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Real-Time Ultrasound-Guided Catheter Navigation for Approaching Deep-Seated Brain Lesions: Role of Intraoperative Neurosonography with and without Fusion with Magnetic Resonance Imaging

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Keywords
Real time · Ultrasound · Catheterization · Brain tumor

Abstract
Background/Aims: Brain shift during the exposure of cranial lesions may reduce the accuracy of frameless stereotaxy. We describe a rapid, safe, and effective method to approach deep-seated brain lesions using real-time intraoperative ultrasound placement of a catheter to mark the dissection trajectory to the lesion. ***Methods:*** With Institutional Review Board approval, we retrospectively reviewed the radiographic, pathologic, and intraoperative data of 11 pediatric patients who underwent excision of 12 lesions by means of this technique. ***Results:*** Full data sets were available for 12 lesions in 11 patients. Ten lesions were tumors and 2 were cavernous malformations. Lesion locations included the thalamus ($n = 4$), trigone ($n = 3$), mesial temporal lobe ($n = 3$), and deep white matter ($n = 2$). Catheter placement was successful in all patients, and the median time required for the procedure was 3 min (range 2–5 min). There were no complications related to catheter placement. The median diameter of surgical corridors on postresection magnetic resonance imaging was 6.6 mm (range 3.0–12.1 mm). ***Conclusions:*** Use of real-time ultrasound guidance to place a catheter to aid in the dissection to reach a deep-seated brain lesion provides advantages complementary to existing techniques, such as frameless stereotaxy. The catheter insertion technique described here provides a quick, accurate, and safe method for reaching deep-seated lesions.

Introduction

In many cases, surgical approaches to deep-seated brain lesions are challenging [1]. Targets located in the ventricles, periventricular white matter, thalamus, and mesial temporal lobe often need an approach via cortisec-

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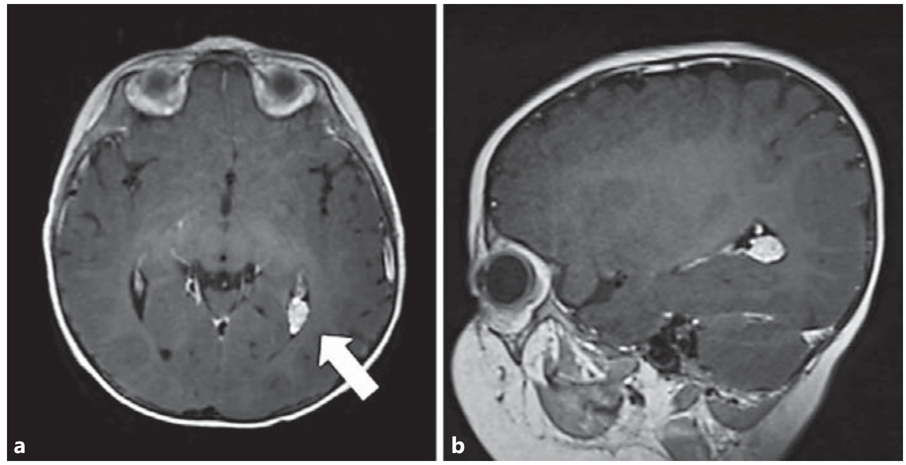

Fig. 1. Preoperative MRIs of a 13-month-old boy (Case 1). **a** On an axial T1-weighted image, a small Gadolinium-enhancing choroid plexus papilloma is seen in the left trigone (arrow). **b** A sagittal T1-weighted image. The volume of the mass was 0.9 mL.

tomy, with long dissections through normal white matter. In such cases, the lack of landmarks in homogenous subcortical white matter, coupled with the inherent difficulties of navigating along a fixed path, can result in long operation times, with an increased risk of neural injury. Here, we describe an easy technique of inserting a catheter from the surface of the brain to the lesion under real-time ultrasound guidance, followed by microscopic dissection along the catheter, to increase the speed, safety, and accuracy of the approach.

Patients and Methods

Surgical Techniques

The surgical method, patient position, and site of cortisectomy were determined preoperatively, based on magnetic resonance imaging (MRI) and the presumptive nature of the lesion (Fig. 1). If a transcortical approach is mandatory, the primary choice for a surgical corridor is the shortest route from the cortex to the lesion, while avoiding eloquent cortex.

Frameless stereotaxy was employed to identify the planned entry site. A craniotomy was performed, followed by dural opening and introduction of the ultrasonography probe (Fig. 2). Identification of the lesion and the relevant surrounding structures was followed by a small cortisectomy at the planned entry point. A standard ventricular catheter (outer diameter: 3.0 mm) was introduced under real-time ultrasound guidance into the cortex towards the lesion. When the catheter tip reached the lesion, the catheter was cut on the surface, leaving a small stump as a landmark. The surgical microscope was then introduced and the dissection was performed via the catheter (Fig. 3). Retraction systems and hand-held retractors were placed as needed. Once the margin of the lesion was exposed, the catheter was then removed. The surgical corridor was subsequently secured with retractors (Fig. 4). Resection of the lesion was then performed using a standard microsurgical technique.

Patient Population

We searched the operative database of the Department of Neurosurgery, Boston Children's Hospital, Boston, MA, USA, for patients who underwent surgery that made use of this technique. The medical records and radiological data of the patients were reviewed retrospectively. Preoperative MRI and/or computerized tomography (CT) scan were reviewed for the location and size of the lesion concerned. The size of the lesion was calculated using the formula $(a \times b \times c)/2$, in which a, b, and c represent the maximal diameters in 3-dimensional planes. Intraoperative and postoperative MRIs were reviewed to assess the degree of lesion removal. The width of the surgical corridor was calculated as the mean of the horizontal and vertical diameters assessed in an MR plane perpendicular to the midpoint of the surgical corridor. This study protocol was approved by the Institutional Review Board of the Boston Children's Hospital.

Results

From 2005 to 2012, full data sets were available for 12 lesions in 11 patients approached with this technique. Seven patients were female and 4 were male. The median age of the patients at surgery was 8 years (range 4 months to 19 years). One patient had a tumor resection at the age of 10 years, and then underwent surgery again for a recurrence 7 years later (also using the catheter technique). Preoperative MRI was available for all lesions except 1 (only a preoperative CT scan was available). Patient data are summarized in Table 1.

Ten lesions were tumors and 2 were cavernous malformations. Of the 10 tumors, 2 were pilocytic astrocytoma, 2 were choroid plexus papilloma, 2 were pleomorphic xanthoastrocytoma (1 primary tumor and 1 recurrence), 1 was an oligoastrocytoma, 1 was a central neurocytoma,

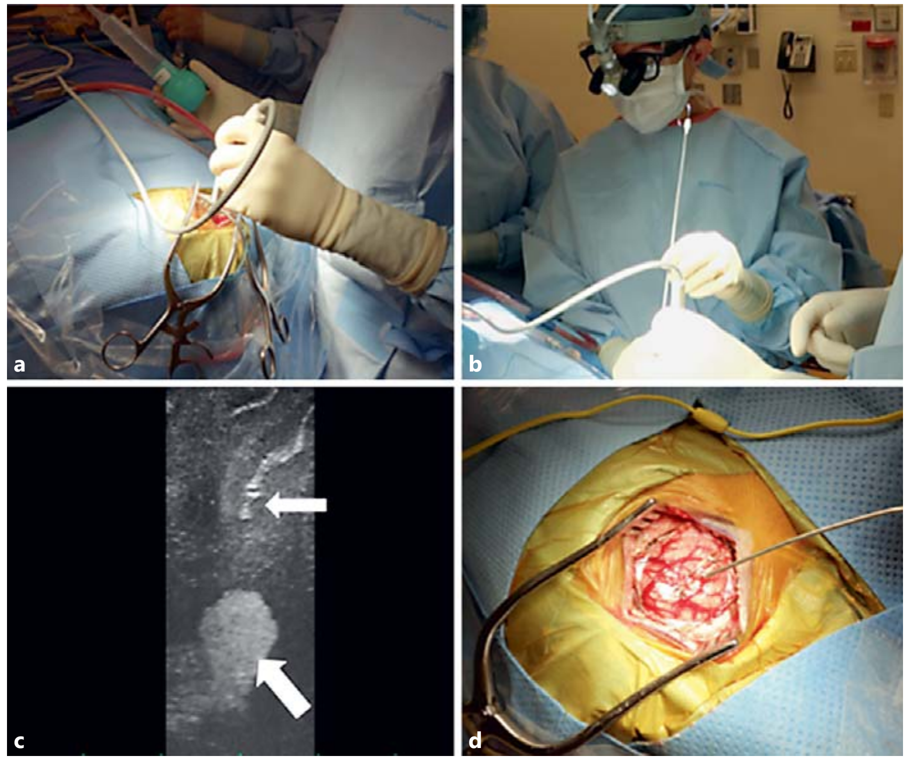

Fig. 2. The placement of the catheter with ultrasound guidance. **a** After craniotomy and dural opening, the ultrasound probe is applied. **b** Insertion of the catheter with the probe, showing the lesion. **c** Ultrasound image showing the tumor (large arrow) and advancing catheter tip (small arrow). **d** After inserting the catheter, it is cut, leaving a short stump as a marker.

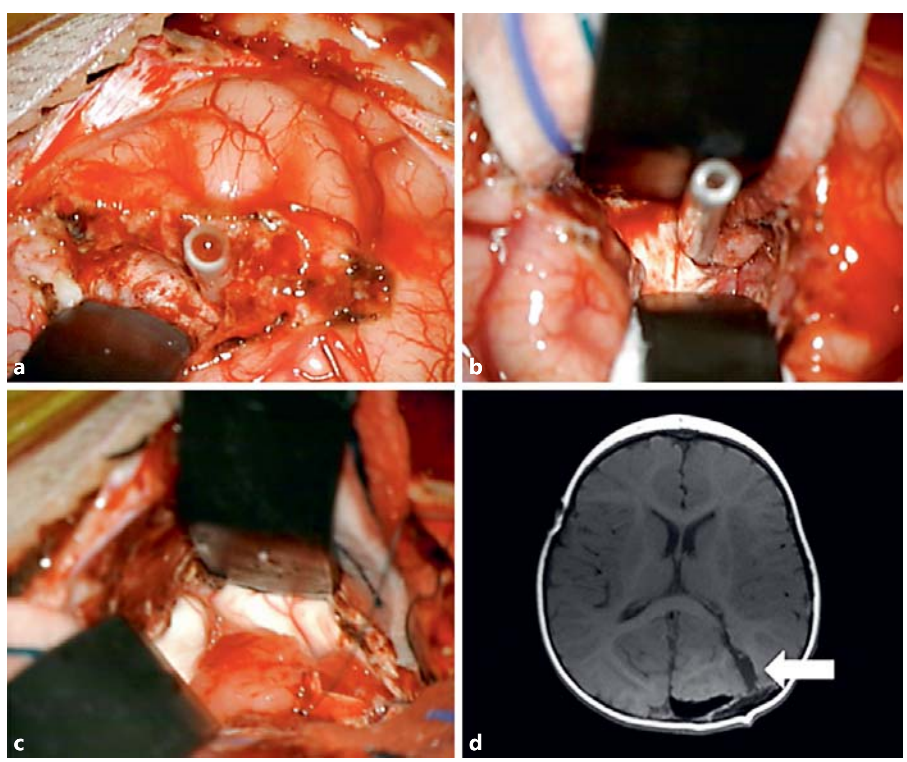

Fig. 3. a Microscopic view of the cortisectomy around the catheter stump. **b** Dissection is proceeded following the catheter in situ. **c** Completion of dissection and exposure of the tumor. **d** Postresection MRI reveals complete removal of the tumor and the narrow surgical corridor (diameter: 10.5 mm).

Table 1. Clinical data on 11 patients (12 lesions) to whom the technique was applied

Case No.	Sex	Age at surgery	Tumor location	Side	Tumor volume, mL	Pathology	Technique duration, min	Corridor	Resection	Corridor diameter, mm	Complications
1	M	13 months	trigone	left	0.9	CPP	5	O	GTR	10.5	none
2	F	4 months	trigone	left	62.5	CPP	2	O	GTR	3.0	none
3	F	12 years	trigone (wall)	left	0.1	central neurocytoma	5	O	GTR	8.2	none
4	M	3 years	thalamus	left	16.8	CM	3	Fr	GTR	3.5	transient aggravation of right hemiparesis (improved)
5	M	14 years	thalamus	right	0.8	pilocytic astrocytoma	3	T	GTR	7.0	transient aggravation of left hemiparesis (improved)
6	F	3 years	thalamus-midbrain	left	11.6	oligoastrocytoma	4	T	STR	6.3	none
7	F	6 years	thalamus-midbrain	left	8.9	pilocytic astrocytoma	2	T	GTR	10.3	none
8	F	19 years	Fr	left	0.4	CM	3	Fr	NTR	3.7	none
9	F	6 years	O	left	0.3	ATRT metastasis	3	O	GTR	3.2	none
10	M	15 years	mesial T	left	1.6	DNT	3	T	GTR	11.6	none
11[a]	F	10 years	mesial T	left	4.4	PXA	4	T	GTR	4.4	none
11.1[a]	F	17 years	mesial T	left	6.8	PXA recurrence	4	T	GTR	12.1	none

F, female; M, male; Fr, frontal lobe; O, occipital lobe; T, temporal lobe; CPP, choroid plexus papilloma; CM, cavernous malformation; ATRT, atypical teratoid rhabdoid tumor; DNT, dysembryoplastic neuroepithelial tumor; PXA, pleomorphic xanthoastrocytoma; GTR, gross total resection; STR, subtotal resection; NTR, near total resection. [a] The same patient who experienced tumor recurrence.

1 was a dysembryoplastic neuroepithelial tumor, and 1 was a metastatic atypical teratoid rhabdoid tumor.

The locations for surgery included the thalamus (n = 4, including 2 lesions extending into the midbrain), mesial temporal lobe (n = 3), trigone (n = 3), frontal lobe (n = 1), and occipital lobe (n = 1). Eleven lesions were located on the left side and 1 was on the right side. The median lesional volume was 3.0 mL (range 0.1–62.5 mL).

The placement of a catheter was successful under ultrasound guidance in all cases, with no complications. In the patient with the recurrent tumor, 2 catheters were inserted at opposing ends of the tumor to mark its boundaries (the so-called "picket fence" technique). The surgical corridor was made in the temporal lobe in 6 cases, the occipital lobe in 4 cases, and the frontal lobe in 2 cases, according to the site of the lesion. The median time required for the catheter insertion was 3 min (range 2–5 min).

Postresection MRI was performed for all lesions (intraoperatively in 10 cases and postoperatively in 2, i.e., within 72 h). Complete resection of the lesion was confirmed for 11 lesions. Subtotal resection (>95% of tumor volume removed) was noted for 1 oligoastrocytoma situated in the thalamus and midbrain, with a small remnant nodule in the midbrain. The median diameter of the surgical corridor on postresection MRI was 6.6 mm (range 3.0–12.1 mm). Two patients with thalamic lesions (one a cavernous malformation and the other a pilocytic astrocytoma) experienced transient worsening of preexisting hemiparesis which subsequently resolved at follow-up.

Discussion

During the neurosurgical approach to a deep-seated, small lesion, maintenance of an accurate surgical trajectory to the lesion is paramount. Several methods have been developed to achieve this objective. The most popular method is the use of frameless stereotaxy with neuronavigation systems [2]. Frameless stereotaxy is currently widely available and provides accurate lesion targeting. However, there are inherent risks in registration and application errors with this method [3]. Brain shift after dural opening and cerebrospinal fluid release can also cause a significant discrepancy between the image and reality,

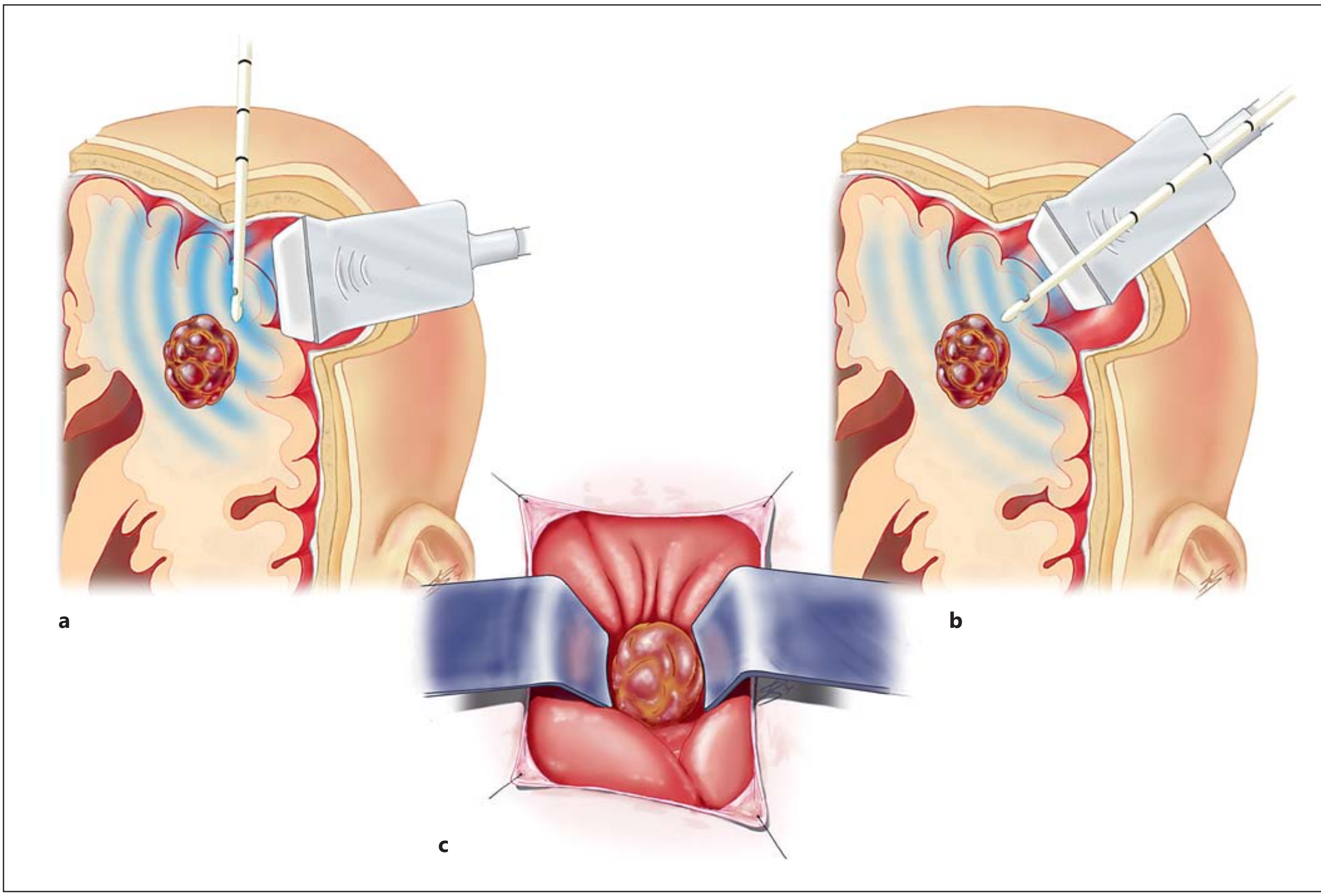

Fig. 4. Basic principles of neurosonography. **a** In-plane ultrasound scan of the brain. **b** Out-of-plane ultrasound scan of brain. **c** View of lesion with subsequent exposure after following the catheter.

especially for relatively small lesions [4]. Maintaining the correct trajectory during the dissection is still problematic, even with up-to-date neuronavigation devices, and confirmation of the location often requires repeated use of the stereotactic wand, prolonging surgery [4].

Real-time ultrasound is a versatile tool to overcome this shortcoming [1]. It provides neurosurgeons with up-to-date information about the surgical field, with ease [5]. Nonetheless, continuous application of ultrasound during the dissection may be difficult and cumbersome. Blood and air in the surgical corridor may also prevent obtaining high-quality images.

The findings support the benefits and efficacy of real-time intraoperative ultrasound in cranial neurosurgery as an important adjunct to frameless stereotaxy. A retrospective review of 202 resections of pediatric brain tumors found that intraoperative ultrasound had near-perfect agreement with postoperative MRI [6]. Petridis et al. [7] reviewed the treatment of low-grade glioma patients, 15 with intraoperative ultrasound and 19 with neuronavigation. They found that neuronavigation alone missed the target in 5 patients while the intraoperative ultrasound localized all targets [7]. Prada et al. [8] fused preoperative MRIs and intraoperative ultrasound images to manage 67 patients with brain lesions, and found improved orientation and panoramic view. Subsequently, Prada et al. [9] used this fusion imaging for 58 patients, and found overlap errors of <3 mm in all cases. Rygh et al. [10] found that 26 of 62 patients with intracranial tumors had their blood vessels preserved by the use of intraoperative ultrasound angiography.

One evolving variation of this technique involves fusing real-time ultrasound data with preexisting neuronavigation imaging. Data sets can thus be updated using intraoperative ultrasound. Farnia et al. [11] reported a hybrid method for intraoperative ultrasound, based on optimized residual complexity, to bypass the problems of registering intraoperative ultrasound images with preoperative MRI. This method resulted in greater accuracy than with conventional approaches.

In this report, we describe a minimally invasive microsurgical approach toward deep-seated brain lesions that used catheter placement to the lesion guided by real-time ultrasonography. It is worth noting that it is highly likely that there are multiple variations of this technique that have independently evolved at numerous institutions by many different surgeons. Nonetheless, there are limited published data on its use, and we demonstrate that our experience was gratifying, with the data confirming a high rate of complete resection and a minimal risk of complications. We used a ventricular catheter that is available in all neurosurgical units; the technique is simple, it complements other navigation methods, and it can be accomplished within 5 min. This approach is also versatile, as demonstrated by our modification of the placement of multiple catheters to delineate the boundary of a tumor (the "picket-fence" technique). Overall, ultrasound and catheter placement allow for the real-time confirmation of accurate placement, speed up the operation by giving the surgeon a visual cue to follow to the target, and facilitate the use of the smallest possible corridor by providing a direct path to the lesion.

There are some limitations, however. First, this technique is potentially contraindicated in the setting of high-flow vascular lesions, such as arteriovenous malformations, since catheter placement could inadvertently cause bleeding from the malformation. Second, the method requires a straight path from the surface to the target, as the catheter cannot be easily curved. A tubular retraction system can allow dissection through the white matter with relatively even pressure, and provide a straight surgical corridor [12–16]. However, targeting the retractor depends on frameless stereotaxy, with its risks of error as noted above. The rigid wall of the retractor can limit visualization of the lesion and its complete resection in some patients. Lastly, ultrasound can only be used for lesions that are visible with this technology, so nonechogenic lesions cannot be targeted. Experience in interpreting intraoperative ultrasound is mandatory.

Conclusions

Intraoperative ultrasound, coupled with placement of a catheter, for guidance to a deep-seated lesion provides the advantage of combining real-time imaging with the simplicity of following a direct path to a fixed end point with a clear visual cue. This technique provides immediate confirmation that the end point is accurate, allows narrow surgical corridors, and facilitates a faster dissection, as demonstrated in our data. This simple technique can be readily adopted in most operating theaters, and offers a powerful, complementary means of increasing the accuracy of intraoperative navigation.

Acknowledgement

While it is impossible to acknowledge all of the iterations and refinements of ultrasound-directed tumor resections that have been utilized by individual surgeons, the contributions of Dr. W.M. Chadduck merit special note, as he described a version of this approach to Dr. R.M. Scott.

Disclosure Statement

The authors have nothing to disclose and report no conflicts of interest.

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