Magnetic resonance imaging as an alternative to computed tomography in select patients with traumatic brain injury: a retrospective comparison

Marie Roguski, MD, MPH,1 Brent Morel, BS,1,2 Megan Sweeney,3 Jordan Talan, BA,1,2 Leslie Rideout, FNP, PhD,3 Ron I. Riesenburger, MD,1 Neel Madan, MD,4 and Steven Hwang, MD1

Departments of 1Neurosurgery, 2General Surgery, and 4Radiology, Tufts Medical Center; and 3Tufts University School of Medicine, Boston, Massachusetts

OBJECT Traumatic head injury (THI) is a highly prevalent condition in the United States, and concern regarding excess radiation-related cancer mortality has placed focus on limiting the use of CT in the evaluation of pediatric patients with THI. Given the success of rapid-acquisition MRI in the evaluation of ventriculoperitoneal shunt malfunction in pediatric patient populations, this study sought to evaluate the sensitivity of MRI in the setting of acute THI.

METHODS Medical records of 574 pediatric admissions for THI to a Level 1 trauma center over a 10-year period were retrospectively reviewed to identify patients who underwent both CT and MRI examinations of the head within a 5-day period. Thirty-five patients were found, and diagnostic images were available for 30 patients. De-identified images were reviewed by a neuroradiologist for presence of any injury, intracranial hemorrhage, diffuse axonal injury (DAI), and skull fracture. Radiology reports were used to calculate interrater reliability scores. Baseline demographics and concordance analysis was performed with Stata version 13.

RESULTS The mean age of the 30-patient cohort was 8.5 ± 6.7 years, and 63.3% were male. The mean Injury Severity Score was 13.7 ± 9.2, and the mean Glasgow Coma Scale score was 9 ± 5.7. Radiology reports noted 150 abnormal findings. CT scanning missed findings in 12 patients; the missed findings included DAI (n = 5), subarachnoid hemorrhage (n = 6), small subdural hematomas (n = 6), cerebral contusions (n = 3), and an encephalocele. The CT scan was negative in 3 patients whose subsequent MRI revealed findings. MRI missed findings in 13 patients; missed findings included skull fracture (n = 5), small subdural hematomas (n = 4), cerebral contusions (n = 3), subarachnoid hemorrhage (n = 3), and DAI (n = 1). MRI was negative in 1 patient whose preceding CT scan was read as positive for injury. Although MRI more frequently reported intracranial findings than CT scanning, there was no statistically significant difference between CT and MRI in the detection of any intracranial injury (p = 0.63), DAI (p = 0.22), or intracranial hemorrhage (p = 0.25). CT scanning tended to more frequently identify skull fractures than MRI (p = 0.06).

CONCLUSIONS MRI may be as sensitive as CT scanning in the detection of THI, DAI, and intracranial hemorrhage, but missed skull fractures in 5 of 13 patients. MRI may be a useful alternative to CT scanning in select stable patients with mild THI who warrant neuroimaging by clinical decision rules.

http://thejns.org/doi/abs/10.3171/2014.10.PEDS14128

KEY WORDS pediatric; head injury; MRI; CT; trauma

TRAUMATIC head injury (THI) is a prevalent condition in the United States; an estimated 1.7 million people sustain THI in this country annually, and within that group, children aged 0 to 14 years account for 473,947 emergency room visits, 35,136 hospitalizations, and 2174 deaths annually.6 X-ray computed tomography (CT) has traditionally been the imaging modality of choice in the evaluation of patients with THI who require imaging, due largely to its ease and rapidity of acquisition. However, increasingly more attention is being focused on the potential cancer risks of CT-related radiation.4,13,17 Brenner et al. estimated the lifetime cancer mortality risk attributable to the radiation from a single CT scan of the head in a 1-year-old child to be 0.07%.6 Although this number is low, many
children with THI undergo more than 1 CT scan, and this risk estimate is an order of magnitude higher than the lifetime cancer mortality risk estimate due to radiation related to a head CT in adults. In addition, this small risk to any given child may, in fact, translate to a large population-level risk, given that THI in children aged 0 to 14 years accounts for nearly half a million emergency room visits annually. Although the use of CT among children has decreased slightly over recent years with the creation and validation of clinical decision rules, such as the New Orleans Criteria (NOC), the Canadian CT Head Rule (CCHR), and the National Emergency X-Radiography Utilization Study II (NEXUS II) for CT scanning in pediatric patients with minor head injury, the utilization of CT in pediatric patients remains high and variable from center to center.

The use of MRI of the brain in THI has historically and largely been limited to prognostication and to further diagnostic evaluation in patients with persistently poor neurological examinations. However, given the success of rapid-acquisition MRI in the evaluation of ventriculoperitoneal shunt malfunction in pediatric patient populations, we were interested in evaluating the feasibility of MRI as a replacement for or adjunct to CT in the radiological evaluation of select patients with mild THI. In doing so, we lay the groundwork for a future prospective study on the utility of MRI in pediatric patients presenting with THI.

Methods

Institutional review board approval was obtained for the study. Patients admitted to Tufts Medical Center, a Level 1 pediatric trauma center, with THI between January 2002 and December 2012 were identified and screened for eligibility; inclusion criteria included age less than 18 years and MRI of the brain obtained within 5 days of CT. Of 574 pediatric patients admitted with THI over the above time period, 35 patients met the inclusion criteria. Thirty patients had images available for review. In general, patients underwent further imaging with MRI for evaluation of continuing neurological impairment, for neurological deficits that were not explained by initial CT findings, or for prognostication. MRI studies included a localizer sequence, T2-weighted sequences, T2-FLAIR images, gradient-echo T2 images, and T1-weighted sequences. Medical records were reviewed for age, sex, Injury Severity Score, Glasgow Coma Scale score, and length of stay. A board-certified neuroradiologist (N.M.) reviewed randomly presented de-identified MR and CT images for presence of skull fracture, subdural or epidural hematoma, diffuse axonal injury (DAI), cerebral contusion, and subarachnoid or intraventricular hemorrhage. Radiology reports were also reviewed for the aforementioned pathologies to assess interrater reliability. Dedicated neuroradiologists generated all radiology reports at the time of the patient’s admission.

Baseline demographic analysis and concordance analysis were performed using Stata version 13 (StataCorp). Results of descriptive analysis are reported as mean ± standard deviation. Spearman rank correlation coefficients were generated separately for DAI, osseous injury, intracranial hemorrhage, and intracranial injury. McNemar’s exact tests for correlated proportions were used to test the hypothesis of no difference between CT and MRI in detecting each category of injury. Sensitivity and specificity calculation used the modality with the highest rate of reporting as the gold standard. A single gold standard was avoided due to differential sensitivities of each modality to different types of injuries. In addition, interrater reliability between official reports and the blinded reviewer was assessed using percentage agreement, unweighted kappa coefficients, and Spearman correlation coefficients.

Results

The cohort comprised 30 patients ranging in age from 2 months to 18 years (Table 1). The mean age was 8.5 ± 6.7 years, and 63.3% of the patients were male. The mean Injury Severity Score was 13.7 ± 9.2, and the mean Glasgow Coma Scale score was 9 ± 5.7. All patients had MRI within 5 days of CT acquisition, but the mean number of days between CT and MRI was only 0.8 ± 1.2 days. The mean length of stay was 8.6 ± 11 days.

In the 60 imaging studies reviewed, 150 abnormal findings were noted. CT missed findings in 12 patients, including DAI (n = 5), subarachnoid hemorrhage (n = 6), small subdural hematomas (n = 6), cerebral contusions (n = 3), and an encephalocele. The CT scan of the head was negative in 3 patients whose subsequent MRI was positive for intracranial injury; the missed findings included a small subdural hematoma, 2 areas of traumatic subarachnoid hemorrhage, and a small area of FLAIR change of uncertain significance. Conversely, MRI missed findings in 13 patients. Missed findings included skull fracture (n = 5), small subdural hematomas (n = 4), cerebral contusions (n = 3), subarachnoid hemorrhage (n = 3), and DAI (n = 1). MRI was negative in 1 patient whose preceding CT

| TABLE 1. Baseline characteristics of 30 pediatric patients* |
|----------------------------------|------------------|
| Variable                        | Value            |
| Age (yrs)                       | Mean 8.5 ± 6.7   |
|                                 | Range 0.2–18     |
| Percent male                    | 63.3% (19/30)    |
| Injury Severity Score           | Mean 13.7 ± 9.2  |
|                                 | Range 1–35       |
| Glasgow Coma Scale score        | Mean 9 ± 5.7     |
|                                 | Range 3–15       |
| Interval btw CT & MRI (days)    | Mean 0.8 ± 1.2   |
|                                 | Range 0–4        |
| Length of stay (days)           | Mean 8.6 ± 11    |
|                                 | Range 0–51       |

* Means are reported ± SD.
scan was read as positive for injury; the missed finding in this patient was a focus of possible cerebral edema. Fig. 1 depicts 1 case in which CT missed a small subdural hematoma and 1 case in which MRI missed a right occipital nondisplaced skull fracture.

With respect to detection of any injury, although MRI of the head more frequently reported a traumatic injury than CT imaging of the head, this difference did not reach statistical significance in this cohort (p = 0.63) (Table 2). The Spearman rank correlation coefficient of CT and MRI reporting of any injury was 0.63. The sensitivity and specificity of CT scanning for detection of any injury were 87% and 85.7%, respectively (Table 3).

MRI missed skull fractures in 5 patients; the Spearman rank correlation coefficient was 0.69, indicating good validity of MRI in the assessment of skull fracture (Table 4). The difference between MRI and CT with respect to their ability to detect skull fractures was almost statistically significant (p = 0.06). The sensitivity and specificity of MRI for skull fracture were 61.5% and 100%, respectively (Table 3). Conversely, CT scanning missed DAI in 5 patients; the Spearman rank correlation coefficient of −0.08 indicates extremely poor validity of CT in the detection of DAI compared with MRI (Table 5). However, the 2 modalities were not significantly different in their abilities to detect DAI (p = 0.22). The sensitivity and specificity of CT for detection of DAI were 0% and 96%, respectively (Table 3).

Despite the above differences, good concordance was noted between MRI and CT for reporting of intracranial hemorrhage; the Spearman rank correlation coefficient of 0.80 indicates excellent concordance of MRI and CT (Table 6). Three CT scans of the head were reported as negative for intracranial hemorrhage when the corresponding MR image was reported as positive. In addition, despite the excellent concordance, CT scanning missed 6 small subdural hematomas and MRI missed 4 small subdural hematomas, but these patients also had other areas of intracranial hemorrhage. However, there was no statistically significant difference between CT and MRI in the detection of intracranial hemorrhage (p = 0.25). The sensitivity and specificity of CT scanning for detection of intracranial hemorrhage were 85.7% and 100%, respectively (Table 3).

Interrater reliability scores between official reports and the blinded neuroradiologist’s review were good to excellent for most of the measured indicators (Table 7) except for the diagnosis of DAI on CT and skull fracture on MRI. Agreement was noted to range from 80% to 93.3% for all categories, and most Kappa statistics were greater than 0.64. However, as mentioned earlier, 2 areas of low Kappa statistic values were noted. Regarding the detection of skull fracture on MRI, the neuroradiologist and official reports agreed with respect to 80% of the MR images, but this translated to a Kappa statistic of only 0.33. The second area of low interrater reliability was in the detection of DAI on CT. The blinded neuroradiologist reported presence of DAI on only 1 of 30 CT scans; the official reports reported presence of DAI in 3 of 30 scans. Thus, although the 2 raters agreed in 86.7% of the scans, the Kappa statistic was −0.05, reflecting extremely poor interrater reliability in the detection of DAI on CT scan.

The results of this study suggest that MRI may be a useful alternative to CT scanning in select patients. Although the study was limited due to the small sample size, MRI more commonly reported THI in general, DAI, and intracranial hemorrhage than the current primary neuroimaging modality used in the evaluation of patients with head trauma. Both imaging modalities missed findings in patients; however, most missed findings were subtle and clinically insignificant and were associated with other findings that were detected on the same scan. MRI reported no injury in 1 patient whose CT was positive for injury; the finding reported on CT was a small area that

**Table 2. Table of results of whether injury was present on CT and MRI of the head**

<table>
<thead>
<tr>
<th>CT: Injury Present?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI: Injury Present?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>No</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

* Concordance analysis and McNemar’s test results are provided. Spearman rank correlation coefficient = 0.67. Exact McNemar’s test, p = 0.63.
was suspicious for cerebral edema. On the other hand, CT reported no injury in 3 patients whose MRI was positive for injury. These injuries included a small subdural hematoma, 2 traumatic subarachnoid hemorrhages, and a small area of FLAIR change that may have correlated with a nonhemorrhagic contusion. Although these types of injuries would not necessarily distinguish between patients who require surgery and those who don’t, they may determine the intensity of medical observation that is required. Overall, however, both modalities agreed on whether injury was present in nearly 87% of the studies. Despite these findings that strongly support the utility of MRI in the evaluation of pediatric THI, our analysis did not demonstrate a statistically significant difference ($p = 0.63$). Similar observations were noted in the detection of DAI and intracranial hemorrhage. Interestingly, although CT is commonly held to be superior at evaluating for intracranial hemorrhage, MRI detected hemorrhage in 3 patients with negative results on CT. On the other hand, CT did not detect any hemorrhage that was missed by MRI. Despite the lack of statistically significant difference between CT and MRI in detection of intracranial hemorrhage ($p = 0.25$), these results strongly support the utility of MRI in the evaluation of intracranial hemorrhage.

To our knowledge, this is the first study to compare MRI and CT in the same individual patients in the setting of acute THI. Given the increasing focus on avoiding radiation and cancers attributable to CT and the comparability of MRI and CT in the detection of THI and intracranial hemorrhage noted above, MRI may be a useful adjunct to dose-reduced CT protocols in stable patients with mild THI who warrant neuroimaging by clinical decision protocols. However, there are several limiting factors regarding the implementation of MRI in the evaluation of pediatric THI. The sensitivity of MRI in the detection of skull fractures in this cohort was low, and MRI missed 5 of 13 skull fractures that were noted on CT scans. The low sensitivity of MRI for detection of skull fractures is a limitation of this modality, and perhaps patients with strong clinical evidence of skull fracture, such as a battle sign, bilateral orbital bruising, or significant scalp swelling, may be better evaluated with CT. Furthermore, the location of MR scanners in most hospitals as well as the limited observation possible within an MR scanner makes MRI unsuitable for many patients with signs and symptoms concerning for severe forms of THI. Lastly, the cost, time necessary for study acquisition, and commonly associated delays in care associated with acquisition of MR scans in the emergency room may limit the feasibility of MRI in the routine evaluation of head trauma. However, many large medical centers have succeeded in incorporating timely MRI in surgical decision making for patients in whom ventriculoperitoneal shunt malfunction is suspected; these patients are often at as high a risk of a negative outcome as many patients with mild to moderate THI, and the successful incorporation of MRI in their care may support the feasibility of MRI in the diagnostic evaluation of select pediatric patients with THI. In addition, regarding the poor sensitivity of MRI in the detection of skull fractures, all skull fractures in our cases were linear and nondisplaced, and none of the patients with skull fractures noted on CT scan required treatment for the skull fracture. Although accurate diagnosis is clearly important in patients with THI, it is notable that not all children with linear, nondisplaced skull fractures require hospital admission. In fact, in a retrospective, cross-sectional study of 3915 children with isolated skull fractures evaluated in emergency departments in US children’s hospitals, only 78% of children were hospitalized, and, of those hospitalized, 85% were discharged within 1 day. The relatively benign natural history of uncomplicated, nondepressed skull fractures may ameliorate the poor sensitivity of MRI.

### TABLE 3. Sensitivity and specificity of MRI and CT according to injury type*

<table>
<thead>
<tr>
<th>Finding</th>
<th>Prevalence (95% CI)</th>
<th>Sensitivity (95% CI)</th>
<th>Specificity (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal</td>
<td>76.7% (57.7%–90.1%)</td>
<td>87% (66.4%–97.2%)</td>
<td>85.7% (42.1%–99.6%)</td>
</tr>
<tr>
<td>DAI</td>
<td>16.7% (6.6%–34.7%)</td>
<td>0% (0%–52.2%)</td>
<td>96% (79.6%–99.9%)</td>
</tr>
<tr>
<td>Osseous injury</td>
<td>43.3% (25.5%–62.6%)</td>
<td>61.5% (31.6%–86.1%)</td>
<td>100% (80.5%–100%)</td>
</tr>
<tr>
<td>ICH</td>
<td>70% (50.6%–85.3%)</td>
<td>85.7% (63.7%–97%)</td>
<td>100% (66.4%–100%)</td>
</tr>
</tbody>
</table>

ICH = intracranial hemorrhage.

* MRI is well established as the gold standard for soft-tissue imaging and thus is considered to be the gold standard for abnormal findings, DAI, and intracranial hemorrhage. CT is well established as the gold standard for skeletal imaging and thus is considered to be the gold standard for skull fracture (osseous injury).

### TABLE 4. Table of results of whether osseous injury was present on CT and MRI of the head.*

<table>
<thead>
<tr>
<th>MRI: Osseous Injury Present?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT: Osseous Injury Present?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>No</td>
<td>0</td>
<td>17</td>
</tr>
</tbody>
</table>

* Concordance analysis and McNemar’s test results are provided. Spearman rank correlation coefficient = 0.69. Exact McNemar’s test, $p = 0.06$.

### TABLE 5. Table of results of whether DAI was present on CT and MRI of the head*

<table>
<thead>
<tr>
<th>MRI: DAI Present?</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT: DAI Present?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>No</td>
<td>5</td>
<td>24</td>
</tr>
</tbody>
</table>

* Concordance analysis and McNemar’s test results are provided. Spearman rank correlation coefficient = −0.08. Exact McNemar’s test, $p = 0.22$. 
in the detection of skull fractures, especially if its implement-
ment succeeds in reducing diagnostic radiation expo-
sure in pediatric patients.

Previous studies that have evaluated MRI in trauma pa-
tients have focused on prognostication.5,16,18,19 Most MRI
examinations performed in previously published studies
were performed several weeks after the injury, and the sensi-
tivity of MRI for intracranial injury may be limited
by the long duration between imaging studies. The role of
MRI in the present study was similar to that in previous
studies: to evaluate continuing neurological impairment
and neurological deficits that were not explained by ini-
tial CT findings, and to prognosticate. However, the mean
time from CT scanning to MRI in this study was only
0.97 days, and in more than 75% of our cases, MR images
were obtained within 3 days. The short duration between
studies of these 2 modalities is a strength of this study,
because the likelihood of substantial change between im-
aging studies is lower with a shorter elapsed time.

The study has a few limitations. First, as mentioned
previously, all patients were admitted to the hospital with
THI, and their inpatient care required both CT and MRI.
MRI of the brain is not routinely obtained in the care of
pediatric patients with THI. MRI in this cohort was often
performed in THI patients in whom CT findings did not
fully explain the severity of neurological impairments or
for prognostication. This is supported by the relatively high
prevalence of DAI in this cohort of 16.7%. The selection
of patients admitted to the hospital with THI and whose
CT images may have only very subtle findings introduces
bias that may skew the estimates in the favor of MRI. Un-
fortunately, due to the retrospective nature of this study,
we are unable to further clarify the indications for further
imaging with MR, and, thus, although we acknowledge a
significant selection bias by selecting patients with both
types of imaging, it is difficult to specify the magnitude
of this bias and its effect on our results and conclusions.

Concordantly, the patients in this series were deemed
medically and neurologically stable for travel to MRI, and
many of the findings were subtle, albeit detectable; it is
logical to assume that MRI would be able to detect larger,
less subtle findings as well. Thus, the strength of evidence
suggests that MRI may be a useful modality to follow im-
aging findings that are found on CT. However, the study
is retrospective and involves a relatively small number of
patients. Because of these methodological limitations, we
are unable to provide an algorithm regarding the optimal
use of MRI in pediatric head trauma or offer suggestions
about its use. Further prospective and randomized studies
in patients with minor THI are needed to confirm whether
MRI is a feasible alternative diagnostic modality. The pa-
tients in this study underwent full pediatric MRI of the
brain with multiple sequences; further study is needed to
determine which sequences most reliably identify intra-
cranial injury and whether rapid acquisition sequences
could be reliably integrated into a protocol. Despite these
limitations, this is the first study to assess the sensitivity of
MRI in the acute THI setting.

The study’s limitations are real and limit our ability
to make strong inferences or recommendations regarding
what role MRI should serve in the evaluation and manage-
ment of pediatric patients with THI; however, it serves as
a feasibility study and as the basis for a future prospective
pilot study of the role of MRI. The results provide some
limited evidence of a substantial potential for radiation
sparing in the vulnerable pediatric population and, thus,
preliminary consideration of the role of MRI in pediatric
THI may help avoid future CT-related excess cancer cases.

**Conclusions**

MRI may be a useful alternative to CT scanning in se-
lect patients with mild THI who warrant neuroimaging by
clinical decision rules. MRI identified abnormalities such

---

**Table 6. Table of results of whether intracranial hemorrhage was present on CT and MRI of the head**

<table>
<thead>
<tr>
<th></th>
<th>MRI: ICH Present?</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT: ICH</td>
<td>Yes</td>
</tr>
<tr>
<td>Present?</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

*Concordance analysis and McNemar’s test results are provided. Spearman rank correlation coefficient = 0.80. Exact McNemar’s test, p = 0.25.

**Table 7. Inter-reader reliability scores between the blinded neuroradiology reviewer and official neuroradiology reports**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Agreement</th>
<th>Kappa (95% CI)</th>
<th>Spearman ρ</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury present?</td>
<td>90%</td>
<td>0.73 (0.45–1)</td>
<td>0.74</td>
</tr>
<tr>
<td>Osseous injury present?</td>
<td>80%</td>
<td>0.33 (~0.03 to 0.68)</td>
<td>0.44</td>
</tr>
<tr>
<td>DAI present?</td>
<td>86.7%</td>
<td>0.64 (0.33–0.95)</td>
<td>0.68</td>
</tr>
<tr>
<td>ICH present?</td>
<td>90%</td>
<td>0.78 (0.56–1)</td>
<td>0.80</td>
</tr>
<tr>
<td>CT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury present?</td>
<td>90%</td>
<td>0.78 (0.56–1)</td>
<td>0.80</td>
</tr>
<tr>
<td>Osseous injury present?</td>
<td>86.7%</td>
<td>0.72 (0.47–0.97)</td>
<td>0.73</td>
</tr>
<tr>
<td>DAI present?</td>
<td>86.7%</td>
<td>0.05 (~0.16 to 0.05)</td>
<td>0.06</td>
</tr>
<tr>
<td>ICH present?</td>
<td>93.3%</td>
<td>0.86 (0.68–1)</td>
<td>0.86</td>
</tr>
</tbody>
</table>
as intracranial hemorrhage and DAI more frequently than CT scanning, but had poor sensitivity in the evaluation of skull fractures. Further prospective study is needed to further clarify what role, if any, MRI should have in the management of pediatric patients with THI.

References


Author Contributions
Conception and design: Hwang, Roguski, Talan, Rideout, Riesenburger. Acquisition of data: Hwang, Roguski, Morel, Sweeney, Talan, Rideout, Riesenburger. Analysis and interpretation of data: all authors. Drafting the article: Hwang, Roguski, Morel, Rideout, Riesenburger, Madan. Critically revising the article: Hwang, Roguski, Rideout, Riesenburger, Madan. Statistical analysis: Roguski, Riesenburger. Administrative/technical/material support: Hwang, Riesenburger. Study supervision: Hwang, Riesenburger.

Supplemental Information
Previous Presentation
Portions of this work were presented in e-poster format at the American Association of Neurosurgeons/Congress of Neurological Surgeons Joint Pediatric Section annual meeting in Toronto, Canada, on December 3–6, 2013.

Correspondence
Steven Hwang, Department of Neurosurgery, Tufts Medical Center, Proger 7, 800 Washington St., Boston, MA 02111. email: shwang@tuftsmedicalcenter.org.