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Review

Pre-operative planning and intra-operative guidance in modern neurosurgery: a review of 300 cases

John Wadley, Neil Dorward, Neil Kitchen, David Thomas

University Department of Neurosurgery, Institute of Neurology, National Hospital for Neurology and Neurosurgery, London, UK

Operative neurosurgery has recently entered an exciting era of image guided surgery or neuronavigation and application of this novel technology is beginning to have a significant impact in many ways in a variety of intracranial procedures.

In order to fully assess the advantages of image guided techniques over conventional planning and surgery in selected cases, detailed prospective evaluation has been carried out during the advanced development of an optically tracked neuronavigation system. Over a 2-year period, 300 operative neurosurgical procedures have been performed with the assistance of interactive image guidance, as well as the development of new software applications and hardware tools.

A broad range of intracranial neurosurgical procedures were seen to benefit from image guidance, including 163 craniotomies, 53 interactive stereotactic biopsies, 7 tracked neuroendoscopies and 37 complex skull base procedures. The most common pathological diagnoses were cerebral glioma in 98 cases, meningioma in 64 and metastasis in 23. Detailed analysis of a battery of postoperative questions revealed benefits in operative planning, appreciation of anatomy, lesion location, safety of surgery and greatly enhanced surgical confidence.

The authors believe that image guided surgical technology, with new developments such as those described, has a significant role to play in contemporary neurosurgery and its widespread adoption in practice will be realised in the near future.

Key words: Stereotaxy – Image guided surgery – Neurosurgery

Correspondence to: Mr J.P. Wadley, University Department of Neurosurgery, Institute of Neurology, The National Hospital, Queen Square, London WC1N 3BG, UK. Tel: +44 171 837 3611; Fax: +44 171 278 7894; E-mail: j.wadley@ion.ucl.ac.uk

Precise pre-operative planning and intra-operative localisation and orientation have always been paramount issues in neurosurgery. This owes as much to the delicate and unforgiving nature of the human brain as to the difficulty of localising a hidden lesion in three-dimensional space. Neurosurgeons have, for many years, been able to locate intracranial lesions with a high degree if accuracy using stereotactic frame systems, and these devices have reached a high level of engineering sophistication utilising both CT and MR imaging.[1]

Nevertheless, despite their proven accuracy, stereotactic frames are bulky and cumbersome, require invasive fixation to the patient's head and waste valuable theatre time whilst the patient is anaesthetised with the frame applied prior to imaging. They are essentially designed only to deliver a point-based instrument such as a biopsy needle to a target along a linear trajectory and are certainly impractical as a means of guidance during complex skull base surgery, for example.

In recent years, many technical advances in neurosurgery have made possible ever more complex and demanding procedures, and with this progress has come an increasing necessity to accurately ascertain the position and orientation of the surgical field.

With these problems in mind, several neurosurgical groups around the world have been committed to the development of more advanced methods of intra-operative orientation that can provide the surgeon with interactive, dynamic feedback during surgery and permit visualisation and avoidance of vital structures such as major arteries and venous sinuses as well as the confident localisation of lesions such as tumours and vascular malformations.[2–6] This core technology, which relies upon powerful computer workstations to process imaging data and run advanced software applications, has come to be known by a variety of titles including image guided surgery, computer assisted surgery, and neuronavigation.

Our institution has been involved in the advanced development and detailed clinical validation of a prototype navigation system.[7,8] We have evaluated this technology in 300 varied intracranial procedures over a 2-year period, and performed detailed studies of accuracy and functionality as well as developing a number of new tools and techniques.

Methods

The EasyGuide Neuro navigation system consists of a Sun-based workstation with a high resolution monitor housed in a mobile cabinet that may be easily moved into the operating theatre (Fig. 1). The workstation runs the advanced image processing algorithms and dedicated software applications that provide the surgeon with detailed graphical feedback during surgery. The position of hand-held pointers (Fig. 2) that incorporate light emitting diodes (LEDs) in a preset geometry are precisely determined by a three-dimensional camera array that attaches to the operating table and projects over the operative field (Fig. 1).

In order to maximise the potential utilisation of the system within the operating department of our institution, we have established a dedicated protocol for the efficient operation of the system through all the steps

Figure 1 EasyGuide system in the operating theatre. The position of the pointer that the surgeon is holding on the skull is determined by the camera array attached to the table at the left of the picture. The EasyGuide platform is to the right of the surgeon, the three orthogonal views of the images show the exact pointer position during the planning stage of a craniotomy to resect a larger parafalcine meningioma.

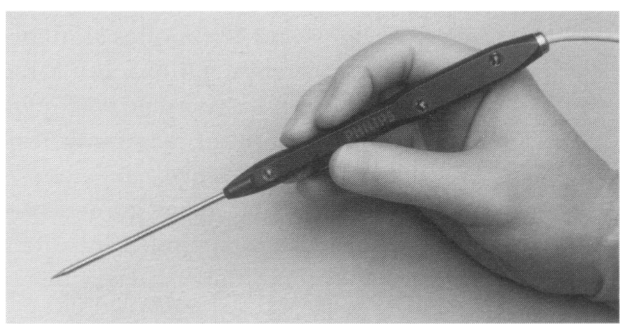

Figure 2 Hand-held pointer instrument. The pointer instruments are available in variable lengths, both straight and bayonet. The three LEDs are seen on the handle of the instrument, the infra-red flashes of light from which are detected by the three-dimensional camera array and thus the exact position of the pointer tip calculated.

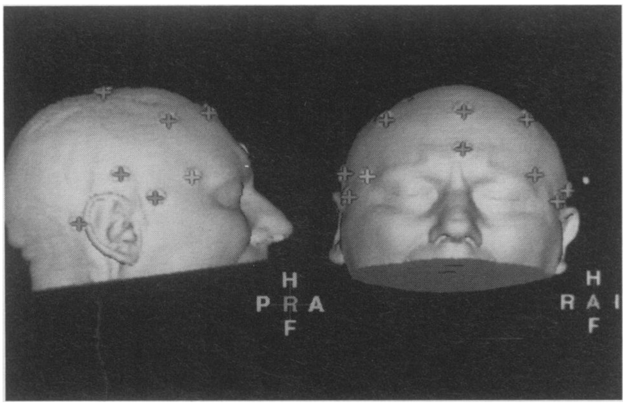

Figure 3 Three-dimensional segmentation of patient's head from MR images showing distribution of scalp fiducial markers, appearing as crosses after registration is complete.

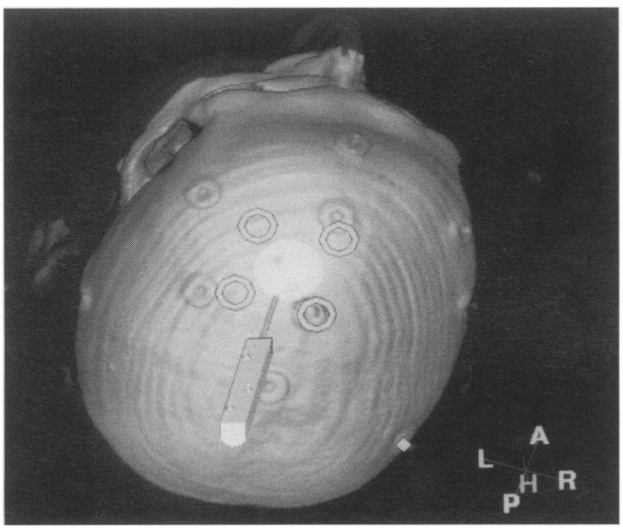

Figure 4 Advanced interactive craniotomy planning: a three dimensional segmentation has been generated (bone from CT) and a small superficial right frontal meningioma marked as a volumetric ellipse. After registration the pointer position is dynamically displayed in three dimensions, enabling the surgeon to exactly trace the contours of the tumour and effecting a small, minimally invasive craniotomy that is highly accurate, thus minimising brain manipulation.

in the process. Prior to surgery, adhesive fiducial markers are placed in predetermined positions in a surrounding volume upon the patient's scalp and imaging with standardised protocols, either CT or MRI or both, is carried out the day before surgery or sometimes immediately prior to surgery. For complex skull base procedures, dual registration with both CT and MRI is usually performed. The imaging dataset is transferred via the DICOM (Digital Imaging Communication) imaging network to the system in the theatre, the patient's head is secured in Mayfield pins and, after positioning of the camera array, patient-to-image registration is carried out.

The exact centre of each marker in the images is defined and stored on the workstation screen using the mouse-driven cursor (Fig. 3) and the position of that marker upon the patient matched by placing the tracked pointer into each marker in turn. Once this process of patient-to-image registration is complete, the system displays the accuracy of registration (the measure of 'fit' of the patient with the images) as a mathematical expression, the root mean square error (RMSE) of registration. If this value is unacceptably high, the operator may assess each marker for shift from its position in the images, and choose to delete, after consideration of their importance, any markers that have an unacceptably high value of error, thus improving the 'fit'. Once registered, the dynamic position of the pointer relative to the patient's head is displayed superimposed upon the images on the screen and the surgeon can further check the level of accuracy by placing the pointer tip on visible structures – such as the nose, ear or inner canthus – and correlating the position of the pointer upon the screen.

Using a variety of hand-held pointers, the surgeon uses the system to plan the craniotomy site and exact lesion margins with or without interactive craniotomy planning (Fig. 4), to navigate intra-operatively (Figs 5 & 6) or using specially developed tools and techniques, to perform interactive 'frameless' stereotactic biopsy (Fig. 7) or guided neuroendoscopy (Fig. 8).

Detailed information for each case is entered into a separate *Clinical Evaluation Protocol* (CEP) booklet. These CEPs are filed and the data entered into a relational database.

An important part of the introduction of such a system into neurosurgical practice is the detailed assessment of the true value to the operating surgeon. Scorings have enabled us to rank the subjective surgical impression of the advantages (or any disadvantages) of the tool. The surgical assessment survey is completed immediately after surgery and consists of a set of eight questions scored on a visual analogue scale from –5 (hindered / compromised) through zero (no effect) to +5 (greatly enhanced / advantageous). The questions are, what was your impression of the system on:

1. *Appreciation of anatomy.*
2. *Effect on surgical planning.*

3. *Localisation of the lesion.*
4. *Extent of resection.*
5. *Safety of surgery.*
6. *Effect upon confidence.*
7. *Duration of surgery.*
8. *Overall score.*

Results

Patient and case analysis

Between June 1996 and June 1998, a total of 295 patients underwent 300 intracranial operative procedures with interactive image guidance. Cases were selected for image guidance when the referring surgeon felt that there would be benefits – such as minimally invasive and more accurate approaches, more rapid localisation of small intracerebral lesions, guidance of a neuro-endoscope in difficult cases, avoidance of vital neuro-vascular structures, particularly in complex skull base cases, and more rapid performance of accurate biopsies without a stereotactic frame. These 300 cases represented 21% of the total of 1433 intracranial procedures performed during the study period, reflecting our groups' aim that this technology should not be used in routine cases but only when genuine benefits were

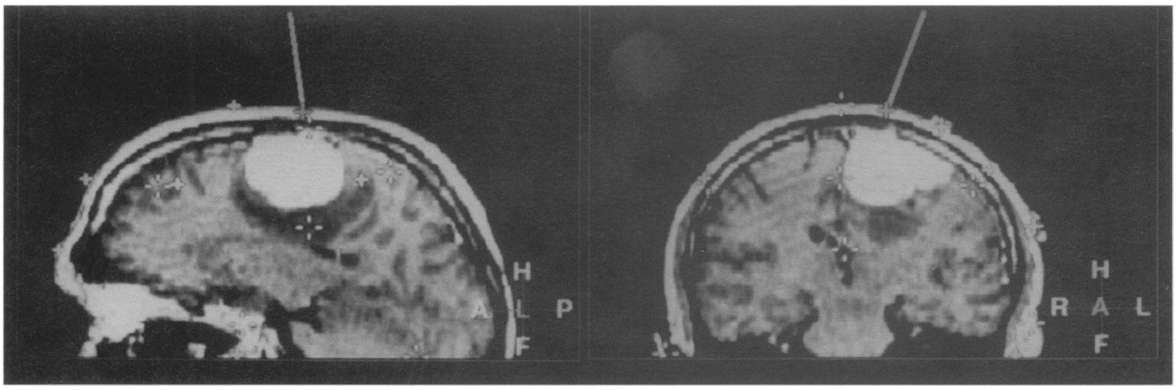

Figure 5 Sagittal and coronal MR views from workstation during planning stage of resection of a large parafalcine frontal meningioma. The pointer is seen on the scalp and its position enables the exact margins of the craniotomy to be determined. The midline sagittal venous sinus can be located and avoided during surgery, and during intratumoural resection the precise distance to the lesion edge ascertained.

Figure 6 Pointer position in sagittal and axial MR images during mid-facial degloving approach to a large recurrent pituitary tumour. In this particular case, the carotid arteries bilaterally and the basilar artery at the rear aspect of the tumour can be seen clearly in the images, and thus potentially catastrophic vascular injury avoided, as well as the position of the anterior aspect of the brainstem. A more radical resection may be carried out in the confidence of the exact anatomical position of the surgeon's instruments.

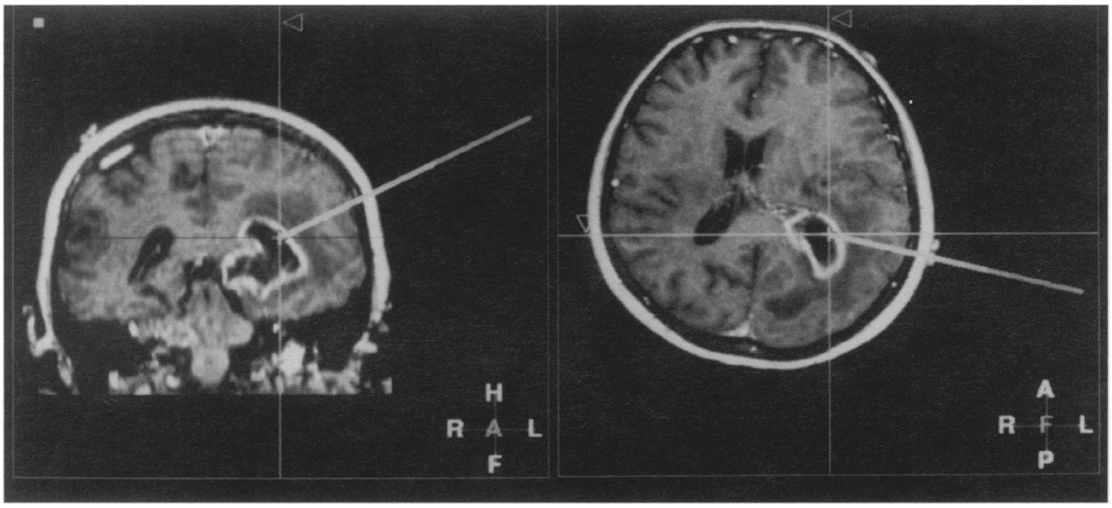

Figure 7 'Frameless' interactive stereotactic biopsy of a deep left parieto-occipital glioma, intra-operative coronal and axial MR images from EasyGuide. The pointer is held above the burr hole in a specially designed adjustable biopsy arm, and by 'virtual elongation' of the tip length the exact trajectory and depth to the tumour can be determined. The pointer is then replaced by the biopsy needle that passes to the tumour along this trajectory through the guide of the biopsy arm.

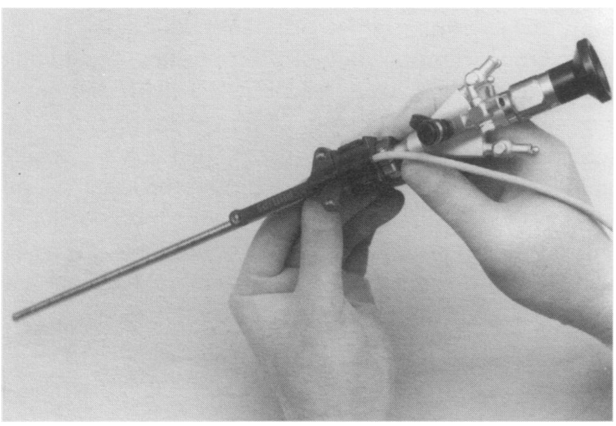

Figure 8 Image guided neuroendoscopy. The LED array attaches around the shaft of the rigid neuroendoscope, allowing the instrument to be tracked and appear as a 'pointer' on the workstation screen. The exact entry point and trajectory to the ventricles may then be planned, and the precise position and orientation of the endoscope tip within the brain continuously determined.

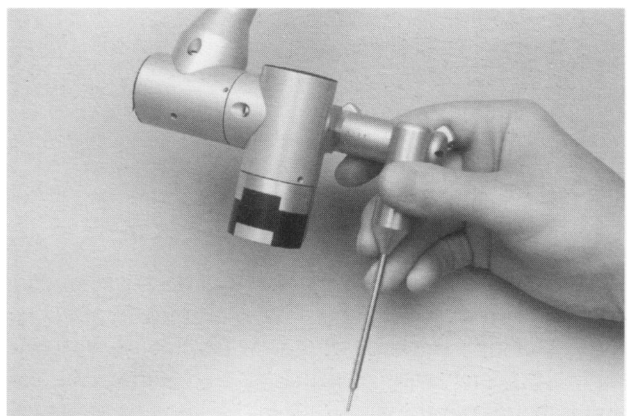

Figure 9 Mechanical surgical arm: the ISG Viewing Wand. The hand-held end of the arm is shown, the surgeon's hand manipulating the sterile metal pointer that acts a digitiser and localising device. The arm consists of four articulated joints and is connected to the operating table prior to surgery.

expected or new techniques were being validated. A summary of the proportions of some chosen cases is given in Table 1, reflecting the differing contribution and importance of image guidance to different types of procedure.

A steady increase in the use of the system was seen over the 2-year period as the advantages became apparent to individual surgeons. There was an even sex ratio with 153 male patients and 142 female patients. The age range of the patients was from 15 years to 77 years, with a mean of 45.5 years. The only exclusions to image guided surgery, apart from failure to visualise a lesion sufficiently upon imaging (no cases) were removal of scalp fiducials by the patient (three cases) and inability to remain still in the CT or MR scanner (two patients).

Table 1 Image guided surgery versus conventional cases

Number	Conventional	Image guided surgery	Total	% Image guided surgery
Craniotomies for glioma and metastasis	138	68	206	33
Craniotomy for meningioma	61	64	125	51
Craniotomy for vascular lesions	240	17	257	7
Neuroendoscopy	4	7	11	64
Stereotactic biopsy	25	53	88	60
Posterior fossa craniectomy	19	23	42	55
Complex skull base approaches	10	37	47	79

Table 2 Operations by subtype

Procedure	Number of cases
Craniotomy for glioma	53
Craniotomy for meningioma	64
Craniotomy for epilepsy	18
Craniotomy for metastasis	15
Other craniotomies	13
Posterior fossa craniectomy	23
Frameless stereotactic biopsy	53
Image-guided neuroendoscopy	7
Complex skull base	
Mid-facial degloving	9
Maxillotomy	8
Petrous approaches	7
Transglabellar	7
Transoral	2
Other skull base	4
Miscellaneous	17

Types of procedure

The system has been used by a total of twelve surgeons: eleven neurosurgeons and one otorhinolaryngologist during complex interdisciplinary skull base surgery. Eight surgeons were consultants, two senior trainees and two junior trainees.

The basic subgroups of operative procedure are summarised in Table 2. Image guided techniques proved applicable to the entire range of intracranial neurosurgical approaches. Imaging was MR in 231 cases, CT in 53 and dual registration with CT and MRI was performed in 16 complex skull base procedures.

The mean duration of surgery was 2.2 h (range 0.33–11.5 h, SD ± 1.37 h). Assessments were made by the operating surgeon as to the additional time that the image guided process made to the procedure in a cohort of 100 cases. This additional time was estimated to be less than 5 min in 72 cases, 5–10 min in 20 and greater than 10 min in 8. However, it was regarded that the benefits provided by computer assistance recouped this time in 82 of these cases. Interactive biopsy of tumours showed significant time savings over frame-based biopsy. In two matched cohorts of 40 cases results were: frame-based biopsy, mean time 140 min (range 110–190 min, SD ± 24.6 min), and image guided biopsies, mean time 90 min (range 60–150 min, SD ± 24.8 min).

Pathological diagnosis

An enormous variety of pathological diagnoses were encountered in the 300 cases, demonstrating the versatility of the system. By far the most common cases in which image guidance proved its value were operations for intracranial neoplasms, whether craniotomy and excision, craniotomy and debulking, or stereotactic biopsy. From a total of 237 tumours, 23 different histological types were encountered with the most common neoplasms being glioma (98), meningioma (65), metastasis (23) and pituitary adenoma (7). Image guidance also enabled a large number of other varied lesions to be approached, such as seizure foci in epilepsy surgery (24), complex cerebral aneurysms (3), subcortical cavernomas (5), deep intracerebral haematomas (3), abscesses (3) and arachnoid cysts (5).

Accuracy studies

Detailed studies have been conducted to assess the accuracy of the system both in clinical use and by laboratory studies of accuracy using artificial phantoms. Measurement of the accuracy of an interactive tool developed for stereotactic tumour biopsy revealed a mean error for 1.5 mm slice CT of 1.3 mm, SD 0.35 mm and for 3 mm slice CT this was 1.5 mm, SD 0.17 mm. The error with 1.5T MR imaging was 1.5 mm, SD 0.25 mm. Differences were statistically significant between 1.5 and 3 mm CT ($P < 0.05$) and between CT and MRI ($P = 0.018$).

In comparison, it is impossible to precisely measure the accuracy of the system in clinical use since there are no anatomical structures with which to precisely correlate a position in three-dimensional space. Nevertheless, an estimation of this 'application accuracy' (which must be distinguished from registration accuracy) has been made in a subset of 75 cases in the series by the calculation of the vectoral co-ordinates of two scalp markers not included in the registration set. Figures reveal a mean error for CT imaging of 2.0 mm (0.9–3.8 mm, SD 0.85 mm) and a mean of 1.63 mm for MRI (0.6–4.1 mm, SD 0.85 mm).

These figures compare favourably, and in most cases exceed, the accepted accuracy figures for stereotactic frame systems. We have found that in every one of 300 cases the 'real-world' application accuracy has been excellent in the majority and always sufficient for lesion localisation.

Registration accuracy as assessed by the root mean square error (RMSE) was seen to be remarkably consistent across six 50-patient cohorts (3.7, 3.6, 3.4, 3.7, 3.3, 3.2, respectively) with a mean of 3.5 mm (range 1.7–8.5 mm, SD 0.97 mm).

Table 3 Analysis of postoperative questionnaires

	Hindered (%)	No effect (%)	Enhanced (%)
Appreciation of anatomy	1	9	90
Effect on surgical planning	1	8	91
Localisation of the lesion	1	6	93
Extent of tumour resection	1	40	59
Safety of surgery	1	13	86
Effect upon confidence	0	1	99
Duration of surgery	11	20	69
	Det.	Amb.	Adv.
Overall score	0.3	1.7	98

Det. = detrimental; Amb. = ambivalent; Adv. = advantageous

New tools and techniques

During this project, dedicated tools and techniques were developed to enhance the functionality of our system. These included a lockable surgical arm and biopsy instrument guides to perform rapid and highly accurate 'frameless' stereotactic biopsy (Fig. 7), integration of a neuroendoscope (Fig. 8) with image guidance to improve targeting and orientation within distorted ventricular systems, advanced interactive planning software (Fig. 4), precise insertion of catheters into very small ventricles and techniques for the enhancement of complex skull base approaches (Fig. 6).

Surgical assessments

Analysis of the detailed postoperative questionnaire completed by each surgeon is summarised in Table 3. Significantly, for these selected 300 cases, 99% of responses showed enhanced levels of the surgeons' confidence and the overall score for the system demonstrated that in 96% of cases surgeons believed that there were significant advantages over conventional techniques.

Discussion

The objective of stereotactic methodology is to localise structures within the cranium by linking the surgical field; in other words the physical space of the patient's head, with pre- or peroperative images by the use of accurate registration of these two co-ordinate systems.[1]

Neuronavigation technology dispenses with the previously used rigid stereotactic frame systems as a registration method and uses instead anatomical points upon the patient's head. These may be adhesive markers or bone screws applied to the head prior to imaging, or a series of surface points sampled over the 'volume' of the scalp. The additional feature that differs with these new systems is the tools that are used to both establish these reference points (the digitiser) and to provide the method of surgical localisation (the pointer).

The era of interactive image guided surgery began in the mid-1980s when Roberts and co-workers adapted an operating microscope with sonic emitters to perform the dual function of a three dimensional digitising system and the method of localisation.[2] In this way, the focal point of the microscope was used as the point of localisation and the outline of the determined target structure incorporated into the microscope eyepiece as a 'head-up' display.

The first realisation of a digitising system using a hand-held device was by Watanabe, who used an articulated surgical arm for this purpose.[3,4] Since these pioneering examples, a number of other research groups around the world have independently developed similar systems with variations in digitising systems and registration algorithms. Most successful systems at the current time, including the system described in this paper, utilise LED based localisation first developed by Bucholz.[5]

The first commercial system was introduced in the early 1990s, the ISG Viewing Wand (Fig. 9), an arm-based system. Considerable experience has accrued in several centres around the world with this system, and a few publications have reported these series and demonstrated the considerable benefits to be obtained.[9,10]

Doubts have been expressed by some neurosurgeons about over-reliance upon technology and the effect that this type of guidance may have upon surgical skill and judgement. We have found that the increased appreciation of normal and pathological anatomy that interactive methods provide has actually had the reverse effect and led to a fundamental improvement in operative planning. This attitude has often been the case in the past when new advances occur, and our group has been careful to validate these techniques only in operative cases where genuine assistance was needed or expected. It has thus been our experience in this extensive series that distinct benefits may be expected in many types of procedure. In general, it has been observed that craniotomies are smaller and more precise owing to the accuracy afforded by image guidance, with potentials for time-savings and reduced blood loss. The finding upon opening that tumour margins are beyond the edge of the access has become a thing of the past and thus unnecessary brain manipulation is minimised. The confidence to pinpoint lesions below the cortical surface and again minimise access and trauma is regarded as a significant advance. We have been able to guide neuroendoscopes accurately within distorted ventricular systems and place catheters at depth 'first time' into ventricles as small as 2.5 mm. Complex skull base procedures have benefited from detailed pre-operative assessment and simulation of approaches and the visualisation and avoidance of vital neurovascular structures during drilling of bone at the cranial base, for example.[7] Accurate biopsies have been carried out in a fraction of the time that a frame based biopsy has taken in the past and with the ability to plan multiple targets and trajectories to lesions during surgery.[11] Although the postoperative assessments are, by definition, subjective, they have been overwhelmingly positive and may be seen as the views of a group of highly experienced surgeons who have critically appraised these techniques.

Experience such as that detailed in this paper with neuronavigation systems has now reached the stage where accuracy[10,12] and functionality[7,9] have been proven and the unique advantages of this technology clearly demonstrated. It is likely that, as systems continue to improve and evolve, and if criteria such as acceptable cost and reliability are realised, within several years it will be common-place in most neurosurgical units for a significant proportion of intracranial procedures to be performed with computer assistance. Indeed, it is possible that medicolegal considerations may reinforce this process. Critics may comment that benefits to patient outcome are harder to prove, and we would agree. It has not been the aim, or indeed the point, of this project to undertake such a task, or of any other publication to date in this field, but the actual advantages to the surgeon during surgery are so marked that these benefits are implied in the wider sense. Indeed, no such outcome analysis was ever undertaken in the past for advances in neurosurgical technology that are now regarded as indispensable, such as the operating microscope, bipolar diathermy or ultrasonic aspirators. The fundamental advance is the ability to further facilitate the surgical procedure and assist the surgeon in a technically demanding and challenging task.

There are still recognised problems that mean further research and development is needed in this field. Since imaging is performed pre-operatively, any deformation or 'shift' of the brain during surgery may lead to errors of localisation, although our studies have shown that patterns may be predicted and this is rarely detrimental.[13] Integration of intra-operative ultrasound may lead to correction of imaging datasets to account for this phenomenon.[14] There are inherent problems of scalp deformation with adhesive fiducials, and it is probable that registration methods under development may increase application accuracy further. The issues of distortion in CT and MR images also need to be addressed: we have developed a dedicated phantom to detect distortion and, in conjunction with specially designed geometric distortion correction software, we have observed a significant increase in accuracy in phantom studies with CT image datasets.[8]

The technology of intra-operative CT and MR scanning is now well developed in several centres and, whilst currently expensive and impractical for widespread use, with future development these machines may further add to the armamentarium of image guided surgery. [15]

Neuronavigation in the spine has, as yet, not reached a comparable level of accuracy, with significant problems of segmental mobility leading to poor registration accuracy.

It is possible that a modular system may become the preferred format in the future, with multiple registration methods and optional integration of tools such as the microscope, intra-operative ultrasound, endoscope, and even interventional CT or MRI.[16,17]

Conclusions

It is an undoubted fact that image guided neurosurgery is increasingly being adopted into routine practice. Clear and significant advantages have been established and it is now possible to extend stereotactic levels of accuracy, as well as interactive feedback, to the complete range of neurosurgical procedures. It is our belief that the widespread adoption of neuronavigational technology will lead to enhanced accuracy of surgery, minimal access and minimised trauma, improved operative planning and anatomical appreciation, better intra-operative orientation and markedly enhanced surgical confidence. It is anticipated that, as a result of these points and as part of general progress in surgical science, increased patient safety and better outcomes may be observed in a range of situations.

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