Image-guided neurosurgery

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Accurate localization of lesions and minimization of trauma to the surrounding brain are of paramount importance in intracranial surgery. Stereotactic frame systems provide highly accurate methods of localization, which has been further enhanced by the introduction of sophisticated imaging modalities, and recently by the development of interactive image-guided neurosurgical technology.

Precise preoperative planning and intraoperative localization 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 localizing a hidden lesion in three-dimensional space.

Early attempts at localized surgery of the cranium dating from as long ago as 3000 BC may be evidenced by the many skulls excavated by archaeologists in many parts of the world, showing the apertures in the skull created by trephination. It was until only recently, towards the end of the last century, that pioneering neurologists such as Rolando, Hughlings Jackson and Ferrier formulated the concepts of cerebral topography and organization, enabling the modern discipline of neurosurgery to begin to develop based upon attempts at accurately localizing lesions within the head.

The true visualization of lesions within the brain would have to wait until imaging modalities were devised later in the 20th century, but the science whereby anatomical structures may be located within the cranium with a high degree of accuracy was born in the early years of this century. This concept is known as stereotaxy (from the Greek *stereo* three-dimensional, *taxis* to move towards) and the therapeutic application of these methods has been termed stereotactic surgery.

In order to precisely locate an object within three-dimensional space its exact coordinates must be known and a method devised to define this ‘coordinate system’, a process analogous to using map reference points to find a geographical location, but in three rather than two dimensions.

THE ORIGINS OF STEREOTAXY

The first time that a true stereotactic apparatus was used was the frame system devised by Sir Victor Horsley and Richard Clarke at the National Hospital, Queen Square in 1906 (Thomas, 1993). This precision apparatus used a metal frame that attached to fixed landmarks upon the head of a monkey, and was used to accurately pass needles to reproducible points defined by three-dimensional coordinates that could be set upon the frame. Its use, however, was restricted to the investigation of the structure of the cerebellum and the technique was not applicable to humans since such landmarks are highly variable in man.

EARLY STEREOTACTIC SURGERY

It was not until imaging modalities allowed the visualization of the metal frame attached to the patient’s head that the patient’s anatomy could be mapped to an external coordinate system. In 1947 Spiegel and Wycis developed a system that utilized pneumoencephalography, enabling the exact position of deep brain nuclei to be calculated with respect to their known relationship to the third ventricle (Thomas, 1993). Coordinates were calculated with reference to a detailed brain atlas and the stereotactic frame used to pass a needle to the target.

The ability to approach and produce lesions within deep brain nuclei led to a blossoming of functional neurosurgery for movement disorders such as Parkinson’s disease, but after the introduction of L-dopa stereotaxy nearly died out in neurosurgery. Lesions such as brain tumours still could not be seen using the plain X-ray imaging techniques that were being used and thus stereotactic biopsy of these lesions had not yet been realized.

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MODERN STEREOTACTIC SURGERY COMES OF AGE

The development of computed tomography (CT) scanning and modern computer technology in the early 1970s allowed for the first time the clear visualization of tumours and other lesions in the brain, and neurosurgeons were quick to adapt existing frame systems such as the Leksell, and develop new dedicated systems such as the BRW (Brown–Roberts–Wells) and CRW (Cosman–Roberts–Wells) to enable the true potential of stereotaxy to be realized (Thomas, 1993). Modern systems have been further adapted to operate with sophisticated imaging techniques, such as magnetic resonance imaging (MRI), positron emission tomography (PET) and angiography, and coordinate calculations are rapidly performed by computer algorithms. In the last 15 years this has led to the routine biopsy of brain tumours and the performance of functional neurosurgery with a high degree of accuracy and a concomitant reduction in morbidity and mortality to very low levels.

The core objective of stereotactic methodology is to localize structures within the cranium by linking the surgical field, in other words the physical space of the patient's head, with preoperative or peroperative images, by the use of accurate registration or 'linking' of these two coordinate systems. With classical stereotactic frame-based systems this is achieved by fixation of the rigid frame to the patient's head, which serves a dual purpose. First it supports the 'fiducial' array during imaging (*Figure 1*), the fiducial rods appear as dots in cross section around the patient's head on the slices of the CT scan, and by using these fiducials to establish the coordinate system in which the head and target are sited, a target may be identified on the computer screen and its coordinates calculated using a mathematical algorithm. Second, after the patient is returned from the scanner to the operating theatre the base frame then provides a stable support for the arc system that is used to localize the target intraoperatively (*Figure 2*).

Figure 1. Stereotactic frame system: base-ring (gold) attached to patient's head under anaesthetic. The circular fiducial rod assembly is placed upon the base-frame in preparation for the stereotactic computed tomography scan.

PIONEERS OF IMAGE-GUIDED SURGERY

Despite their high degree of precision and accuracy, there are several fundamental problems with stereotactic frames. Frames are 'point-based' systems, meaning they are designed to pass a single instrument to a target, which is satisfactory for tumour biopsy or lesioning, but the use of a frame to help localize a tumour at craniotomy considerably encumbers the surgical field and the surgeon has very little intuitive feedback as to where his/her instruments exactly are within the brain or where he/she is hoping to go. In addition, the scanning of the patient with the frame in place is both invasive and time consuming (Macunias, 1993, 1995).

It was for these reasons that in the mid 1980s several groups of neurosurgeons began to explore methods by which the spatial registration of imaging data with the surgical field could be

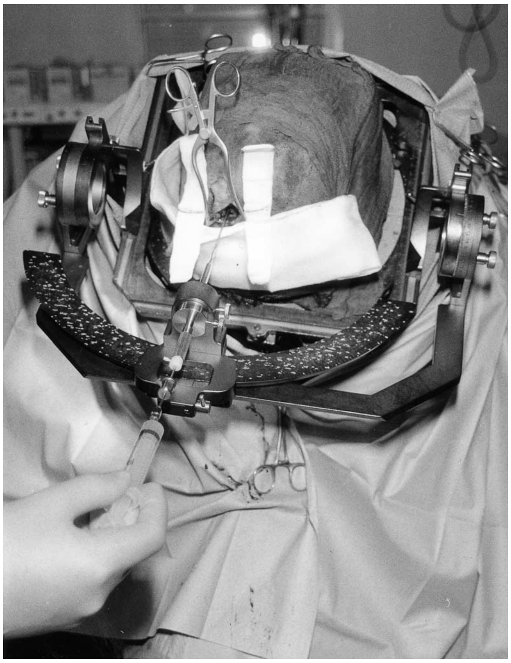

Figure 2. Stereotactic biopsy: the adjustable arc assembly is in place upon the base-ring and the stereotactic coordinates (x, y, and z) have been set on the arc assembly. A biopsy needle is then placed through the guide to the correct depth and will exactly reach the chosen target in three-dimensional space. The biopsy chamber is opened and a specimen taken by suction with a syringe.

achieved without the use of a frame attached to the patient's head, allied to computer technology that would dynamically localize structures and give the surgeon continual feedback about the position of his/her instruments relative to the brain and target lesion.

This era of interactive image-guided surgery began in 1985 when Roberts and co-workers in a multidisciplinary team reported the development of the first image-guided system (Roberts et al, 1986). Their answer was to adapt an operating microscope to perform the dual function of a three dimensional 'digitizing system' and the method of localization. This was achieved by fitting the microscope with sonic emitters, the signals from which were detected by a microphone receiver array positioned in the operating room. In this way the focal point of the microscope was used as the point of localization. The patient and image coordinate systems were then registered by localizing the position of five metallic marker balls attached to the patient's scalp with the microscope focal point, and matching or linking these positions with the markers as they appeared in the preoperative CT scans. In this way the exact position of the focal point as the microscope was moved was displayed upon the preoperative CT images on a computer screen.

The first realization of a digitizing system using a hand-held device was by Watanabe and his group in 1986 who used an articulated surgical arm for this purpose (Watanabe et al, 1987, 1991). The 'Neuronavigator' arm consisted of a pointer tip and six joints each with an integral high resolution potentiometer, in order that the three-dimensional coordinates of the arm tip could be calculated. The arm is thus able to act as both the spatial digitizer for registration and the tool for intraoperative localization.

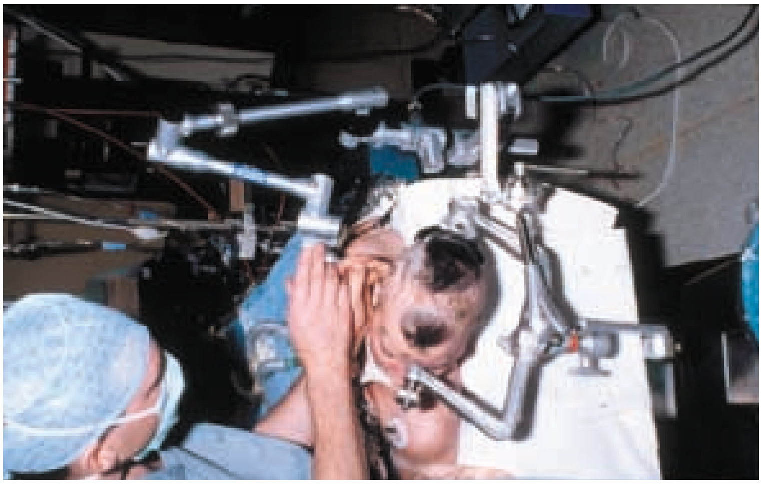

Figure 3. ISG Viewing Wand: the surgeon is supporting the multi-jointed mechanical arm and placing the localiser tip upon each of the scalp fiducial markers during the registration process.

CONTEMPORARY IMAGE-GUIDED NEUROSURGERY

The first commercial system used by several neurosurgical groups around the world including our own was the ISG Viewing Wand introduced in 1991 (*Figure 3*), a mechanical arm system that helped to establish the many benefits that neuronavigation has to offer the surgeon (Golfinos et al, 1995; Sipos et al, 1996).

Since mechanical arms can be cumbersome during surgery, rather like a stereotactic frame, alternative digitizers that have been developed include ultrasonic and microwave wands, magnetic digitizers, video-based detection, and most recently infra-red light-emitting diodes (LEDs) (Bucholz and Smith, 1993).

This field has come to be known by a variety of names: image-guided or image-directed surgery, computer-assisted surgery, and neuronavigation.

The system that has been developed and validated by our group (EASI: European Applications in Surgical Interventions Project), the Philips EasyGuide Neuro, utilizes optical LED localization (Wadley et al, 1998). Preoperative imaging is carried out with CT or MRI after the attachment of adhesive scalp fiducial markers (*Figure 4*). The surgeon holds various pointers (*Figure 5*) which are detected by a

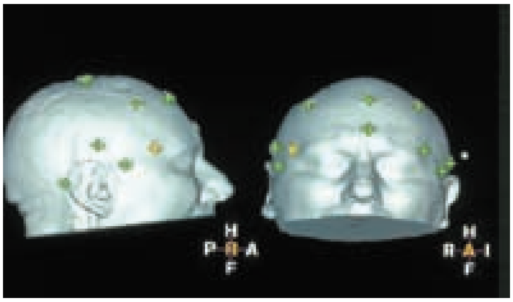

Figure 4. Fiducial marker positioning: three-dimensional segmented view from the workstation screen after patient–image registration showing the marker positions as green crosses surrounding the head.

Figure 5. Infra-red optically tracked surgical 'pointer'. The pointer is held by the surgeon and its exact position calculated by the neuronavigation system by the detection of flashes from the three infra-red light-emitting diodes by a three-dimensional camera array.

three-dimensional camera array attached to the operating table (*Figure 6*). After patient–image registration the surgeon may place the pointer upon the head to exactly localize a lesion before surgery and use sophisticated planning software to enhance this process (*Figure 7*) and even interactively simulate a plan (*Figure 8*). During surgery intraoperative localization enables true navigation: exact orientation within the brain, visualization and avoidance of eloquent brain and vital structures (*Figure 9*) and plotting of trajectories to deep structures. The powerful computer workstation allows for further enhancement of preoperative planning by detailed image manipulation and simulation (*Figures 10a* and *b*).

Our research with this technology in nearly 400 operative cases in 2.5 years has shown many benefits that have led to a revolution in many neurosurgical procedures (Wadley et al, 1998). The ability to perform highly accurate and minimally invasive craniotomies reduces blood loss and operative time and minimizes manipulation of healthy brain. Intraoperative navigation also reduces trauma, leads to rapid localization of lesions within the brain, and helps the surgeon to assess the degree of resection of tumours. Vital structures such as dural venous sinuses and major vessels may be pinpointed and avoided, and techniques have been developed to stereotactically biopsy tumours without a frame and with interactive feedback to the surgeon. Attaching an LED array to a neuroendoscope allows tracking of its position within the ventricles and we have also seen an enhancement of surgical confidence during difficult procedures.

CONCLUSIONS AND FUTURE PERSPECTIVES

Experience with neuronavigation systems has now reached the stage where accuracy and functionality have been proven and the unique advantages of this technology clearly demonstrated (Golfinos et al, 1995; Sipos et al, 1996; Wadley et al, 1998). It is likely that within several years it will be commonplace in most neurosurgical units for a significant proportion of intracranial procedures to be performed with the assistance of neuronavigation.

There are many areas where allied technologies are being directed towards the field of image-guided neurosurgery. Intraoperative brain deformation may cause errors in localization (Dorward et al, 1998) and integration of intraop-

Figure 6. Neuronavigation system in use in the operating theatre. The surgeon is holding a pointer on the exposed skull of the patient during the planning of a minimally invasive craniotomy. The mobile system is seen to the surgeon's right and the camera array on the left attached to the operating table.

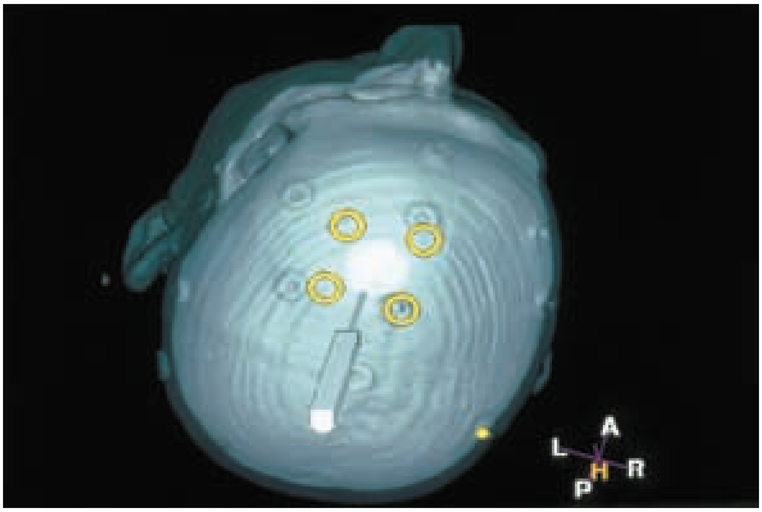

Figure 7. Advanced craniotomy planning: a dynamically updated three-dimensional representation of the pointer is seen tracing the outline of a tumour defined as an ellipse upon a segmented view of the skull and scalp. In this way the surgeon may plan a highly accurate and minimally invasive craniotomy immediately before surgery.

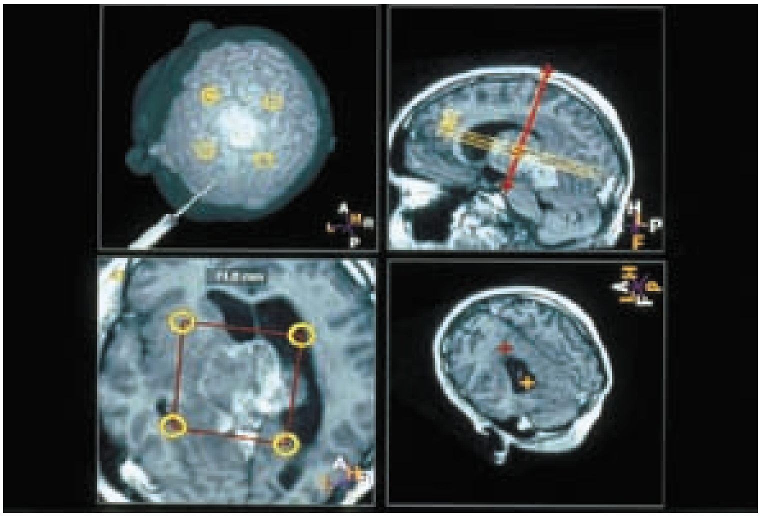

Figure 8. Advanced craniotomy planning: simulation of surgical plan. The composite magnetic resonance images show a large tumour of the deeply situated pineal region. The pointer is seen tracing a plan which is then defined within the yellow circles upon the three-dimensional views upper left, and lower left shows one slice from the stack of images that are reformatted, simulating a 'zoomed movie', along this chosen trajectory, seen at upper right. The dimensions of this plan and the trajectory may then be altered accordingly before surgery, lower right, when the surgeon may exactly follow the correct path (red cross) with the pointer (yellow cross).

erative ultrasound, which provides ‘real-time’ images, may lead to correction of this ‘brain shift’ (Moringlane and Voges, 1995). The technology of intraoperative CT and MR scanning is now well developed in several centres, and while currently expensive and impractical for widespread use, with further development these machines may further add to the armamentarium of the neurosurgeon (Black et al, 1997).

Neuronavigation in the spine has as yet not reached an acceptable level of accuracy, with significant problems of segmental mobility leading to poor registration accuracy. This will undoubtedly also improve with further research and development. 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, intraoperative ultrasound, endoscope, and even interventional CT or MRI (Benabid, 1993; Apuzzo, 1996).

The technology of surgical robotics continues to advance and will undoubtedly have a role to play in the future of image-guided neurosurgery. **HM**

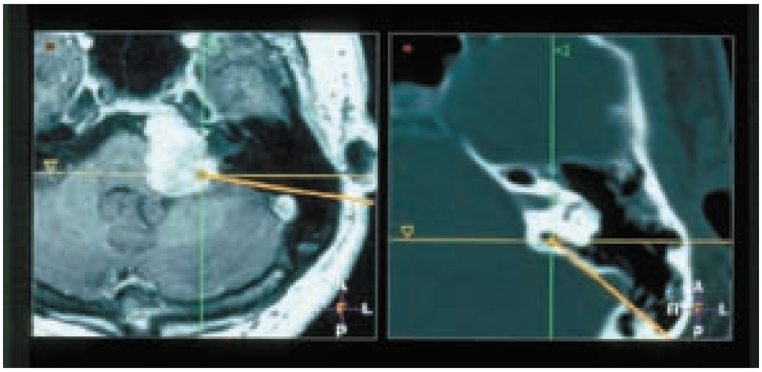

Figure 9. Intraoperative navigation in complex skull base surgery: image guidance during the transpetrous excision of a deep tumour in the cerebellopontine angle using dual registration with computed tomography (CT) and magnetic resonance (MR) scans. The CT (right) allows clear visualization of the inner ear and facial nerve during bone drilling and the surgeon may then switch to navigation with MR images when the tumour is reached (left).

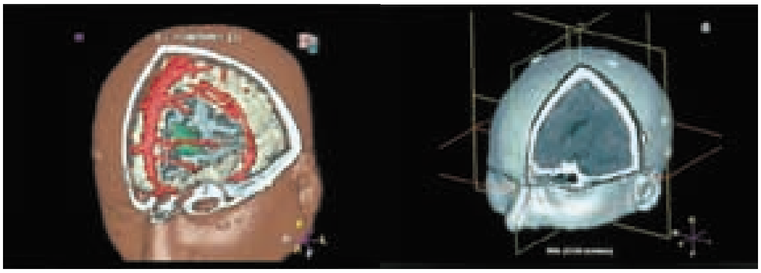

Figure 10. Advanced three-dimensional segmented views. a. Magnetic resonance images showing cutaway view of the brain with superimposed segmented outline of a frontal tumour (green) and the major cortical veins and dural venous sinuses (red). b. Computed tomography images with cut-away view of the brain. Such images may be created and infinitely manipulated in a short space of time and the anatomy inspected in great detail, allowing the surgeon a degree of preoperative planning unheard of until recently.

KEY POINTS

- Stereotactic frame systems enable neurosurgeons to approach point targets within the brain with a great deal of accuracy and safety.
- Recent advances in technology have enabled the development of interactive image guided neurosurgery that realizes stereotactic accuracy without a frame.
- Such systems utilize powerful computer workstations and sophisticated imaging modalities to provide the surgeon with a high degree of intraoperative feedback.
- Benefits proven are more accurate and minimally invasive craniotomies, better lesion localization, reduced brain manipulation, better intraoperative orientation and enhanced surgical confidence, and better surgical planning.
- Continuing developments in this field will lead to further advances in surgical technique and even further enhancement of patient safety.

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