SPECIAL ARTICLE

NEURONAVIGATION — DESTINATION UNKNOWN

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Neuronavigation, which enables neurosurgeons to find targets as small as 1 mm within the brain and spinal cord and to plot safe pathways to them, is fast becoming a subspecialty in its own right. Operating rooms are being filled with computer workstations, monitors, virtual keypads and wands. In essence, what these systems do is not only allow the surgeon to view previously performed scans of the patient's brain while he or she is operating, but actually indicate in real time where the surgeon is working. Areas of interest such as a tumour may be outlined and highlighted, as are structures to be avoided; three-dimensional views are created and images are presented from a surgeon's-eye view.

The potential benefits of this technology are enormous. Tumours may be safely and radically excised by pre-operatively defining the limits of resection; operating times could be reduced and patients could be protected from surgeon error or fatigue. At its most advanced state neuronavigation could conceivably exclude the surgeon from the operation, which would be performed by a robot. There is already pressure to make the use of neuronavigation devices mandatory, with the implication being that if a device is not used the patient may be subject to undue risk.

It may be premature at this stage to suggest that a new technology should be a standard of care. Herein lies the problem. Modern scientific medicine is easily seduced by new technology. The faster the development and the more sophisticated the technology, the more readily we are persuaded of its value. Could this be the case with neuronavigation? There are also considerations of a more general nature as regards technology in medicine. This review traces the development of neuronavigation and looks at some of the issues that need to be considered.

THE BRAIN AS A THREE-DIMENSIONAL STRUCTURE — STEREOTAXIS

One of the pioneers of neurosurgery, Sir Victor Horsely, was interested in experimental neurology but experienced difficulty placing lesions accurately in the brains of laboratory animals. He enlisted the help of a young engineer, Ronald Clarke, to design an apparatus that would assist him to locate consistently various intracranial structures in laboratory animals.[1]

Clarke's great insight was to consider the brain as a three-dimensional structure that could be described in terms of three axes at right angles to each other (i.e. three orthogonal axes termed x, y and z). Any point in the brain could therefore be described in terms of a unique set of co-ordinates (Fig. 1). This utilised an elementary principle of geometry, first described by the French mathematician René Descartes in the 16th century, whereby a point may be described in relation to the surrounding frame, which serves as the reference system.

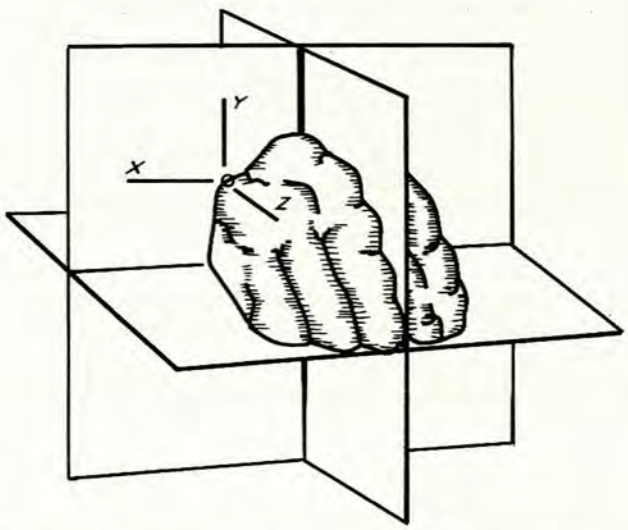

Fig. 1. Any point in the brain can be described as a set of co-ordinates taken from three orthogonal axes (x, y, *and* z).

The Horsley-Clarke frame was based on fixed anatomical landmarks that were located extracranially. Initially this was not very reliable, but it was to be another four decades before Spiegel and Wycis[2] developed a system in Philadelphia utilising radiology. A great proliferation of stereotactic devices followed, with neurosurgeons in many centres developing their own frames.[1] The majority of procedures undertaken were for movement disorders, but this was cut short by the discovery of L-dopa in 1960. Despite the dramatic drop in the number of neurosurgeons practising stereotaxis, some continued, as not all patients responded adequately to medication and increasingly the delayed complications of therapy became apparent.

Godfrey Hounsfield's development of computed tomography (CT) culminated in the first clinical images taken at Atkinson Morley's Hospital in 1971. A substantial contribution had been made by the Cape Town-trained physicist Alan Cormack, and both received the Nobel Prize.

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The impact of this discovery was rapidly appreciated by various neurosurgeons who swiftly adapted their stereotactic frames for use in the CT scanner. Once again there was a proliferation of instruments and the commonest target now became the previously invisible morphological brain abnormalities (Table I).

Table I. Common indications for stereotaxis in neurosurgery

Functional procedures (ablation or stimulation of non-visualised targets)
Movement disorders
Psychosurgery
Pain
Morphological procedures (visualised targets)
Biopsy of a mass
Aspiration of an abscess or cyst
Haematoma evacuation
Placement of a catheter
Brachytherapy
Stereotactic-guided craniotomy

This progress continued with the introduction of magnetic resonance imaging (MRI). Although spatial accuracy is less than that achieved with CT, the superb anatomical detail and multiplanar capacity has proved very useful in planning surgery.

IMAGE-GUIDED SURGERY

The ability to reach a single point in the brain reliably was an important milestone, but in many instances, for example resecting a tumour, additional points of interest corresponding to the tumour margins would provide substantial benefit during surgery. Although techniques for performing a craniotomy with the help of a stereotactic frame were described, the frame tended to get in the way.[3] There was therefore a quest for frameless stereotaxis that would enable the neurosurgeon to reach any intracranial point during the operation and know the anatomical location in real time. Computers provided the solution.

The basic concept is essentially an extension of stereotaxis. Three or four external markers (fiducials) are affixed to the patient's scalp and then CT or MRI images are obtained. These markers remain in place until the patient has been anaesthetised and the head rigidly fixed. Using a variety of techniques the locations of the markers in space are measured and registered by a computer. As the markers are also visible on the scan the computer is able to relate the patient's three-dimensional space to that of the previously performed scan. At any stage in the operation the surgeon can find out where he is by having the computer call up the appropriate scan. This is done by using a pointer (wand), which also has markers on it that the computer is able to track.

The number of such systems is increasing rapidly, with a proliferation of terminology, but essentially all systems are dependent on the use of computers. These may be broadly classified as active or passive systems.[4] An example of the former is the PUMA robotic arm that was pre-programmed to do specific tasks.[4]

Passive systems have gained considerable acceptance to date. These may be incorporated directly into the operating microscope (for example Zeiss MKM), or they may utilise localisation arms (for example the ISG Wand) or optical systems (such as the BrainLab VectorVision) or Stealth Surgivision. A recent publication reported successful use of such a system in 125/131 cases with an application accuracy of 4 ± 1.4 mm.[5]

BENEFITS

Commercial producers of neuronavigation devices are quick to emphasise their possible benefits. Surgery becomes more accurate for the patient and less stressful for the surgeon.[6] The ability to reduce morbidity by limiting surgical invasiveness is an attractive one, but is there any evidence to support these claims?

There can be no doubt that conventional stereotaxis has reduced the exposure required for many brain operations and has been of benefit in tumour biopsy and functional neurosurgery, such as pallidotomy for Parkinson's disease. By extension, then, it can be said that neuronavigation offers the same benefits. While this is true, it must be remembered that the complexity of these devices has increased significantly and the uses are no longer confined to the conventional passing of a probe into a specific location in the brain. In short the answer to whether there is benefit in using neuronavigation in surgery is as yet unknown. In the last 3 years there have been more than 45 peer-reviewed publications on the subject and not one has shown improved patient outcome, reduced operating time or more complete tumour resection.[5,7]

Furthermore, it seems unlikely that this will become a research priority in the future. New devices with faster technology and more sophisticated graphics appear every year. Before it can be established that there is any benefit in using one system, the next model is released. Regulatory authorities cannot be relied upon to provide guidance in this regard. The assessment of surgical devices tends to be more concerned with electrical and engineering safety than with the benefits afforded to patients.

As alluring as it is to be guided through an operation by planned incisions, safe trajectories and complete lesion removal, surgeons should remain open-minded until more evidence is available.

COST

Technological innovation does not come cheap, and someone has to pay. The cost of modern medicine is soaring, making medical care expensive for a select few and inaccessible for most. Neuronavigation is no exception, and a commercial system costs in the region of a few million rands. That is of course without the ancillary requirements of CT and MRI scanners, and in some cases a robot-operated microscope through which the computer-generated images are projected.

From the perspective of African neurosurgery, this technology is unlikely to become widespread in its current form. Systems are designed for the developed world, which means using state-of-the art work stations for image processing, large monitors for viewing, and sophisticated software. The aim is to present the most up-to-date system in a competitive environment. System support is also specialised and most companies provide 24-hour product support, including an engineer who will fly from Europe should it be necessary. This adds to the cost of the product.

Is all this elaborate equipment essential to do the job? We believe not. It makes sense to provide inexpensive technology that can achieve the same objectives. This way if there are benefits they will be available to more surgeons and their patients. An example is the Cape Town Stereotactic Pointer (CTSP), which was developed jointly by the departments of Biomedical Engineering and Neurosurgery at the University of Cape Town in an effort to make frame-based stereotaxis affordable.[8] We are currently undertaking similar work on a neuronavigation device.

ETHICAL CONSIDERATIONS

As with other areas in medical practice, technological advance is occurring faster than the surrounding ethical issues can be formulated and considered. The interface of man and machine has long been a story-line of science fiction. Until recently any tool the surgeon used was manipulated by his hand under direct control of his or her own intellectual processes and motor commands. Neuronavigation blurs that direct relationship between the surgeon and his instruments.

The surgeon's line of sight may now be directed to an area of interest, as determined by something seen on a MRI scan, or a tumour boundary can be outlined by an image projected onto the patient's brain. These subtle changes may influence the course of an operation and its outcome. Progress in this field has inevitably led to more responsibility for a procedure being handed over to the computer, and where this process will end is unclear. Some attempts have already been made at remote surgery via a robot or allowing a robot to perform part of a procedure.[9]

Should we as physicians be comfortable with handing over part of the responsibility for our patients to microchips, and what is our legal position in this regard? The old maxim 'rubbish in, rubbish out' may help up to a point, in that if an error was found in the information presented by a computer one need only look to who entered the raw data to find the guilty party. Unfortunately things have already become far more complex in neuronavigation. Raw data are often entered directly from one computer to another, such as from a MRI scanner to a workstation. Software incompatibilities may lead to data corruption or network transmission may result in incomplete transmission. Who would carry responsibility — the software designer or the network administrator? These are but a few examples of how errors may creep into a system presenting vital information to the surgeon.

This technology will undoubtedly also have a direct impact on patients as well. Patients are being driven further and further away from their doctors. As more machines surround them and more devices image their insides, patients can't help but feel alienated and exposed. Neuronavigation is mostly performed while the patient is under anaesthesia, but this is not invariable. Awake craniotomy is becoming more and more popular. Patients also need to be informed about the use of new technologies being used in their management. How should we familiarise patients with this technology? Are we making them feel more secure or afraid about their therapy? It would seem appropriate for ethical discussion to take place around the development of new technology. Industry can't be expected to initiate this as their bottom line is clearly profit. Surgeons and ethicists must take the lead in this neglected area.

PHILOSOPHY

Can the images that neuronavigation depends on ever represent reality? Are we placing undue emphasis on pictures of our patient's pathology? The answers to these questions may be answered in terms of Ludwig Wittgenstein's comment in the *Tractatus Logico-Philosophicus*, 'Um zu erkennen, ob ein Bild wahr oder falsch ist, müssen wir es mit der Wirklichkeit vergleichen'.[10] He states that in order to assess if an image is real or not we must compare it with reality. Reality can never be represented in a static two-dimensional plane without temporal relationships. An image is always open to interpretation by the viewer and the image can only represent a moment in time. Past and present can only be suggested by what is seen.

It can be argued that a CT or MRI scan are as close to reality as one can get; after all, aren't they in effect images of the patient's real brain? While this is true, the limitations of scans must be appreciated. The first limitation is that the images are planar and orthogonal views can never show the three-dimensional nature of the brain. Rendered views are often made by creating a digital volumetric reconstruction and displaying a shaded pseudo-three-dimensional image. This recreation can only give approximate depth perception at best.

The second problem is that scan images represent structures in varying shades of gray. The impact of colour is lost in this monochromatic image. Thirdly, the issue of spatial accuracy needs to be considered. A pixel is the smallest rectangle that an image can be broken down into on a computer monitor. Current scanning resolution allows for a real space pixel representation of 1 mm. This may not sound like a lot, but many operative targets in neurosurgery are in the order of a few millimetres. The claim of most manufacturers that their neuronavigation systems are accurate to within less than a millimetre can't be true. On the scan alone an error of 1 mm is possible, and at each step of image manipulation, of which there are several, error can creep in.

In effect the computer images that the surgeon looks at are a virtual creation or virtual reality. Jaron Lanier, who coined the term 'virtual reality', has shrewdly commented that ultimately the most vivid experience of virtual reality is the experience of leaving it. 'After having been in the reality that is manmade, with all the limitations and relative lack of mystery inherent in that, to behold nature is directly beholding Aphrodite; . . . a beauty that's intense in a way that just could never have been perceived before we had something to compare reality to.'[11]

How important is time in neuronavigation? In practice the past is probably of the least concern. How rapidly a tumour has grown is important when considering if surgery is an appropriate therapy, but the time it has taken to grow plays little role in the actual surgery. The future as it turns out is of far greater importance and represents the greatest problem with neuronavigation. A scan of the brain represents the organ at the instant of scanning only. During surgery a number of changes occur, which change the position of the brain relative to the images the surgeon looks at, that is images from the time of scanning. The patient's head may be positioned differently, cerebrospinal fluid is drained and the brain is retracted at the time of operation. All of these changes lead to brain movement that is not reflected in the computer images. Of equal concern is the fact that operative goals such as tumour removal are not shown. At the end of the operation the images are precisely the same as at the start of the procedure.

Ingenious attempts have been made at overcoming this problem, from intra-operative MRI scanning to ultrasound tracking of brain shifts.[12-14] All have met with only limited success, which brings us to the next important philosophical consideration. Does the addition of more observations to a complex problem lead to a more realistic representation, or does it further cloud the problem? For all its complexity neuronavigation only concentrates on one aspect of the brain, that of spatial representation. As systems become more complicated in an effort to overcome the problems of spatial accuracy, are we overlooking other important factors? Are we ignoring our other senses in seeking only visual gratification? Is not the texture of a tumour vital in determining if safe excision is possible?

It has been suggested that some of the problems of information assessment and presentation could be resolved by looking at the neurobehavioural and cognitive interaction of the surgeon with the computer.[15] An example of this would be improving the positioning of a computer monitor so that it falls into the surgeon's central field of vision. The central visual field can detect spatial accuracy better, whereas peripheral vision detects movement better.

CONCLUSION

Neuronavigation is undoubtedly a significant technological advance that is here to stay. Changes in the training and practice of neurosurgery are sure to follow. In earlier years neurosurgeons had to use their minds to visualise the three-dimensional anatomy of their patients. Younger surgeons may come to depend on a computer to do this for them.

Specialties will need to be redefined. Neuroradiology has always been integral to brain surgery, but now surgeons will be using images to actually direct their surgery. This is further compounded by changes in therapeutic alternatives. Radiosurgery is becoming an accepted therapy for many pathologies previously treated with the surgeon's knife. When radiosurgery becomes coupled to image guidance, the paths of the radiologist, physicist, radiotherapist and neurosurgeon cross. New partnerships and boundaries will need to be formed.

Patient confidentiality will undoubtedly be put at risk with the digitalisation and transmission of images used in neuronavigation. An X-ray film can easily be stored somewhere where access to prying eyes is limited. The same is not true where digitised images are considered. Computer databases may be hacked, even in the most secure settings, and images transmitted over networks are even more susceptible to interception. Digital images are also easily altered. The dictum 'a picture cannot lie' no longer holds. The alteration of an image may be very tempting in the world of contract research and audited surgical results.

The intention of neuronavigation is to simplify and improve the work of the surgeon. In practice, however, it often leads to a crammed space filled with blaring alarms and flashing pictures. Our senses are assaulted and concentration is broken just at the time when it should be devoted to one task only. The ability of the human mind to multi-task is considerable, but there is merit to the insistence of some surgeons on a quiet and calm operating room.

C Adams, an eminent British neurosurgeon, has recently said that world-class neurosurgery can be performed with only an operating microscope, a self-retaining retractor, a micro-instrument set, and bipolar cautery.[16] His views are supported by other surgeons who feel that much of modern intra-operative monitoring serves only to confuse the surgeon. In some centres the trend is toward the simplest principle of

clinical examination while operating on an awake patient. If new technology is developed, perhaps an effort should be made to integrate it into the background, rather than thrusting it into the face of the surgeon.

However, neuronavigation remains an exciting new addition to the neurosurgeon's range of tools that takes us firmly into the cyberage. Let us make certain that we know where it is taking us, and hopefully it will be an improved means to an improved end.

References

1. Dagi TF. History of stereotactic surgery. In: Greenblatt SH, ed. *A History of Neurosurgery*. Park Ridge, Ill: The American Association of Neurosurgeons, 1998.
2. Spiegel EA, Wycis HT, Marks M, Lee AJ. Stereotaxic apparatus for operations on the human brain. *Science* 1947; **106:** 349-350.
3. Grunert P, Muller-Forell W, Darabi K, *et al.* Basic principles and applications of neuronavigation and intraoperative computed tomography. *Comput Aided Surg* 1998; **3:** 166-173.
4. Maciunas RJ. (Frameless stereotactic) interactive image-guided neurosurgery. In: Wilkins R, Rengachary SS, eds. *Neurosurgery*. Baltimore: McGraw-Hill, 1996.
5. Gumprecht HK, Widenka DC, Lumenta CB. BrainLab VectorVision Neuronavigation system: technology and clinical experiences in 131 cases. *Neurosurgery* 1999; **44:** 97-104.
6. Spetzger U, Laborde G, Gilsbach JM. Frameless neuronavigation in modern neurosurgery. *Minim Invasive Neurosurg* 1995; **38:** 163-166.
7. Alberti O, Dorward NL, Kitchen ND, Thomas DG. Neuronavigation — impact on operating time. *Stereotact Funct Neurosurg* 1997; **68:** 44-48.
8. Peter JC, Fieggen AG, van Geens BA, Wynchank S, Adams LP. The Cape Town Stereotactic Pointer — a cost-effective stereotactic system. *Childs Nerv Syst* 1995; **11:** 540-541.
9. Urban V, Wapler M, Neugebauer J, Hiller A, Stallkamp J, Weisener T. Robot-assisted surgery system with kinesthetic feedback. *Comput Aided Surg* 1998; **3:** 205-209.
10. Wittgenstein L. *Tractus Logico-Philosophicus*. London: Kegan Paul, 1922: 223.
11. Lanier J. 'Lucy in the Sky with Computers': Interview by Adam Heilbrun. *The Boston Phoenix*, 2 March 1990: 8.
12. Jodicke A, Deisberger W, Erbe H, Kriete A, Boker DK. Intraoperative three-dimensional ultrasonography: an approach to register brain shift using multidimensional image processing. *Minim Invasive Neurosurg* 1998; **41:** 13-19.
13. Wirtz CR, Bonsanto MM, Knauth M, *et al.* Intraoperative magnetic resonance imaging to update interactive navigation in neurosurgery: method and preliminary experience. *Comput Aided Surg* 1997; **2:** 172-179.
14. Dorward NL, Alberti O, Veali B, *et al.* Postimaging brain distortion: magnitude, correlates and impact on neuronavigation. *J Neurosurg* 1998; **88:** 656-662.
15. Linke DB, Schaller C, Meyer B, van Roost D. Cognitive neuroscience foundations for a theory of neuronavigation. *Comput Aided Surg* 1997; Abstracts from CIS 97:S03-016.
16. Adams C. *A Neurosurgeon's Notebook*. Oxford: Blackwell Science, 1998: 105.

Accepted 4 July 1999.