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Utility of Frameless Stereotaxy in the Resection of Skull Base and Basal Cerebral Lesions in Children

ABSTRACT—Since 1991, we have performed nearly 300 stereotactic procedures using the ISG viewing wand on a variety of cranial lesions in patients under 22 years of age. Of these, 38 procedures were performed on 34 patients for basal cerebral and skull base lesions. Our patients ranged in age from 3.5 months to 22 years with a mean age of 9.45 years. There were 18 females and 16 males. Twenty-one patients had basal cerebral lesions located in the thalamus (10), basal ganglia (2), third ventricle (2), and hypothalamus (7). Thirteen patients had skull base lesions located within the anterior optic apparatus (3), sella turcica (4), middle and posterior cranial fossae (4), and craniocervical region (2). Preoperative CT and/or MRI scan images were taken as a volume acquisition and transferred to the computer workstation utilizing the ISG Wand software. This workstation was transferred to the operating room where it was calibrated to a faro Surgicom arm which interfaces with the patient and the three-dimensional radiological image. The ISG Wand was utilized to plan the scalp and bone flaps and to select the optional trajectory to lesion. The surgical approaches which were specifically used in this series with the ISG Wand included transcallosal (15), pterional (5), frontal (3), subtemporal (4), transsphenoidal (3), temporal (3), tumor cyst shunt insertion (1), burr hole drainage (1), transoral (2), bifrontal (1), bifrontal mid facial (1), and transnasal (1). Although brain shift occurred following craniotomy and with brain retraction, the relative immobility of these lesions at the skull or cerebral base permitted an accurate targeting of all lesions with an error range of 1.0–2.5 mm throughout the entire procedure. This relatively precise intraoperative feedback led to more accurate recognition of tumor landmarks. It is the authors' impression that a more aggressive resection of these lesions was achieved than could be without the device. We conclude that a frameless stereotactic device such as the ISG Wand is particularly valuable in the approach to skull base and basal cerebral tumors in children.

The ISG Viewing Wand (ISG Technologies, Mississauga, ON) has been gaining in popularity among neurosurgeons since its introduction at the beginning of this decade. In pediatric neurosurgery, the ISG Wand is used for tumor removal, vascular malformations, epilepsy surgery, treatment of hydrocephalus in combination with endoscopy, aspiration of brain abscess, and brain biopsy. Several reports have confirmed the accuracy of this system in providing continuous stereotactic guidance throughout an intracranial procedure.¹⁻⁶ This system has also proved to be quite versatile.

A major concern with any frameless stereotaxy device is the drift which occurs secondary to manipulation of a lesion which can lead to improper image guidance. In addition, rigid skull fixation is usually necessary to achieve accurate stereotactic guidance, and this may be problematic in young children and infants.

Since 1991 we have utilized the ISG Wand at The Hospital for Sick Children in over 300 pediatric patients for different lesions. In this report, we review the utility of the ISG Wand in the resection of skull base and basal cerebral lesions in order to evaluate the applicability of this frameless stereotactic system among this group of pediatric patients.

CLINICAL MATERIAL AND METHODS

Patients

We identified 34 children with deep cerebral (n = 21) or skull base lesions (n = 13) from 300 patients who underwent nearly 325 ISG Wand directed surgical procedures between 1991-1996 at The Hospital for Sick Children in Toronto. A total of 38 procedures were performed in this subgroup using ISG viewing Wand guidance.

Viewing Wand System Components

As the details of this system have been previously reported,² only the essentials are provided here. The Viewing Wand consists of a mechanical articulated arm which acts as the three-dimensional (3D digitizer), interfaced to a computer graphics workstation which displays reformatted computed tomography (CT) and magnetic resonance imaging (MRI) images in a variety of configurations.

The Viewing Wand, manufactured by ISG Technologies (Mississauga, Ontario) is comprised of the following parts:

1. an articulated passive robotic arm (the SURGICOM manufactured by FARO (Orlando, FL) with interchangeable probe tips;
2. a Hewlett-Packard Apollo Series 710 computer;
3. a Hewlett-Packard CRX Graphics Color 19" monitor;
4. an uninterruptible power supply;
5. input pre-processor for the arm;
6. a keyboard and a mouse;
7. a mounting device to the operating table or head fixation frame;
8. multiple tape drives; and
9. specialized software that operate under the UNIX System.

The system is assembled onto a mobile cabinet, which facilitates the movement of the equipment to any location.

Image Acquisition

CT or MRI slices are taken in an axial plane contiguously at 3-mm intervals. The gantry angle is slightly reduced in order to include the nose and eyes for use as landmarks during registration. MRI images are taken as a volume acquisition making sure that the nose and eyes are included. CT/MRI images are then transferred to the main computer where the data can be reformatted and displayed in three orthogonal planes. In addition to the triorthogonal image display, an image outlying the trajectory of the probe tip to the lesion is routinely employed prior to lesion removal. This mode is particularly valuable for surgical planning and intraoperative localization of deep seated lesions.

Stereotactic Registration

At The Hospital for Sick Children a fully dedicated ISG Wand technician attends every frameless stereotactic guided procedure to reduce the chances for registration error and to reduce the time spent in registration. In the operating room the head is fixed to the operating table with the Sugita head frame. The articulated arm is then rigidly attached to the head frame and to the surgical table. The arm is then calibrated. The registration of the mechanical arm with the patient's head is initiated using surface landmarks such as the medial and lateral canthal margins and the anterior tip of the tragus on each side. These surface landmarks are then correlated with the same points on the three-dimensional CT/MRI surface reconstructions of the skin. After this, over 80 random surface points on the face and scalp are registered with the probe allowing the computer to generate a best fit analysis of these points to the previously captured CT/MRI data set. Each point is assigned an error based on this fit, and a root mean square error is calculated.

The registration is accepted if the root mean square error is less than 2.5 mm. Points with a large error are

deleted to improve the overall fit. During the neurosurgical procedure, prior to turning the bone flap, precautionary re-registration is carried out using four points around the periphery of the craniotomy. In the event that the head moves with the craniotomy, these four points can be used to rapidly re-register the patient to the CT/MRI data. Following the craniotomy, and dural opening, the ISG wand probe is passed along the surface of the cerebral cortex or along the skull base until MRI images are obtained which identify both the probe tip and the mass lesion of interest. If dissection is carried out in the depth of the brain or skull base, correlation of the Wand tip with rigid anatomical structures such as the clinoid process, sella turcica, or circle of Willis, will aid the neurosurgeon in recognizing if brain shifts have occurred.

ILLUSTRATIVE CASES

Case 1

A 14-year-old boy had a 2 year history of progressive facial asymmetry. On examination, there was left supraorbital prominence. The lesion was biopsied in another institution which confirmed the diagnosis of fibrous dysplasia involving the frontal orbital bone. The patient was referred to the Hospital for Sick Children and CT and MRI scans were performed (Figs. 1A and B). Due to ophthalmologic evidence of early visual deterioration, the patient underwent surgical excision of this monostotic fibrous dysplasia. Decompression of the superior orbital fissure and the optic canal was performed using a totally extradural approach using the ISG Wand. The ISG Wand was helpful in identifying the optic nerve without the need for an intraorbital or intradural dissection (Fig. 1C). Both the orbital roof and the frontal bone defects were reconstructed using autologous split calvarial bone grafts. His postoperative course was uneventful, and he has had no further deterioration in his vision with an excellent cosmetic result (Fig. 1D).

Case 2

This 13-year-old boy presented with an 18 month history of mouth breathing. His neurological examination was normal. Preoperative radiological investigations showed a retropharyngeal tumor eroding the clivus which coursed posteriorly to occupy the epidural space compressing the high cervical spinal cord (Figs. 2A–C). A transoral approach was performed to expose this lesion. The ISG Wand was utilized to guide the extent of tumor removal (Figs. 2D and E). A gross total excision was achieved as confirmed by a postoperative study (Fig. 2F). The diagnosis was chordoma. His post-

operative course was uneventful, without neurological deficit. He underwent posterior cervical fusion 10 days post-tumor removal using a titanium rectangle, wires, and bone graft. He received a curative dose of radiation therapy including a stereotactic boost to the region of the clivus.

Case 3

This 9-year-old boy presented with a brief history of headaches, visual loss, and progressive obtundation. On examination he had marked papilledema with a bitemporal field cut. Preoperative radiological studies showed a large suprasellar tumor obstructing his third ventricle causing hydrocephalus (Figs. 3A and B). The patient required urgent VP (ventriculo peritoneal) shunt insertion. Three days later, a subfrontal approach to the suprasellar lesion was performed. The tumor took origin from the undersurface of the optic chiasm. The ISG Wand was utilized to identify the surrounding critical structures and to guide tumor removal (Fig. 3C). A small portion of the tumor which invaded the chiasm was not removed (Fig. 3D). The final pathology report was low-grade astrocytoma. His postoperative course was unremarkable with no evidence of endocrinopathy. His visual acuity has gradually improved in both eyes over the past 12 months. He has received no further treatments and his residual tumor has been stable.

RESULT

Clinical Features of Study Population

Over 300 ISG Wand-guided procedures have been performed at the Hospital for Sick Children for different cranial lesions in patients less than 22 years of age. Of these, 40 procedures were performed on 34 patients for skull base and basal cerebral lesions. There were 18 females and 16 males with a mean age of 9.45 years and a range of 3.5 months to 22 years. There were 21 patients with basal cerebral lesions. These lesions were distributed in the thalamus (10), basal ganglia (2), third ventricle (2), and hypothalamus (7). The clinical features of these patients varied according to the site of the lesion (Table 1). The common clinical findings were headache (13), hemiparesis (10) ataxia (4) tremor (3), and precocious puberty (3). There were 13 patients with skull base lesions. These lesions were found in the anterior cranial base (3), the sella turcica (4), middle cranial base (2), foramen magnum (2), clivus, or high craniocervical region (2). The most common clinical features were visual loss (14), mass (4), headache (3), panhypopituitarism (3), and breathing difficulties (2) (Table 2).

Figure 1. Fourteen-year-old boy with left orbital fibrous dysplasia. (A) Axial CT, bone windows, through the orbits showing marked fibrous dysplasia of the sphenoid wing narrowing the right optic canal. (B) Axial T1-weighted MRI scan through the orbits showing loss of orbital fat signal in the apical region of the orbit posteriorly. (C) Intra-operative ISG Wand screen save showing the approach to the decompression of the optic can. The optic canal was unroofed in its entirety from a completely extradural approach. The point where the cross hairs intersect represents the tip of the ISG Wand in space, and it is pointing on the surface of the optic nerve after it was successfully decompressed. (D) Postoperative 3D CT reconstruction showing resection of fibrous dysplastic bone and reconstruction of the frontal-orbital region using autogenous, split-thickness bone grafts taken from the right posterior parietal region.

Figure 2. Thirteen-year-old boy with clival chordoma. (A) Sagittal MRI showing large retropharyngeal mass lesion destroying the clivus and compressing the upper cervical spinal cord. (B) Axial MRI scan through the upper cervical region depicting the indentation of the dural sac by the lesion. (C) Three-dimensional CT reconstruction of chordoma. Left: Sagittal image clearly demarcating bony erosion by tumor. Right: Trans-basal skull view showing relationship of tumor to posteriorly displaced vertebral and basilar arteries. Figure continues on page 34.

Figure 2 (Continued). (D) Demonstration of the intra-operative usage of ISG Wand in patient undergoing transoral approach to clival chordoma. The soft palate has been split. The ISG Wand probe is resting on the surface of the tumor. (E) Intra-operative ISG Wand screen save showing approach to clival chordoma. The tip of the probe at this point in the operation is resting on the tumor to the right side of the odontoid process. As tumor removal proceeded, the ISG Wand was valuable in determining the rostral-caudal extent of the tumor. (F) Postoperative MRI showing surgical changes in the pharyngeal tissues. The upper cervical spinal cord is now nicely decompressed. Posterior fusion was performed using a titanium rectangle supplemented with bone graft 1 week after the patient's chordoma was removed.

Figure 3. Nine-year-old male with large optic chiasmatic glioma. (A) Axial gadolinium-enhanced MRI showing large suprasellar tumor enveloping right middle cerebral artery. (B) Sagittal MRI showing tumor invaginating into third ventricle causing obstructive hydrocephalus. (C) Intra-operative ISG Wand screen save showing tip of probe resting on the right oculomotor nerve at the level of the cerebral peduncle, an observation which was correlated directly and visually at surgery. (D) Postoperative axial MRI scan showing tumor resected from the suprasellar region. Tumor has been removed from around the middle cerebral artery on the right. A small amount of residual tumor is seen in front of the brainstem.

Table 1. Clinical Findings Among Patients with Basal Cerebral Lesions

Headache	13
Hemiparesis	10
Papilloedema	9
Ataxia	4
Precocious puberty	3
Tremor	3
Past history	3
Seizure	2
Nausea/vomiting	2
Dysarthria	2
Diplopia	1
Visual loss	1
Precocious puberty	1
Secondary amenorrhea	1
Asymptomatic	1
Decreased memory	1
Optic atrophy	1
Sixth nerve palsy	1
Neurofibromatosis 1	1

Table 2. Clinical Finding Among Patients with Skull Base Lesions

Visual loss	15
Mass	7
Headache	3
Panhypopituitarism	3
Hemiparesis	2
Weakness	1
Precocious puberty	1
Secondary amenorrhea	1
Proptosis	1
Nasal mass	1
Hypertelorism	1

Operative Procedures

The patients with basal cerebral lesions underwent a total of 24 ISG-guided procedure (Table 3). The most common neurosurgical approaches included transcallosal (11), temporal (5), and pterional (3). Two procedures were performed on two patients with thalamic lesions and one patient with a third ventricular lesion. Fourteen ISG Wand-guided procedures were performed on patients with skull base lesion (Table 4). The most common approaches were transsphenoidal (3), pterional

Table 3. Surgical Approaches for Basal Cerebral Lesions

Transcallosal	11
Temporal	5
Pterional	3
Parietal occipital	2
Frontal	1
Shunt insertion	1
Burr hole drainage	1
Total	24

Table 4. Surgical Approaches for Basal Skull Lesions

Transsphenoidal	3
Pterional	2
Frontal	2
Transoral	2
Subtemporal	1
Bifrontal	1
Bifrontal mid facial	1
Transnasal	1
Parietal temporal	1
Total	14

(2), frontal (2), and transoral (2). One patient with a sellar tumor underwent two neurosurgical procedures: the first to drain a tumor cyst and the second for tumor removal.

Pathology and Extent of Resection

As defined in Tables 5 and 6, generally the histopathology of the lesions in both groups of patients was predominantly low grade. Only one patient with a high grade glioma was identified.

All patients underwent postoperative contrast-enhanced radiological studies to assess the degree of surgical resection. The ISG Wand helped the neurosurgeons to achieve a gross total resection in 10 patients with basal cerebral and 6 patients with skull base lesions. The degree of resection achieved in the various procedures is outlined in Table 7.

Table 5. Histopathological Finding Among Patients with Basal Cerebral Lesions

Astrocytoma low grade	10
Oligoastrocytoma	4
Astrocytoma high grade	1
Ependymoma	1
Subependymoma	1
Ganglioglioma	1
Cavernous hemangioma	1
Hamartoma	1
Fungal abscess	1
Total	21

Table 6. Histopathological Finding Among Patients with Skull Base Lesions

Astrocytoma low grade	3
Craniopharyngioma	2
Pituitary adenoma	2
Fibrous dysplasia	2
Chordoid meningioma	1
Hemangioma	1
Encephalocele	1
Chordoma	1
Total	13

Figure 4. Four patients with basal cerebral lesion had transient postoperative neurological complication, and six patients with lesions in thalamic hypothalamic regions had permanent motor deficit of variable degrees.

Table 7. Extent of surgical resection

	<i>Basal Cerebral</i>	<i>Skull Base</i>
Drainage	2	1
Biopsy	1	2
Subtotal	11	4
Gross total	10	6
Decompression	—	1
Total	24	14

Surgical Morbidity and Outcome

There was no permanent postoperative deficit in patients with base of skull lesions. However, four patients with basal cerebral lesion had transient postoperative neurological complication, and six patients with lesions in thalamic hypothalamic regions had permanent motor deficit of variable degrees (Fig. 4).

DISCUSSION

In the past decade several frameless stereotactic systems have been introduced into neurosurgical practice. These systems have revolutionized the practice of neurosurgery and have definite advantages over frame-based stereotactic systems. Frameless stereotaxy enables intraoperative navigation with an accuracy of 1–2 mm, but also provides continuous radiological data that are linked to the patient.¹¹ The main disadvantage of all stereotactic systems is loss of accuracy following brain shift.⁷ We have been using ISG Wand for 5 years in over 300 cases. As such, we have eliminated most of the intrinsic technical problems, that were identified in the early phases of development of the ISG Wand.

The ISG Wand requires rigid fixation of the patient's head to the operating table. With the Sugita head frame, we have been able to use the ISG Wand in infants as young as 4 months of age. This has been achieved by using six short infant pins that are gently tightened to

the scalp. Other methods to keep the head relatively immobile in young children or infants is to use tape or a facial stocking that wraps around the Mayfield headrest while the scalp and skull flaps are being raised. We have generally found that these procedures will provide adequate head stability to perform the procedure without encountering significant ISG Wand drift.

Several recent reports have confirmed the accuracy of the ISG Wand as an intraoperative navigational device.^{3–9,11} Most of these reports described the use of fiducial marks as a method for registration rather than surface fit registration. However, we have utilized a surface fit registration which we have also confirmed to be accurate.²

In pediatric neurosurgery, the ISG Wand can be used to guide the neurosurgical excision of an intra-axial brain lesion or skull base lesion,^{3,4,6,9} for epilepsy surgery,⁸ for vascular lesions such as cavernous malformation,³ in combination with endoscopy for the treatment of a loculated ventricular system, for brain biopsy, and for aspiration of brain abscess.¹⁰

A unique feature of skull base lesions in children are their benign nature and frequent attachment to bone or dural.³ These features make them ideal lesions for the application of frameless stereotaxy since they are attached to relatively immobile structures. As such, the accuracy of targeting lesions at the skull base can remain fixed in the 1–2 mm range, whereas with the parenchymal lesions postcraniotomy with CSF venting, brain shifts of up to 1–2 cm can occur.⁶ Even basal cerebral lesions as defined here are relatively immobile compared to more superficial cerebral lesions.

The ISG Wand is a surgical tool for frameless stereotaxy which, in our opinion, improves the confidence of the surgeon by providing detailed information regarding the surgical location and the relationship to the important neurovascular structures. It is our impression that possession of such detailed anatomical information may ultimately reduce patient morbidity.^{4,6} Admittedly it is impossible to prove that the use of the

device improves surgical outcome compared to traditional surgical technique, but it is difficult to conceive of the design of a prospective controlled study in which the use of ISG Wand can be subjected to more rigorous analysis. However, as a surgical tool, the ISG Wand and all frameless stereotactic devices must be judged first and foremost by the neurosurgeon conducting the procedure.² As this paper has demonstrated, we have found the ISG Wand to be of particular benefit for children with skull base and basal cerebral lesions.

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REVIEWER'S COMMENTS

Based on a large experience in the pioneer work and the development of frameless stereotaxy, this article focuses on skull base tumors and basal cerebral lesions in the pediatric population and describes the authors' experience in such lesions. They favorably review their experience and express the benefit of this technique in skull base lesions. They highlight the distinguished advantages of skull base lesions in regard to frameless stereotaxy and these are the stable bony landmark and the minimal shift of the deep basal cerebral lesion. Our experience with frameless stereotaxy is identical to theirs in terms of the reliability of the intraoperative feedback because of the immobile bone or dural landmark on the skull base. I think with the increasing use of this technology more assertive and radical skull base tumors can be achieved.

The authors have indicated six permanent deficits with lesions at the basal cerebral location suggesting that although the use of frameless stereotaxy might facilitate the exposure and precise localization it might not change the morbidity in handling such tumors.

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