Skull-fixated fiducial markers improve accuracy in staged frameless stereotactic epilepsy surgery in children

Clinical article

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Object. Surgery to monitor and resect epileptogenic foci may be undertaken in 2 stages, providing an opportunity to use skull-fixated fiducials implanted during the first stage to improve the accuracy of cortical resection during the second stage. This study compared the intrinsic accuracy of skin-based and skull-fixated fiducial markers in registering frameless stereotaxy during pediatric epilepsy surgery. To the authors’ knowledge, these modalities of registration have not previously been directly compared in this population.

Methods. The authors undertook a retrospective review of pediatric patients who underwent resection of epileptogenic foci in 2 stages with frameless stereotactic assistance, performed by a single surgeon at Oregon Health & Science University. For the first stage (subdural grid implantation), 9 skin fiducial markers were used to register anatomical data in a frameless stereotactic station. Intraoperatively, four 3-mm screws were placed circumferentially around the craniotomy. Postoperatively, thin-slice brain MR and CT images were obtained and fused. For the second stage, the 4 screws were used as fiducial markers to register the stereotactic anatomical data. For both stages, accuracy (difference in millimeters from zero of the manual fiducial registration compared with the computer model) was determined using navigation software. The intrinsic accuracy of these 2 methods of fiducial registration was compared using a paired Student t-test.

Results. Between 2004 and 2009, 40 pediatric patients with epilepsy underwent frameless stereotactic surgical procedures. Fourteen patients who had 2-stage procedures using skin-based and skull-fixated registration with complete accuracy data were included in this retrospective review. Mean registration error was significantly lower using skull-fixated fiducials (1.35 mm, 95% CI 1.09–1.60 mm) than using skin-based fiducials (1.85 mm, 95% CI 1.56–2.13 mm; p = 0.0016).

Conclusions. A significantly higher degree of accuracy was achieved using 4 skull-fixated fiducials compared with using 9 skin-based fiducials. This simple and accurate method for registering frameless stereotactic anatomical data does not involve the potential time, expense, discomfort, and morbidity of extraoperative skull-fixated fiducial placement. The method described in this paper could also be extrapolated to other planned 2-stage cranial surgical procedures such as combined skull base approaches. (DOI: 10.3171/2010.10.PEDS10352)

KEY WORDS • stereotaxy • frameless • accuracy • epilepsy

Abbreviation used in this paper: EEG = electroencephalography.
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es (that is, which are present at the time of preoperative navigation imaging). Typically, markers affixed to either the skin or skull, or skin surface contours, are used for coregistration.9

There are few reports that describe the use of frameless stereotaxy for pediatric epilepsy surgery, and none, to our knowledge, regarding the accuracy of frameless stereotaxy for this surgical indication. The purpose of this study was to evaluate a novel and technically simple method of registering fiducial markers during 2-stage cranial procedures and to compare the accuracy of skin-based versus skull-fixated fiducials in registering frameless stereotaxy for pediatric epilepsy surgery.

Methods

We undertook a retrospective review of pediatric patients who underwent resection of epileptogenic foci in 2 stages with frameless stereotactic assistance by a single surgeon (N.R.S.) from 2004 to 2009 at a single pediatric tertiary referral institution. The institutional review board of Oregon Health & Science University approved this retrospective single-institution study.

For the first stage (subdural grid implantation), 9 skin fiducial markers were used to register anatomical data from 3-T MR images in a Stealth frameless stereotactic station (Medtronic, Inc.). At our institution, the 9 skin fiducial markers are placed in the following standard anatomical locations to minimize scalp distortion during scanning: in the midline just anterior to the hair line, approximately 3 cm off the midline bilaterally just anterior to the hair line, bilaterally over the root of the zygoma, bilaterally over the mastoid process, and approximately 4 cm off the midline and 2 cm posterior to the coronal suture. Specific MR imaging parameters such as slice thickness, repetition time, and echo time were individually tailored to each patient based on lesion characteristics shown on MR imaging. Intraoperatively, following the craniotomy but prior to the dural incision, 4 titanium 3-mm screws (Synthes) were placed circumferentially around the craniotomy within the standard confines of the exposed operative field. These “fiducial” screws were placed distant from other hardware intended for cranial plate fixation at closure, using the same system. This distance reduces the amount of artifact on postoperative CT imaging that might otherwise obscure the fiducial screws or cause them to be misidentified (Fig. 1 left). After placement of the screws, they were registered as fiducial markers using the Stealth system 3-ball registration probe, the tip of which fits snugly and reproducibly in the cross-hatch of the screw head.

Postoperatively, patients were observed in the pediatric intensive care unit for 3 days. During this time, continuous EEG from the subdural electrodes was monitored and cortical stimulation mapping undertaken by the pediatric neurology service as indicated. On the day preceding the second-stage operation, thin-slice brain MR and CT images (slice thickness 1.5 mm, interslice distance 0 mm), were obtained and fused using Stealth navigation software. The thin-slice MR imaging is repeated because the placement of the subdural electrodes in the first stage distorts the anatomy of the surgical area of interest. Magnetic resonance imaging allowed for optimal characterization of cortical and gyral anatomy and lesional targets while CT imaging allowed for precise skull-fixated screw fiducial localization. During the second stage (resection of epileptogenic foci), the 4 skull-fixated screws were used as fiducial markers after scalp opening to register the fused stereotactic anatomical data set (Fig. 1 right). Following cortical epileptogenic foci resection, the 4 skull-fixated screws were removed prior to standard closure.

For every 2-stage procedure, the same clinicians registered the frameless stereotaxy system for operation. Frameless stereotaxy accuracy (difference in millimeters from zero of the manual fiducial registration compared with the computer model) was generated by the Stealth software during the registration for each stage. The accuracy of these 2 methods of fiducial registration was analyzed using Stata version 10 (StataCorp LP) and compared using a paired Student t-test.

Results

Between 2004 and 2009, 40 pediatric patients with epilepsy underwent frameless stereotactic surgical procedures. Fourteen patients who had 2-stage procedures using skin-based and skull-fixated registration with complete accuracy data were included in our retrospective review (Table 1). One patient (Case 4) had 2 separate 2-stage procedures 3 years apart. Median age was 11 years (range 2–18 years). No patient experienced an adverse event related to skull-fixated fiducial placement or removal. Twelve of 14 patients had greater registration accuracy using skull-fixated fiducials; only Cases 5 and 8 had greater registration accuracy with skin-based fiducials. Using a paired Student t-test, the mean registration error was significantly lower using skull-fixated fiducials (1.35 mm, 95% CI 1.09–1.60 mm) than using skin-based fiducials (1.85 mm, 95% CI 1.56–2.13 mm; p = 0.0016).
was followed in 1995 by Pollack and colleagues 8 who less stereotaxy in pediatric neurosurgery in 1994. This was abandoned early in our series, would be much more racy using skin fiducials for second-stage surgery, which placement in the first stage. Although not measured, we percutaneous EEG leads following subdural EEG grid with significant postoperative soft-tissue edema and with placing skin-based fiducials on pediatric patients the anatomical inaccuracy and inconvenience associated The use of subgaleal, skull-fixated fiducials also avoids 118 J Neurosurg: Pediatrics / Volume 7 / January 2011

Discussion

Drake and colleagues4 first reported the use of frameless stereotaxy in pediatric neurosurgery in 1994. This was followed in 1995 by Pollack and colleagues8 who published a report on a series of patients with diseases that included tumors, epilepsy, vascular malformations, and others. Since that time, few other patient series have been published. A Medline search on June 18, 2010, that included the terms, “((children) AND frameless) AND stereotactic,” yielded only 72 articles, the majority of which consisted of adult patient reports. To our knowledge, we report the first series of pediatric patients undergoing epileptogenic foci resection using frameless stereotaxy to compare the accuracy of skin-based and skull-fixated fiducial markers. In 2008, Chamoun and colleagues4 published a technical note describing a similar method of neuronavigation registration to the one that we describe in this study, in which they used four 1.5-mm drill holes in lieu of skull-fixed screws to register the frameless stereotactic system in 2-stage epilepsy surgery. However, they did not explore the accuracy of skin- and skull-fixed fiducial markers.

Computed tomography–guided navigation is inherently more accurate than MR imaging–guided navigation3,10. Additionally, accuracy is improved by positioning fiducial markers closer to the target area of interest5 and equally distributing them around the target.10 The use of subgaleal, skull-fixated fiducials also avoids the anatomical inaccuracy and inconvenience associated with placing skin-based fiducials on pediatric patients with significant postoperative soft-tissue edema and percutaneous EEG leads following subdural EEG grid placement in the first stage. Although not measured, we suspect based on early experience that registration accuracy using skin fiducials for second-stage surgery, which was abandoned early in our series, would be much more inaccurate even than that observed during the first-stage surgery we describe.

Skull-fixated fiducials for second-stage procedures have a number of inherent advantages: 1) registering 4 fiducials is faster than registering 9; 2) patients and caretakers may not remove skull-fixated fiducials while awaiting surgery; and 3) as we describe, using skull-fixated fiducials is significantly more accurate than skin-based fiducials as the former are affixed to a rigid structure, whereas skin is subject to a variety of forces both during image acquisition or application of rigid fixation.

We have observed no adverse effects attributable to skull-fixated fiducials in our series. Drawbacks of the method we detail are the expense related to placement of 4 additional titanium screws and the radiation exposure of a stereotactic head CT scan.

Although we found a statistically significant difference in the accuracy of skull-fixated fiducials compared with skin-based fiducials, our series is limited by the small number of patients and by its retrospective nature. Nevertheless, our series does reflect real-world usage in an active clinical environment. The technique described here is only applicable to neurosurgical procedures with an existing requirement for 2 stages and is limited to registration methods using manually identified fiducials, and cannot be used with laser-guided surface topographical registration. Of note, the real, as opposed to inherent, accuracy of the method we describe for the identification of MR-based cortical landmarks may also be limited by the accuracy of MR and CT imaging merger software. Additionally, this study does not address inaccuracy secondary to brain shift during neurosurgical procedures, which remains a limitation of this method. Although in practice we have encountered perfect correspondence of major gyral and venous anatomy using the merged images in all cases, this variable requires further formal study.

Because the position of subdural electrodes may shift upon dural opening during second-stage surgery, we have not used the position of these electrodes on the fused interoperative imaging for navigation purposes. We have also abandoned the use of skin fiducials for the second stage of 2-stage surgery due to inaccuracy added by the presence of significant scalp edema. The accuracy error of these alternative approaches, however, was not quantitatively addressed by the current study. Our results have demonstrated a high level of accuracy for skull-fixated fiducials in the second stage of 2-stage cranial procedures. Future investigation may compare the accuracy of our method to other approaches.

Conclusions

In this study, a significantly higher degree of inherent accuracy was achieved using 4 skull-fixated fiducials when compared with using 9 skin-based fiducials to register frameless stereotaxy in pediatric epilepsy surgery. The method we describe takes advantage of both the inherent accuracy of CT-based navigation and of skull-based fiducials, but is limited by the accuracy of the CT-MR data set merger. We advocate using this simple and more accurate method for registering frameless stereotac-
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tic anatomical data. This technique can easily be generalized to other planned 2-stage intracranial surgical procedures such as combined skull base approaches.

Disclosure

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

Author contributions to the study and manuscript preparation include the following. Conception and design: Selden, Anderson, Hunt, Roberts. Acquisition of data: Thompson, Anderson, Hunt. Analysis and interpretation of data: Selden, Thompson, Anderson, Roberts. Drafting the article: Selden, Thompson, Anderson, Hunt. Critically revising the article: all authors. Reviewed final version of the manuscript and approved it for submission: all authors. Study supervision: Selden.

Acknowledgment

The authors would like to express their appreciation and thanks to Shirley McCartney, Ph.D., for editorial assistance.

References


Portions of this work were presented at the 2010 Congress of Neurological Surgeons Annual Meeting, San Francisco, California, October 16–21, 2010.

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