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ORIGINAL PAPER

Pinless frameless electromagnetic image-guided neuroendoscopy in children

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Abstract

Objectives Frameless imaged-guided neuronavigation is a useful adjunct to neuroendoscopy in paediatric patients, especially those with abnormal or complex ventricular or cyst anatomy. The development of electromagnetic neuronavigation has allowed the use of image-guided navigation in the very young patient in whom rigid fixation in cranial pins is contraindicated. The technique and the authors' experience of its use in a series of paediatric patients are described.

Materials and methods Nineteen paediatric patients were treated with endoscopic surgery at two paediatric neurosurgery centres over a period of 18 months. A total of 29 endoscopic procedures were performed. The cases were reviewed and surgical outcomes assessed. In all of the cases, the goal of surgery was realised successfully at the time of surgery, as confirmed by post-operative imaging. No technical failures were encountered. None of the patients suffered worsened neurological function as a result of their procedures.

Conclusion Pinless, frameless electromagnetic neuronavigation was found to be a safe technique that can supplement endoscopic surgery in the very young patient. It allows the use of direct navigation of the endoscope in patients that are unable safely to undergo rigid cranial fixation in pins due to young age or thin skull vaults. This has proven to be a useful adjunct to neuroendoscopy in the subset of infants who have complicated or distorted ventricular anatomy and can improve the safety and accuracy of this type of surgery. It is also an alternative to optical neuronavigation in conjunction with neuroendoscopy in patients of any age.

Keywords Neuronavigation · Neuroendoscopy · Frameless stereotaxy · Hydrocephalus · Arachnoid cyst

Introduction

Stereotactic neuronavigation has proven itself to be of great utility in the management of many neurosurgical problems. The development of frameless optically based neuronavigation technology has expanded the role of navigation in intracranial neurosurgery, and it is increasingly being utilised in both routine and complex neurosurgical procedures. However, both frame-based and frameless optical neuronavigation have been limited in their use in young paediatric patients, largely due to the hazards of fixing young patients' heads in pinned cranial fixation. The recent development of electromagnetic neuronavigation techniques has led to the greater use of stereotactic navigation in patients in whom cranial fixation would not be tolerated.

Endoscopic surgery in paediatric patients is well described for a variety of intracranial pathologies. The use of stereotactic navigation as an adjunct to neuroendoscopy is similarly a recognised and growing technique. The improved accuracy and safety afforded the surgeon by stereotaxy has allowed the development of neuroendoscopic techniques for biopsy or resection of intraventricular and periventricular lesions, the fenestration of cysts, cerebrospinal fluid (CSF) diversion procedures and the placement of catheters, even in the presence of abnormal or difficult

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anatomy. However, due to the restrictions imposed by the risks of rigid pinned cranial fixation, these techniques were not always suitable for very young patients.

Electromagnetic stereotactic neuroendoscopic techniques have recently been described [3, 4, 8], which have allowed the safe performance of image guided neuroendoscopy in very young patients. We report our experience in the use of electromagnetic image-guided neuroendoscopy in 29 paediatric surgical cases in two centres in Brisbane, Australia over a period of 18 months.

Materials and methods

Between July 2007 and December 2008, 19 paediatric patients underwent a total of 29 separate image-guided endoscopic operations in two paediatric neurosurgical units in Brisbane, Australia. In 14 cases, more than one type of procedure was performed under the one anaesthetic—for example, three patients underwent fenestration of ventricular cysts, aqueductoplasty and placement of a fourth ventricle shunt catheter during the one operation.

Patients were initially selected on the basis of having complex ventricular anatomy, complicated cysts and having thin skulls that precluded the use of pinned cranial fixation. As we became more familiar with the technique, five older children with complex anatomy were also included despite being suitable for pinned fixation, as we found that the technique had other advantages over optical neuronavigation techniques.

The ages of the patients ranged from 1 month to 13 years and included five ex-premature infants less than 3 years of age. Twenty-one of the procedures were performed on 14 children younger than 3 years old, and the remaining eight procedures were performed on five older children. There were 12 males and seven females. The details of the patient population and pathologies treated are shown in Table 1.

The pathologies treated and operative procedures performed are shown in Table 2. All patients had abnormal or difficult ventricular or cyst anatomy, which would have made endoscopy using normal anatomical landmarks difficult or impossible. Three children had tumour-associated hydrocephalus. Six patients had arachnoid cysts, which were fenestrated in eight procedures. Eight patients underwent treatment of multiloculated hydrocephalus secondary to infection or haemorrhage. Nine CSF diversion procedures were performed, including four endoscopic third ventriculostomies, four aqueductoplasties and one septum pellucidostomy. A total of 15 shunt catheters were placed with stereotactic endoscopic assistance, many of which were performed in combination with other procedures.

Illustrative cases

Case 1 A 13-month-old girl with a previous history of a multicystic optic chiasm hypothalamic glioma presented with progressive lethargy, reduced interactivity with her mother and an increase in her head circumference. Magnetic resonance imaging demonstrated an increase in the size of a tumour cyst, with obstructive hydrocephalus. Due to her macrocephaly and thinned skull, she was not suitable for pinned fixation. She underwent electromagnetic image-guided neuroendoscopic fenestration of the tumour cysts through a precoronal burr hole. A cystoperitoneal shunt was placed at the same procedure. The absence of rigid head fixation allowed her head to be repositioned intraoperatively for the shunt procedure without loss of navigational accuracy. Post-operative imaging demonstrated the shunt catheter well positioned within the tumour cyst and an improvement in the size of the cyst and hydrocephalus. Her neurological status improved significantly post-operatively (Fig. 1).

Case 2 A 4-year-old girl with cerebral palsy presented with a decrease in her functional state and alertness. She had a history of shunted hydrocephalus from intraventricular haemorrhages related to prematurity. She had a large scaphocephalic head, with a thin skull for her age. Magnetic resonance imaging demonstrated complex multiloculated hydrocephalus and an entrapped fourth ventricle. Her previous ventriculoperitoneal shunts were found to have failed and were removed. Through a single burr hole, she underwent endoscopic fenestration of her ventricular cysts, aqueductoplasty and placement of a fourth ventricle shunt. At surgery, no normal anatomical landmarks could be identified, and the procedure was entirely dependent on image guidance. Post-operative magnetic resonance imaging confirmed correct positioning of the catheter and subsequent improvement in the hydrocephalus. Six months later, she presented with a shunt infection. The shunt was removed and she undertook a period of antibiotic treatment. A second fenestration and aqueductoplasty procedure was then performed and a new fourth ventricle shunt positioned (Fig. 2).

Case 3 A 3-month-old boy presented with a full fontanelle and macrocephaly secondary to a large loculated parietal periventricular arachnoid cyst. Image-guided endoscopic fenestration of the cysts into the ventricle was performed. The cysts did not satisfactorily improve on follow-up imaging, and he underwent a second image-guided cyst fenestration with placement of a cystoperitoneal shunt. He recovered without complication, and post-operative imaging confirmed correct satisfactory positioning of the shunt catheter and reduction in the size of the cysts (Fig. 3).

Table 1 Characteristics of patients undergoing neuroendoscopic procedures with electromagnetic navigation July 2007 to December 2008

Patient	Age	Gender	Ex-premature	Diagnosis
1	13 months	F	No	Cystic hypothalamic tumour
2	4.5 years	F	Yes	Multiloculated hydrocephalus Entrapped fourth ventricle
3	18 months	M	Yes	Multiloculated hydrocephalus Entrapped fourth ventricle
4	2 years	M	Yes	Multiloculated hydrocephalus
5	5 months	F	Yes	Multiloculated hydrocephalus Ventriculitis
6	20 months	M	Yes	Periventricular cysts post-meningitis
7	13 years	M	No	Periventricular cysts post-meningitis
8	12 months	M	No	Periventricular cyst
9	12 months	M	Yes	Periventricular cyst Entrapped fourth ventricle
10	1 month	M	No	Posterior fossa arachnoid cyst
11	2.5 years	F	No	Arachnoid cyst
12	3 months	M	No	Arachnoid cyst
13	7 months	M	No	Arachnoid cyst
14	10 years	M	No	Arachnoid cyst
15	8 months	F	No	Posterior fossa arachnoid cyst Hydrocephalus
16	4 months	F	No	Dandy Walker
17	4 years	F	No	Fourth ventricle tumour Hydrocephalus
18	9 months	M	No	Pineal tumour
19	5 years	M	No	Hydrocephalus

Operative technique

The equipment required for the procedures comprised the StealthStation AxiEM Neuronavigation System (Medtronic, Louisville, CO, USA), which utilises a coil to generate an electromagnetic field around the patient's head. Navigation stylets (Fig. 4) within this field are accurately localised with reference to a small array, which is secured to the patient's head. In all of our cases, the adhesive-based scalp array was used, rather than an alternative which requires fixation to the cranial bone. A rigid 0° rod-lens neuroendoscope with an external light source and monitor was utilised for all procedures.

The AxiEM navigation stylet fits easily into the working channel of the rigid endoscope (Fig. 5). The accuracy of the system was tested prior to clinical use, to ensure that the metal of the endoscope did not interfere with the detection of the radiofrequency stylet in the electromagnetic field. A trial evaluation of the system on a model head found that the system navigated accurately when the stylet was positioned in the endoscope's working channel.

The patients all underwent routine pre-operative stereotaxy-protocol magnetic resonance imaging scans, and these were registered on the AxiEM system after induction of anaesthesia. Rigid fixation of the skull was not used, with all patients positioned either on a jelly head ring or the Mayfield headrest. The AxiEM coil was positioned near the patient's head and attached to the side of the theatre table, and the reference array was taped to the patient's scalp for registration to the navigation system (Fig. 6). The patient's head could be moved at any stage within the AxiEM coil's electromagnetic field without compromising accuracy.

The AxiEM navigation stylet is longer than the shaft of the rigid endoscope, and the tip could easily protrude beyond the end of working channel. This could potentially be injurious if this occurred inadvertently whilst operating. We found that the stylet could be bent so that its tip reached the end of the endoscope, but did not protrude further (Figs. 5 and 7). An alternative means of preventing protrusion of the stylet was to affix a steristrip to the stylet at the point corresponding with the length of the endoscope barrel.

The Stealth workstation and the endoscope monitor were positioned so that both could be visualised by the surgeon simultaneously. Surgery proceeded with Stealth guidance to position the initial incision and burr hole. After durotomy, the endoscope was passed into the ventricle or cyst with the

Table 2 Neuroendoscopic procedures performed with electromagnetic navigation July 2007 to December 2008

Patient	Diagnosis	Operation
1	Cystic hypothalamic tumour	Cyst fenestration Cystoperitoneal shunt
2	Multiloculated hydrocephalus Entrapped fourth ventricle	Multiple cyst fenestrations Aqueductoplasty Fourth ventricle shunt
2	Multiloculated hydrocephalus Entrapped fourth ventricle	Multiple cyst fenestrations Aqueductoplasty Fourth ventricle shunt
3	Multiloculated hydrocephalus Entrapped fourth ventricle	Multiple cyst fenestrations Aqueductoplasty Fourth ventricle shunt
3	Multiloculated hydrocephalus Entrapped fourth ventricle	Fourth ventricle shunt
4	Multiloculated hydrocephalus	Multiple cyst fenestrations
4	Multiloculated hydrocephalus	Multiple cyst fenestrations
4	Multiloculated hydrocephalus	Multiple cyst fenestrations Ventriculoperitoneal shunt
5	Multiloculated hydrocephalus Ventriculitis	Multiple cyst fenestrations External ventricular drain
6	Periventricular cysts post-meningitis	Multiple cyst fenestrations
6	Periventricular cysts post-meningitis	Multiple cyst fenestrations
7	Periventricular cysts post-meningitis	Multiple cyst fenestrations
7	Periventricular cysts post-meningitis	Multiple cyst fenestrations Ventriculoperitoneal shunt
7	Periventricular cysts post-meningitis	Multiple cyst fenestrations External ventricular drain
8	Periventricular cyst	Cyst fenestration Cystoperitoneal shunt
9	Periventricular cyst Entrapped fourth ventricle	Cyst fenestration Aqueductoplasty Fourth ventricle shunt
10	Posterior fossa arachnoid cyst	Cyst fenestration
10	Posterior fossa arachnoid cyst	Cyst fenestration Cystoperitoneal shunt
11	Arachnoid cyst	Cyst fenestration
12	Arachnoid cyst	Cyst fenestration
12	Arachnoid cyst Cystoperitoneal shunt	Cyst fenestration
13	Arachnoid cyst	Cyst fenestration
14	Arachnoid cyst	Cyst fenestration
15	Posterior fossa arachnoid cyst Hydrocephalus	ETV Cyst fenestration
15	Posterior fossa arachnoid cyst Hydrocephalus	Cystoventricular conduit
16	Dandy Walker	ETV
17	Fourth ventricle tumour Hydrocephalus	ETV
18	Pineal tumour	ETV
19	Hydrocephalus	Septum pellucidostomy Ventriculoperitoneal shunt

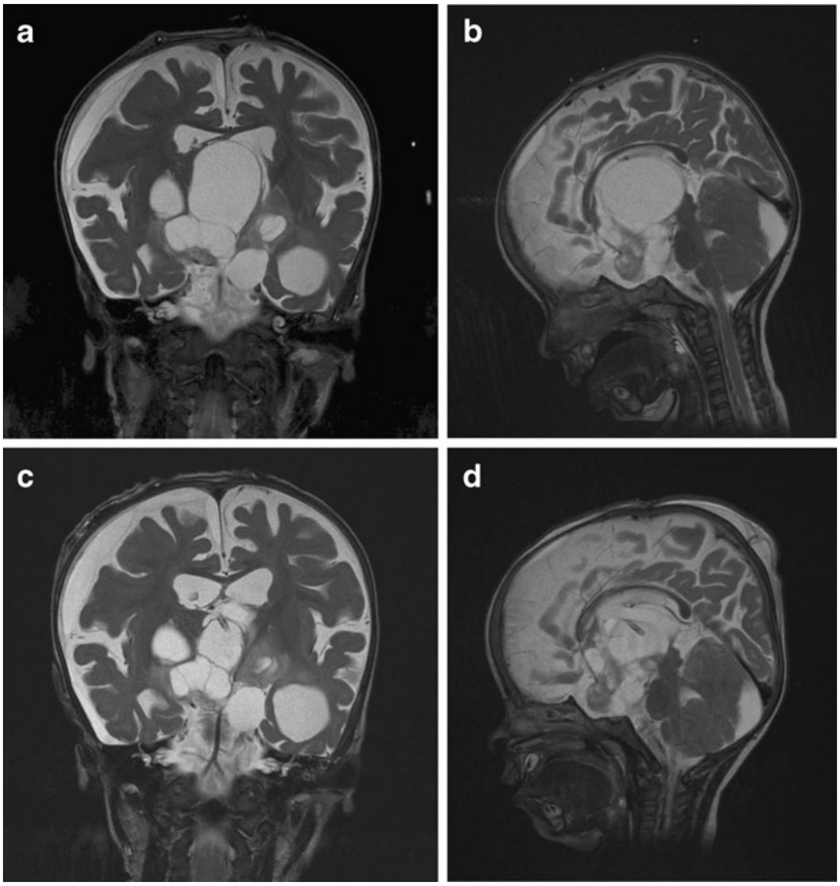

Fig. 1 **a**–**d** Pre- and post-operative magnetic resonance images of case 1, demonstrating a reduction in the size of the tumour cyst and correct placement of the shunt catheter. **a** Pre-operative coronal T2-weighted MRI, **b** pre-operative sagittal T2-weighted MRI, **c** post-operative coronal T2-weighted MRI, **d** post-operative sagittal T2-weighted MRI

navigation stylet in the working channel. In this way, the endoscope's trajectory and position could be tracked in real time. Correct positioning of the endoscope within the ventricles or cyst could be confirmed with direct endoscopic vision and simultaneously with the Stealth navigation system. Once the endoscope was satisfactorily positioned, the AxiEM stylet could be removed to allow use of instruments such as diathermy, scissors or balloon catheter through the working channel of the endoscope under direct vision. If the endoscope needed to be repositioned, the navigation stylet could easily be replaced in the endoscope's working channel to confirm the location of the tip of the instrument, even in the absence of normal anatomical landmarks.

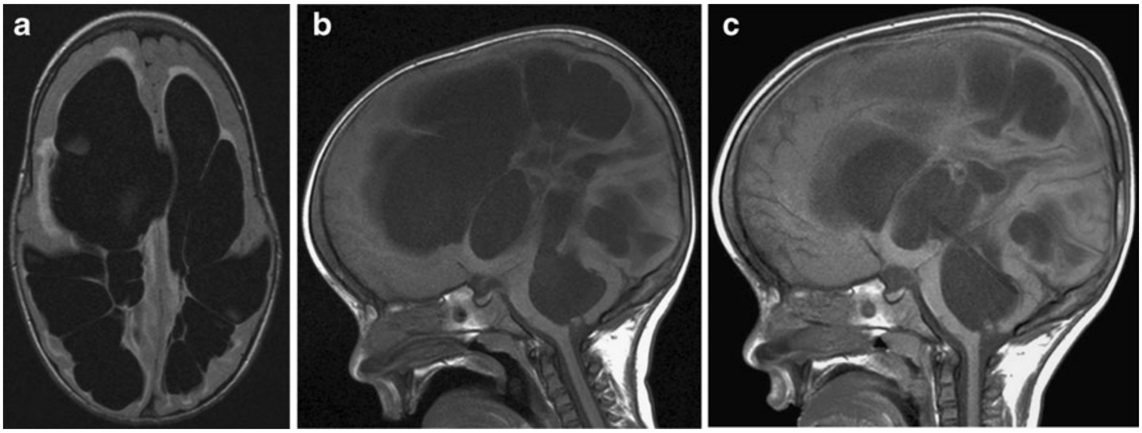

Fig. 2 **a**–**c** Pre- and post-operative magnetic resonance images of case 2, demonstrating complex ventricular anatomy and correct placement of the fourth ventricle shunt catheter. **a** Pre-operative axial T1-weighted MRI, **b** pre-operative sagittal T1-weighted MRI, **c** post-operative sagittal T1-weighted MRI

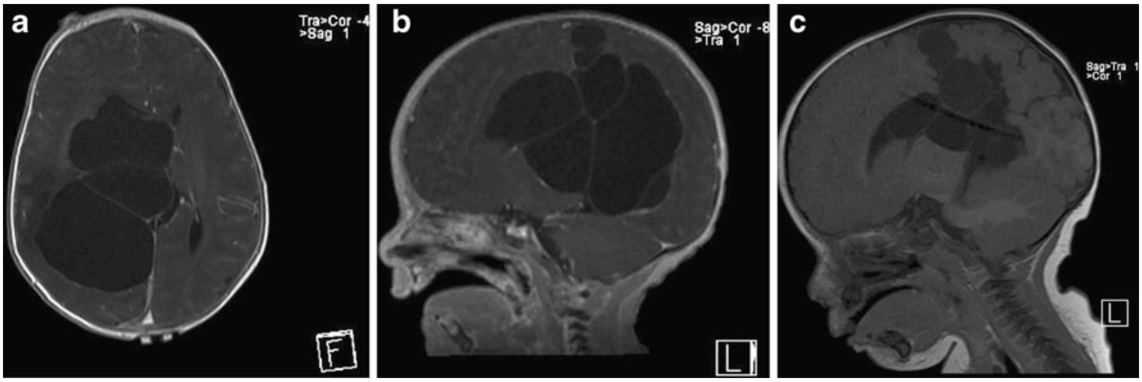

Fig. 3 **a**–**c** Pre- and post-operative magnetic resonance images of case 3, demonstrating a loculated arachnoid cyst and subsequent reduction in cyst size after fenestration and shunt placement. **a** Pre-operative axial T1-weighted MRI, **b** pre-operative sagittal T1-weighted MRI, **c** post-operative sagittal T1-weighted MRI

In some cases, it was advantageous to reposition the patient's head during the procedure. For example, one patient underwent endoscopic fenestration of a large posterior fossa arachnoid cyst, after which an endoscopic third ventriculostomy was performed through a separate frontal burr hole. Both stages of this operation were able to proceed under stereotactic guidance as the technique allows a degree of repositioning of the patient's head with no loss of navigational accuracy. This would have been technically very difficult if the patient had been fixed in cranial pins. Post-operatively, the patients were scanned with magnetic resonance imaging to confirm adequate decompression of cysts, correct placement of ventricular catheters and patency of fenestrations and stomas.

Results

In all of our cases, the goal of surgery (fenestration, placement of catheters) was realised successfully. This was confirmed in all cases by post-operative imaging. No technical failures were encountered. None of the patients suffered new neurological impairment as a result of their procedures.

We found that the use of simultaneous electromagnetic neuronavigation and endoscopy made the procedures safer and more accurate. Many of the cases had distorted anatomy, and without the use of navigation, it would have been difficult to ensure the accurate positioning of the endoscope and instruments.

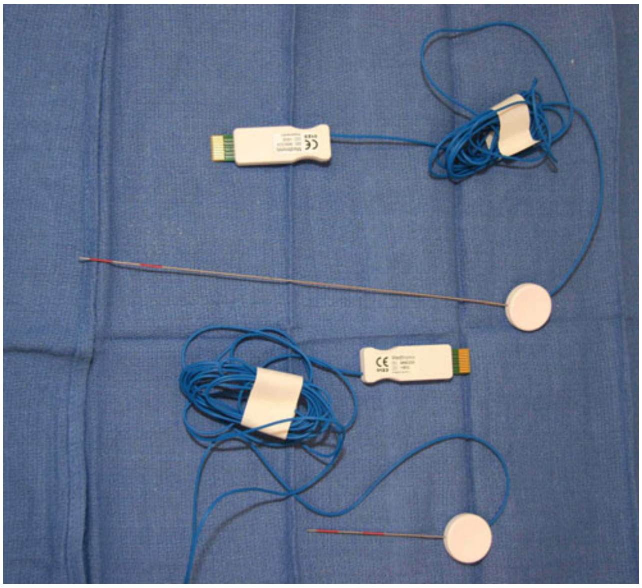

Fig. 4 AxiEM navigation stylets. A shorter stylet is used for initial registration of the patient to the navigation system and a longer stylet used for intraoperative navigation

Fig. 5 The AxiEM navigation stylet positioned in the working channel of the rigid endoscope. The stylet has been bent to prevent it protruding beyond the tip of the endoscope

Fig. 6 Patient positioning and registration, demonstrating the position of the AxiEM coil and the reference array taped to the forehead

Many of the patients were young or had thin skulls and would not have tolerated rigid pinned cranial immobilisation for optical stereotactic navigation. With the use of the non-invasive attachment of the reference arc and the placement of the patients' heads on jelly mats rather than in pins, we had no complications from positioning.

The only additional theatre time required was to allow initial registration of the Stealth neuronavigation system. We felt that this time loss was compensated by the resulting improved accuracy and surgical confidence.

Discussion

Neuronavigation technologies have shown themselves to have great utility in increasing accuracy and improving safety in surgical procedures. Framed stereotactic techniques have the limitations of interfering with free movement of instruments and do not afford real-time control. The more recent development of optically based frameless computerised stereotactic navigation techniques has significantly broadened the spectrum of utility of navigation technologies. Frameless neuronavigation allows the surgeon to enjoy free movement of guided instruments in real time and may enhance the safety and accuracy of surgical procedures even in the presence of abnormal or distorted anatomy when usual landmarks may not be available.

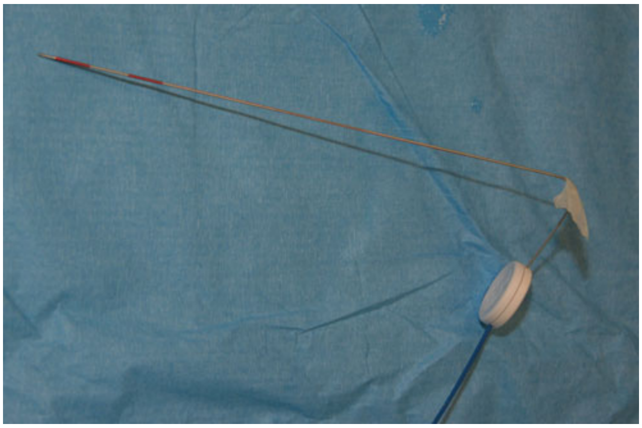

Fig. 7 The AxiEM navigation stylet bent to prevent protrusion of the tip beyond the tip of the endoscope

The integration of both framed and frameless stereotactic neuronavigation technologies with neuroendoscopy to improve surgical accuracy is well described in both adult and paediatric patients [2, 5, 6, 10]. Image guidance in endoscopic surgery can be particularly useful in patients who have distorted ventricular anatomy or intracranial cysts [7, 11]. Previous neuronavigation technologies such as the Medtronic StealthStation and BrainLAB VectorVision rely on the use of optical technology. This necessitates the immobilisation of the patient's head with rigid cranial fixation in pins and a visible reference frame with an unimpeded line of sight. Optical neuronavigation technologies also utilise cumbersome probes that attach to the endoscope, and these can hinder the free manipulation of the instrument by the surgeon. We found that the electromagnetic stereotactic system afforded the desired degree of navigational accuracy with a number of advantages over optical systems. The navigation stylets were less cumbersome than the equivalent optical probes, and the placement of the navigation stylets within the channel of the endoscope did not affect the system's accuracy.

One of the requirements of both frame-based and frameless neuronavigation techniques has been the rigid fixation of the patient's head in cranial pins. This has limited their use in the paediatric patient population, as young children's skulls are relatively thin and fragile, and there is a recognised risk of skull fracture, extradural haematoma or intracranial injury. This is especially significant in neonates and ex-premature infants, who may suffer conditions that distort the normal ventricular and skull anatomy and for whom neuronavigation may be useful. Similarly, older children with long-standing complex hydrocephalus may have thin and fragile skulls, yet these patients are more likely to benefit from stereotactic guidance in endoscopic procedures. Various techniques to overcome this problem have been described, such as the use of vacuum beanbag head holders rather than pins [1, 8]. These techniques have limitations, such as loss of navigational accuracy should the patient's head move during the procedure. However, they avoid the complications of trauma from pinned fixation in cranial tongs. Electromagnetic stereotactic neuronavigation technologies afford the surgeon the ability to accurately navigate in real time without the necessity of immobilising the patient's head in pins.

The reference arc may be attached directly to the patient, either by taping it to the scalp or securing it with screws to the skull through a small skin incision. The patient's head can then be positioned on a soft surface as desired and may even be moved during the procedure without any loss of navigational accuracy. This allows the full use of neuronavigation in paediatric patients in whom it was previously difficult due to the hazards of fixing the head in pins.

The use of AxiEM navigation in neuroendoscopy has been reported before. Karabatsou et al. [3] described four cases in their series of 39 arachnoid cysts managed with endoscopy, and Mangano et al. [4] have reported the successful use of the technique in two cases. Sangra et al. [9] have reported its use in a series of cases in an older paediatric cohort. Our experience of this technique in 29 younger paediatric cases is that the technique is safe and accurate and enhances the performance of endoscopic surgery even in very young patients.

Conclusion

We found the use of simultaneous pinless, frameless electromagnetic stereotactic neuronavigation and neuroendoscopy in children to be safe and accurate in patients as young as 1 month of age. The use of this technology in paediatric patients has a number of advantages over previously described techniques. We found that the system is less cumbersome than optical neuronavigation techniques and has the additional advantage of not requiring rigid cranial immobilisation in pins. It does not prolong operative time significantly and enhances the surgeon's spatial orientation and surgical confidence in patients with abnormal anatomy, complex cysts and hydrocephalus who are undergoing endoscopic procedures.

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