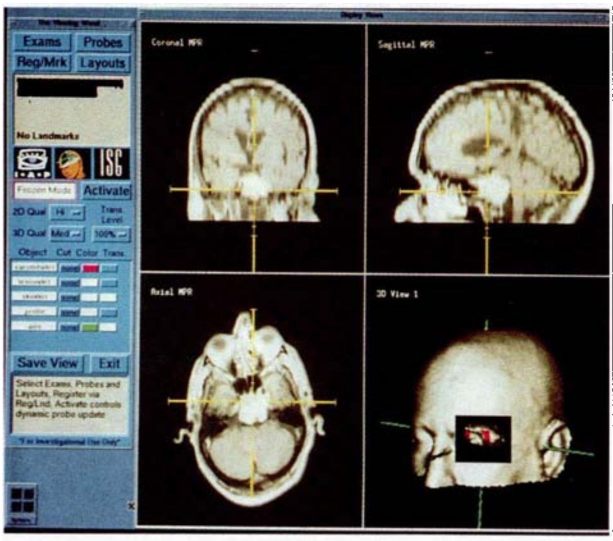

FIG. 5

Intra-operative tri-planar images during trans-sphenoidal dissection of chordoma (centre of cross-wires represents position of probe tip).

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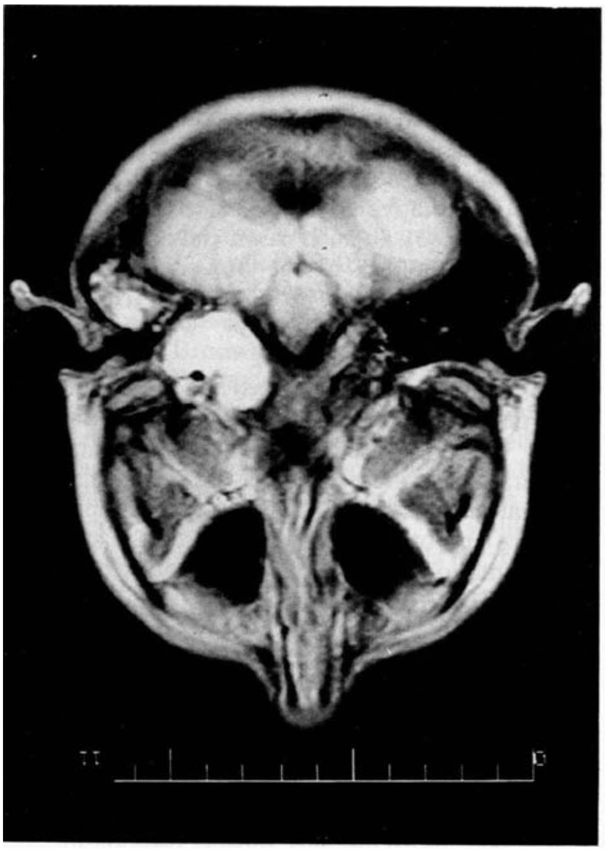

FIG. 6

Pre-operative CT scan showing large left primary cholesteatoma.

chordoma in the posterior part of the clivus, extending from the anterior lip of the foramen magnum to the posterior clinoid process and severely displacing the brain stem. Pre-operative study of triplanar and 3D reconstructed images, revealing the exact position of the carotid arteries (Figure 4), suggested that a significant tumour debulking could be achieved via an anterior trans-sphenoidal approach, avoiding the risks of lower cranial nerve damage.

Following removal of the anterior wall and septum of the sphenoid sinus, the lesion was extensively debulked. The wand provided invaluable information regarding the proximity of the internal carotid arteries at several times during the procedure (Figure 5). It proved technically impossible to resect the most postero-lateral elements of the tumour by this approach and a pre-sigmoid, trans-tentorial resection has subsequently been performed to resect the small amount of residual disease.

Case 3

A 35-year-old woman presented with a progressive left-sided conductive hearing loss. There was no other positive otological history. Facial nerve function was intact, as were other cranial nerves and otoscopy revealed a mass behind the postero-inferior part of an intact tympanic membrane. An MRI scan revealed an extensive primary cholesteatoma destroying a large portion of the petrous temporal bone (Figure 6).

A trans-cochlear approach to the lesion was undertaken, the cholesteatoma presenting just below the Eustachian tube opening. The wand was used to aid temporal bone dissection, identifying the position of the carotid artery and safely locating the inferior margin of the cholesteatoma. The lesion was debulked to allow the medial clival extent of the tumour to be identified. The wand was also used to check the completeness of matrix resection from the posterior fossa. Post-operatively the patient experienced transient vertigo but facial nerve function remained intact and she was discharged home on the sixth post-operative day.

Case 4

Following extensive surgery for resection of a left jugulare lesion six years previously a 25-year-old lady presented with hoarseness, mild left facial weakness and severe headache. A contrast-enhanced MRI scan revealed a lesion originating from the left jugular canal, extending out into the soft tissues of the neck, in keeping with a diagnosis of recurrent glomus tumour. A posterior fossa craniotomy was performed to expose the upper part of the sigmoid sinus. The skull base was then exposed as far as the jugular fossa in order to gain access to the intra-petrous tumour. The wand was used to locate the carotid artery, allowing a safe and precise resection of the entire lesion. The facial nerve was identified early in the procedure and protected throughout.

Post-operatively she had no new neurological findings and was discharged home on the 12th post-operative day.

Discussion

The case histories illustrate many of the ways intra-operative image guidance can facilitate surgical

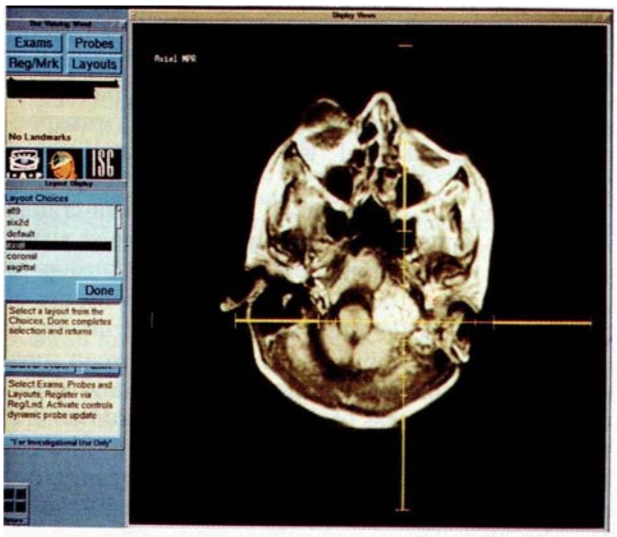

FIG. 7

Intra-operative axial reconstruction showing position of wand tip (cross-wires) during resection of recurrent glomus tumour.

https://doi.org/10.1017/S0022215100133559 Published online by Cambridge University Press

procedures. Using the Allegro computer, pre-operative assessment of the images allows minimally-invasive approaches to be considered (*Cases 1* and *2*). Intra-operatively, 3D reconstruction provides the surgeon with reassurance as to the proximity and orientation of adjacent vessels and neural structures, even though the structures themselves may never be exposed (all four cases). By using the wand to identify the margins of pathological lesions, it maximizes the amount of resection that is safely achievable (all four cases). Tumour tissue may be similar in character to normal or oedematous tissues within the same field but, providing that the lesion is distinguishable on the scan, the wand can easily identify its margins intra-operatively and assess the completeness of resection (*Cases 3* and *4*). By reducing the potential degree of damage to normal tissue and vital structures it therefore also minimizes operative morbidity.

The accuracy of the wand compares favourably to that of frame-based systems. Studies carried out on an ISG prototype report a mechanical accuracy of 1–2 mm when images are recreated from scans with a 4 mm slice thickness (Zinreich *et al.*, 1993) whereas the mean error with an external frame can be up to 3.2 mm (Galloway *et al.*, 1991). In reality, the wand is likely to be even more accurate than this as it is an interactive system whereby the surgeon has the ability to check and monitor the accuracy of the instrument throughout the procedure if any recognizable landmarks are available. The operator can, therefore, recognize any slight error and either compensate for it or re-register the system, something impossible to achieve with external frame devices (Sandeman *et al.*, 1994).

As our experience with the system has grown, mean registration time has come down from 37 minutes (Sandeman *et al.*, 1994) to 22 minutes and for intra-cranial procedures we have observed an approximate reduction of 40 per cent in anaesthetic time which more than compensates for the registration delay. We realize that meaningful comparisons with conventional surgical methods are now becoming difficult as the wand has now revolutionized our clinical practice to such an extent that most neurosurgeons using the system believe a prospective, randomized trial is no longer an ethical possibility.

The wand has largely been used for intra-cranial procedures, mainly because the intra-cranial structures tend to maintain their spatial relationship to one another and to the calvarium. The contours of the face and scalp (on which the instrument is registered) also remain unchanged between pre-operative scanning and intra-operative wand registration. In other areas of the body (e.g. abdomen and thorax) the spatial relationship between internal organs varies with body position and the respiratory cycle, thus precluding accurate wand registration. Despite this, there are other areas where wand accuracy remains high and the system has been used in the resection of peri-orbital tumours and spinal lesions (Dyer *et al.*, 1995; Pollack *et al.*, 1995). It is important to note that the system is calibrated to pre-operative images and although the relationship of the lesion to fixed structures, such as bone, is constant at the start of the procedure, this may not be maintained throughout the operation (e.g. the solid element of a partially cystic tumour may alter its position relative to the other tissues when the fluid is released). In such cases, the accuracy of the images can diminish as the procedure progresses, although this error can be reduced by constant re-evaluation of the registration, with appropriate compensation by the surgeon.

Although skull-base lesions and gross temporal bone pathology are obvious cases within otolaryngology where the use of the wand is advantageous, the para-nasal sinuses and naso-pharynx also fulfil the anatomical criteria that allow accurate image-guidance and other centres have used the system to aid orientation during functional endoscopic sinus surgery (FESS), it proving to be particularly valuable where there is recurrent or invasive pathology close to the cribriform plate or orbital apex (Anon *et al.*, 1994). Similar accuracy is claimed although, as the registration sequences used during FESS differ from those described here, the exact calibration errors have yet to be reassessed using model systems. The wand has also been used to aid the identification of the frontal sinus margins during osteoplastic flap procedures (Carrau *et al.*, 1994). When compared to a six foot Caldwell X-ray template, the system proved to be up to 1.75 mm more accurate in all cases of the reported series.

The optic nerve and other important nasal landmarks in the region of the orbit are easily seen on the reconstructed images and this technology has recently been used to aid trans-nasal orbital decompression, it being claimed that maximal decompression can be achieved easily with greater precision and safety (Hobson and Snyderman, 1996).

With anticipated improvements in accuracy, the wand should also be able to help identify other important landmarks within or adjacent to the temporal bone such as the endolymphatic sac. Localization of a displaced facial nerve is theoretically possible and would allow major resections to be undertaken whilst minimizing the risk of iatrogenic damage. Accurate assessment and exposure of basal skull fractures is also possible, potentially aiding dural repairs. These operative scenarios are likely to become possible in the near future if scientific progress in scan definition and wand accuracy continues.

We have described the wand as it is most frequently used, with a standard pointer attached at the end of the arm. However, other instruments have now been developed for use with the system, including a bayonet probe and biopsy devices (Sandeman *et al.*, 1994). The bayonet probe has also been used to fenestrate the sphenoid (Torrens and Sandeman, 1994), creating a minimally-invasive approach to the pituitary fossa and as other instruments are designed for use with the wand, it is likely that the current range of image-guided procedures will extend still further.

The viewing wand is not the only image-guidance system commercially available at present and there are other systems on the market (Laborde *et al.*, 1992; Takizawa, 1993). Systems which do not have a mechanical arm have also been devised. These use either ultrasound or electromagnetic techniques (Reinhardt and Zweifel, 1990; Barnett *et al.*, 1993) and other systems superimpose images onto the operating microscope field after registering to its focal length (Brodwater *et al.*, 1993; Pillay and Luber, 1996). Per-operative image-guidance is also only one way in which interactive 3D imaging can assist surgeons: computerized surgical simulators are now being introduced and robotic surgery is becoming a practical reality. Further progress in the field of computer-assisted surgery is also very likely to continue, generating exciting prospects for the future (McGovern, 1994).

We believe that intra-operative image-guided surgery represents a significant breakthrough for the treatment of many patients with a variety of conditions. The vast majority of our experience in Bristol has been with intra-cranial pathology but we have shown that the viewing wand has been extremely valuable in aiding the resection of skull-base and temporal bone lesions and is likely to be applicable for several other ENT procedures. Although the safe resection of complex lesions will always ultimately depend upon the skill of the surgeon, intra-operative image guidance can optimize the precision and safety of the procedure in many cases.

Acknowledgements

We are grateful to Mr R. J. Nelson, Consultant Neurosurgeon, Frenchay Hospital, for allowing us to present details of patients under his care.

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