Application of electromagnetic technology to neuronavigation: a revolution in image-guided neurosurgery

Technical note

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Object. The authors investigated the practicality of electromagnetic neuronavigation in routine clinical use, and determined the applications for which it is at the advantage compared with other systems.

Methods. A magnetic field is generated encompassing the surgical volume. Devices containing miniaturized coils can be located within the field. The authors report on their experience in 150 cases performed with this technology.

Results. Electromagnetic neuronavigation was performed in 44 endoscopies, 42 ventriculoperitoneal shunt insertions for slit ventricles, 21 routine shunt insertions, 6 complex shunt insertions, 14 external ventricular drain placements for traumatic brain injury, 5 awake craniotomies, 5 Ommaya reservoir placements, and for 13 other indications. Satisfactory positioning of ventricular catheters was achieved in all cases. No particular changes to the operating theater set-up were required, and no significant interference from ferromagnetic instruments was experienced. Neurophysiological monitoring was not affected, nor did it affect electromagnetic guidance.

Conclusions. Neuronavigation enables safe, accurate surgery, and may ultimately reduce complications and improve outcome. Electromagnetic technology allows frameless, pinless, image-guided surgery, and can be used in all procedures for which neuronavigation is appropriate. This technology was found to be particularly advantageous compared with other technologies in cases in which freedom of head movement was helpful. Electromagnetic neuronavigation was therefore well suited to CSF diversion procedures, awake craniotomies, and cases in which rigid head fixation was undesirable, such as in neonates. This technology extends the application of neuronavigation to routine shunt placement and ventricular catheter placement in patients with traumatic brain injury.

(DOI: 10.3171/2008.12.JNS08628)

Key Words • frameless neuronavigation • electromagnetic neuronavigation • magnetic field

Computer-assisted navigation for surgical procedures has been available for > 2 decades. However, this technology has mainly been applied to tumor resections, procedures for epilepsy, vascular neurosurgery, and to aid in functional localization such as in cases involving the motor cortex or language center. Image guidance using frame-based, robotic arm, or frameless optical tracking systems has limitations due to its cumbersome set-up and interference with the freedom of movement of instruments within the surgical field. Additionally, the role of neuronavigation has traditionally been limited in children by the need for rigid head fixation and inherent risks of skull fracture and epidural hematoma. Neuronavigation is also cumbersome to use in ventricular catheter insertion because of the need to move the head during shunt placement, and it is difficult for the same reason in awake craniotomy, a less frequently performed procedure. However, neuronavigation has the potential to improve the accuracy, safety, and ultimately outcome of any neurosurgical procedure, including CSF diversion procedures, which are commonly performed and in which catheter misplacement is a significant cause of early malfunction.

Electromagnetic technology for image guidance overcomes many of the obstacles inherent to most navigation systems. The small size of the reference sensor allows it to be attached directly to the head, allowing freedom of movement for the head without loss of accuracy of registration or interference with the surgical field. A direct line of sight is not required between tracker and probe. Flexible instruments can be tracked at depth in real time and head fixation is not required, which is a significant advantage in children.

The concept of using an electromagnetic field to provide a frame of reference in which to track anatomy and instruments was introduced in 1991, but the need to develop a system that is not susceptible to interference from adjacent ferromagnetic objects led to its limited adoption. However, advances in the technology have led to the development of systems that are now available to surgeons and can be used for a wide range of procedures.

Abbreviation used in this paper: ETV = endoscopic third ventriculostomy.
standard surgical instruments and equipment has meant that this concept has only recently gained widespread acceptance. One problem is the possible loss of accuracy caused by field distortion, which is potentially unsafe. Other systems tend to stop functioning altogether when problems occur—for example, loss of vision due to problems with the line of sight. To date there have been only sporadic reports of the use of this technology. We report our experience using electromagnetic neuronavigation for a wide range of indications in an adult and pediatric population to establish the practicality of the system’s use, and identify the conditions in which a clear advantage of this technology can be demonstrated. To our knowledge, this is the largest series of electromagnetically guided surgeries yet reported in the literature.

Electromagnetic Technology

The StealthStation Axiem navigation system (Medtronic, Inc.) utilizes a transmitter coil array to encompass the head within a cubital low-energy magnetic field, to provide a volume in which the location and orientation of a pointer in space can be defined digitally. A scalp-applied reference frame identifies the location of anatomy within the frame of reference (Fig. 1). By applying a reference frame to the head, the need for rigid fixation of the head relative to the field generator is avoided so the head can be moved at any time during a procedure. The crucial feature of electromagnetic technology is that the sensors can be made extremely small, using 1–3-mm copper sensor coils. By contrast, an infrared system, whether active or passive, requires several emitters/reflec-tors separated by several centimeters to achieve comparable accuracy. It is this critical difference that makes the use of infrared-based tracking systems impractical if the head must be free to move.

Concerns regarding the stability and accuracy of electromagnetic systems in an operating room environment have limited their widespread acceptance, because ferromagnetic interference may distort the reference field and limit precision. Under experimental conditions, the Stealth system has been shown to demonstrate an undistorted reference measurement of 0.1 mm, and with ferromagnetic distortion a mean deviation of 0.21–0.56 mm.16

Direct comparison of optical versus electromagnetic tracking showed no difference in application accuracy.13 Initially, a screw-in skull-applied reference frame fixed to the skull was used. This required a separate incision, however, and because in an unpublished previous study at our institution no difference in accuracy was shown using a reference sensor simply taped to a convenient point on the scalp and skull-based reference sensor, the use of the latter has been abandoned.

With optical navigation systems, the tracked volume is extracranial and depth is calculated as a derived measure based on probe length rather than tracking the true probe position within the surgical volume, as is the case in electromagnetic navigation. The tracker tools have detector coils at their tips and can be used as instruments, with a high degree of accuracy of tip positioning within the surgical volume (Fig. 2). A direct line of sight is not required between the tracker and transmitter coil. Depth is therefore measured in real time, and continuous reorient-ation of instruments toward the transmitter is not re-quired as it is in optical systems.

The small size and cylindrical geometry of the sensor coils means that for the particular case of ventricular catheter, a stylet can be made that can carry coils to within a centimeter of the tip. This improves the accuracy of placement because the tip of the stylet is then only ~2 cm from the virtual center of the tracked device. Only the last 4–5 cm of the stylet must be a rigid geometric con-struct, and a stylet of any length can be made to suit any length of catheter without affecting the accuracy of tip positioning. The stylet can also be adapted to pass down an endoscope (Fig. 2).

Results

In our institution, we have performed 150 procedures with electromagnetic navigation in adults and childrens. Figure 3 illustrates the types of cases to which electromagnetic navigation was applied.

Almost 90% of procedures performed with electromagnetic technology were for CSF diversion. This included complex endoscopy for multicompartmental hydrocephalus or arachnoid cyst fenestration in 36 patients, ETV in 8 patients with small ventricles, shunt placement for slit ventricles in 42 patients, and Ommaya reservoir placement for drug delivery in 5. In all endoscopy cases, navigation was based on MR volume imaging, and the ad-
Applications of electromagnetic neuronavigation

For access to slit ventricles, the ventricle was cannulated in all cases, on the first pass in 40 patients (95%). There were no intraoperative complications (such as hematomas) in this group. In addition, we used electromagnetic navigation in routine shunt placement in 21 patients to obtain optimal catheter position away from choroid plexus or ventricle wall, thus potentially reducing the incidence of proximal obstruction. Computed tomography–based navigation was used for ventricular access procedures. All ventricular catheters and external drains were placed at the planned target point, and correct placement was confirmed on postoperative CT scans obtained within 72 hours of the procedure.

Five awake craniotomies for lesion resection were performed using electromagnetic navigation. The avoidance of head fixation reduced overall sedation requirements and did not interfere with the intraoperative use of neurophysiological techniques including corticography, cortical motor evoked stimulation for functional localization of the motor cortex, and somatosensory evoked potentials. Electrical stimulation of the cortex for language localization briefly prevented recognition of the magnetic field, but simultaneous stimulation and navigation were not required.

The 13 other cases included routine tumor resection, biopsy sampling, and abscess aspiration, for which electromagnetic navigation replaced the standard optical navigation. The standard head rest and surgical instruments were used without interference in the electromagnetic field.

Anatomical Registration

Preoperative data acquisition is obtained using either CT or MR imaging volume scans. The StealthStation utilizes a surface matching algorithm to register patient anatomy to a 3D skin surface rendering automatically created from segmentation of the diagnostic image dataset encompassing the volume of the patient’s head. Image to anatomical registration is then achieved using point-to-point registration by scalp tracing; fiducials are not required.

The time required for operating room set-up and image registration did not add significantly to the operative time in our series, with a mean time of 17 minutes from positioning to skin incision (range 10–44 minutes).

Accuracy and Field Distortion

An electromagnetic field is potentially susceptible to distortion from ferromagnetic materials within the operating room. In our mixed case series we did not experience interference from equipment outside the surgical field such as anesthetic equipment, the surgical table, or the standard Mayfield head rest. Ferromagnetic instruments moving within the surgical field did not prevent navigation, and we did not have to use special instruments. The use of self-retaining retractors prevented continuous navigation. Removal of the retractor resulted in restoration of an accurate field in all cases. Neurophysiological monitoring with somatosensory evoked potentials was also unaffected where used.

Discussion

Electromagnetic technology provides a frameless, pinless, noninvasive method of neuronavigation. The electromagnetic system allows head movement at any time after registration with no restriction on the freedom of movement of instruments within the surgical field. Theater set-up and registration did not significantly add to operative time. These advantages allow the indications for image-guided neurosurgery to be broadened to include routine cases such as ventriculoperitoneal shunt placement and ETV. The ability to track a flexible instrument at depth in real time lends itself ideally to CSF diversion procedures.

Early concerns regarding application accuracy have not been substantiated, with observed accuracy compara-
ble to optical systems on the order of < 1–3 mm. Surgical instruments containing ferrous materials may distort magnetic fields with a potential risk of navigation inaccuracy. However, we did not experience any interference from surgical instruments that degraded application accuracy. When interference occurred, such as with large self-retaining retractors, we stopped the navigation and continued when the retractors were removed from the field.

**Indications for Electromagnetic Navigation**

The applications for image-guided surgery are ever increasing. Indeed, since the advent of noninvasive neuronavigation some have argued that all neurosurgical procedures should be image-guided to improve safety and limit complications. Table 1 summarizes the standard and relative indications for image-guided procedures. The use of electromagnetic navigation enables image-guided surgery to be easily applied to shunt placement and endoscopy. It is likely that as this technology gains wider acceptance, the relative indications will become standard. Table 2 highlights the advantages and disadvantages of using an electromagnetic system compared with optical navigation. The system is ideally suited for use in children, eliminating the risk of pin-site hematoma or the need for alternative head fixation—such as taping or vacuum beanbag devices—which may limit accuracy.

**Electromagnetically Guided Endoscopy**

The role of image guidance in endoscopy is to allow accurate planning and placement of the entry point, follow an optimal trajectory reducing torque on the cerebral mantle, and reduce the time spent orientating and localizing the lesion. Most previous reports of frameless image-guided endoscopy have been based on optical tracking systems with rigid head fixation. In addition, the optical system currently in use in our institution can only be used on a snapshot basis, because probes must be continually reoriented to the camera. Electromagnetic guidance overcomes both of these issues, allowing uninterrupted navigation and avoiding the need for a bulky probe array attached to the endoscope (see Fig. 5).

The dimensions of the electromagnetic stylet allow it to be passed through the endoscope working channel for use in fenestration of both the arachnoid and floor of the third ventricle.

Intraoperative navigation is particularly useful in cases of distorted anatomy, such as multiloculated ventricles, for facilitating orientation within a cavity and identifying the optimal fenestration point, thus reducing the risk of vascular or neural injury. In addition, we have increasingly offered ETV for CSF diversion even in small ventricles because image guidance using electromagnetic technology allows safe cannulation and navigation within small ventricles.

**Ventricular Catheter Insertion**

In patients with idiopathic intracranial hypertension and slit ventricle syndrome, freehand cannulation of the lateral ventricle can be fraught with difficulty. In this situation there is a clear need for image guidance. However, frame-based or optical navigation systems, while enabling accurate catheter placement, are invasive, add operative time, and restrict head motion, making subsequent tunnelling of the distal catheter difficult. In our experience placing 42 ventricular catheters with electromagnetic navigation into undersized ventricles for idiopathic intracranial hypertension or slit ventricle syndrome, the ventricle was cannulated on the first pass in 40 patients (95%), and placement at the preplanned target point was achieved in all cases and confirmed on postoperative CT imaging. Long-term follow-up will be required to determine whether this technique results in better long-term shunt survival. However, the revision rate due to proximal catheter obstruction is lower than in our previously published experience with lumboperitoneal shunts.

We have included electromagnetic guided external ventricular drainage in our head injury management algorithm. The only addition to the management in these cases is the need to obtain a 0°-gantry angle, 3-mm CT volume dataset. Although this slightly increases the radiation dosage to the optic apparatus, we believe that the advantage of placing ventricular catheters with image guidance far outweighs this disadvantage.

In addition to cannulation of small ventricles, we now use electromagnetic navigation routinely in shunt placements. The high failure rate of new shunts is caused by proximal obstruction in 30–40% of cases. Optimal catheter placement away from the choroid plexus will theoretically reduce overall shunt failure rates and ultimately reduce the complications associated with multiple shunt revisions. Keståle and colleagues multicenter trial of endoscopically placed shunts showed that shunt failure rates were not significantly different between the endoscopic and control groups. However, the rate of placement of the tip of the ventricular catheter away from the choroid...
plexus did not differ significantly between the 2 groups. However, in their study the position of the bur hole and the catheter trajectory were determined without the use of image guidance and were instead based on anatomical landmarks, which may have adversely affected the final catheter position. Sainte-Rose et al. reported that ~4% of ventricular catheters are misplaced outside the ventricle when placed freehand. In the era of noninvasive neuronavigation, this is unacceptable. The need for rigid head fixation has limited the utility of neuronavigation in shunt surgery. Electromagnetic technology enables noninvasive navigation and provides a means of continuous real time navigation to a preplanned target point within the ventricular system (Fig. 4). Using electromagnetic-guided ventricular catheter insertion, Azeem and Origietano reported no incidence of proximal catheter failure. Our experience demonstrates that ventricular catheters can reliably be placed in an optimal position, irrespective of ventricle size. Only a randomized trial with a similar protocol to the endoscopic shunt placement trial, but with the use of navigation for all aspects of the procedure, will determine the efficacy of image-guided shunt placement in reducing shunt mechanical failure rates. However, until these data become available, the use of a noninvasive technique to guide catheter placement is preferable to a blind procedure. In a study of shunt insertions without image guidance at our institution, 20% of shunts were poorly placed, and 75% of these required revision within 4 weeks of insertion. In contrast, no catheter placed using electromagnetic navigation required revision within 4 weeks. Although navigation disposables present an additional cost, this may be offset by the avoidance of the cost of a shunt revision, which is more than 10 times that of the cost of a navigation stylet in the UK.

Awake Craniotomy

Lesion resection in eloquent areas of the brain using awake craniotomy permits intraoperative functional cortical mapping and facilitates maximal tumor resection. Although some neurophysiological techniques allow motor and sensory mapping under anesthesia language localization requires the patient to be awake. Integrating neuronavigation techniques into this procedure has previously

Fig. 4. Screenshot of the navigation interface with preplanned trajectory and integrated endoscopic image.

Fig. 5. Intraoperative photograph of electromagnetic-navigated endoscopy.
required head fixation under local anesthesia, adding to the ordeal for the patient. The use of a scalp-applied reference frame eliminates the need for head fixation without compromising accuracy, enabling greater patient comfort and reducing sedation requirements. Frameless stereotactic surgery for awake craniotomy has been reported using a skull-applied spinal reference arc.\(^3\)\(^9\) The use of electromagnetic navigation eliminates the need for any additional skin incisions or a direct line of sight between probe and emitters, allowing greater freedom of movement within the surgical field. All neurophysiological monitoring modalities can be used without interference from the magnetic field. Significant interference does occur during cortical stimulation, preventing simultaneous navigation. However, we have not found this to impact the procedure. The freedom of head movement risks loss of sterility, but we have not experienced this in our small number of cases.

**Study Limitations**

This study is a single-institution, observational study describing our experience to date of electromagnetic navigation, demonstrating its utility in a wide range of applications. The major application is CSF diversion and a longer follow-up period is required to determine whether a navigated procedure is superior to a nonnavigated procedure.

**Conclusions**

Where such technology exists to allow accurate and safe neuronavigation, the role of the unguided procedure diminishes. The use of a noninvasive, pinless navigation system enables all neurosurgical procedures to incorporate neuronavigation in adults, children, and neonates. The integration of image guidance into routine procedures such as ETV and shunt insertion is likely to become mandatory in the future.

**Disclaimer**

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Manuscript submitted June 15, 2008. Accepted December 9, 2008. Please include this information when citing this paper: published online March 27, 2009; DOI: 10.3171/2008.12.JNS08628.

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