Comparison of Rapid Cranial MRI to CT for Ventricular Shunt Malfunction

AUTHORS: Tehnaz P. Boyle, MD, PhD,1 Michael J. Paldino, MD,2 Amir A. Kimia, MD,3 Brianna M. Fitz, BS,4 Joseph R. Madsen, MD,5 Michael C. Monuteaux, ScD,4 and Lise E. Nigrovic, MD, MPH4
1Division of Emergency Medicine, and 2Department of Neurosurgery, Boston Children’s Hospital, Boston, Massachusetts; and 3Department of Pediatric Radiology, Texas Children’s Hospital, Houston, Texas

KEY WORDS
rapid cranial MRI, cranial CT, ventricular shunt malfunction

ABBREVIATIONS
CI—95% confidence interval
CT—computed tomography
ED—emergency department
IQR—interquartile range
MRI—magnetic resonance imaging

Dr Boyle conceptualized and designed the study, performed and supervised the primary data abstraction and analysis, and drafted the initial manuscript; Dr Paldino performed the blinded imaging review and provided critical review of the manuscript; Dr Kimia identified eligible cases and provided critical review of the manuscript; Ms Fitz performed data collection and provided critical review of the manuscript; Dr Madsen reviewed neurosurgical operative reports and provided critical review of the manuscript; Dr Monuteaux supervised the primary data analysis and provided critical review of the statistical methods; Dr Nigrovic conceptualized and designed the study, supervised the primary data abstraction and analysis, and drafted the initial manuscript; and all authors approved the final manuscript as submitted.

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Address correspondence to Tehnaz P. Boyle, MD, PhD, Division of Emergency Medicine, Boston Children’s Hospital, 300 Longwood Avenue, Boston, MA 02115. E-mail: tehnaz.boyle@childrens.harvard.edu (or lise.nigrovic@childrens.harvard.edu)
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WHAT’S KNOWN ON THIS SUBJECT: Rapid cranial MRI is a radiation-free method to assess children with possible ventricular shunt malfunction. However, the test performance of rapid cranial MRI has never been compared with that of cranial CT, the current reference standard.

WHAT THIS STUDY ADDS: The accuracy of rapid cranial MRI was not inferior to that of CT for diagnosing ventricular shunt malfunction. Rapid cranial MRI is an important radiation-sparing diagnostic alternative for children presenting emergently with possible ventricular shunt malfunction.

abstract

OBJECTIVES: To compare the accuracy of rapid cranial magnetic resonance imaging (MRI) with that of computed tomography (CT) for diagnosing ventricular shunt malfunction.

METHODS: We performed a single-center, retrospective cohort study of children ≤21 years of age who underwent either rapid cranial MRI or cranial CT in the emergency department (ED) for evaluation of possible ventricular shunt malfunction. Each neuroimaging study was classified as “normal” (unchanged or decreased ventricle size) or “abnormal” (increased ventricle size). We classified a patient as having a ventricular shunt malfunction if operative revision for relief of mechanical causes of altered shunt flow was needed within 72 hours of initial ED evaluation. Our primary analysis tested noninferiority of the accuracy of rapid cranial MRI to CT for diagnosing shunt malfunction (noninferiority margin 10%).

RESULTS: We included 698 ED visits for 286 unique patients, with a median age at visit of 10.0 years (interquartile range 5.9–15.5 years). Patients underwent CT in 336 (48%) or rapid cranial MRI in 362 (52%) of ED visits for evaluation of possible shunt malfunction. Patients had operative revision for ventricular shunt malfunction in 140 ED visits (20%). The accuracy of rapid cranial MRI was not inferior to that of CT scan for diagnosing ventricular shunt malfunction (81.8% MRI vs 82.4% CT; risk difference 2.0%; 95% confidence interval, −4.2% to 8.2%).

CONCLUSIONS: Rapid cranial MRI was not inferior to CT for diagnosing ventricular shunt malfunction and offers the advantage of sparing a child ionizing radiation exposure. Pediatrics 2014;134:e47–e54

WHAT THIS STUDY ADDS: The accuracy of rapid cranial MRI was not inferior to that of CT for diagnosing ventricular shunt malfunction. Rapid cranial MRI is an important radiation-sparing diagnostic alternative for children presenting emergently with possible ventricular shunt malfunction.
Surgically implanted ventricular cerebrospinal fluid shunts, the treatment of choice for pediatric hydrocephalus, fail commonly. Ventricular shunt malfunction for various reasons, including mechanical obstruction, overdrainage, and equipment failure. The emergent evaluation of a child with a possible ventricular shunt malfunction presents challenges for clinicians. Signs and symptoms of malfunction overlap with benign childhood illnesses and lack the predictive ability to dictate decision-making. Given the substantial morbidity and mortality associated with shunt malfunctions, current practice relies heavily on emergent neuroimaging, most commonly cranial CT. Repeated CT scans expose children to a cumulative dose of ionizing radiation that has been associated with a significant increase in lifetime malignancy risk. Thus, children with ventricular shunts are among the most vulnerable populations to the long-term deleterious effects of ionizing radiation exposure.

Traditional cranial MRI avoids ionizing radiation exposure, but limited availability, lengthy imaging times, and the frequent need for sedation have limited its use in children. Rapid cranial MRI is a recent technologic advance that dramatically reduces image acquisition time by using a single-shot fast-spin echo technique. Although it is of lower quality than traditional MRI, the resulting image sufficiently permits a reliable assessment of ventricle size within 60–90 seconds, even in an uncooperative patient. Although test performance of rapid cranial MRI is unknown, these benefits have prompted some pediatric centers to adopt this modality for patients with ventricular shunts.

To date, the diagnostic performance of rapid cranial MRI in emergent evaluation of ventricular shunt malfunction has not been compared with that of cranial CT, the current diagnostic standard. Our study objective was to determine whether rapid cranial MRI was noninferior to cranial CT in detecting ventricular shunt malfunction in children evaluated in the ED.

METHODS

Study Design

We performed a single-center retrospective cohort study of consecutive ED visits by pediatric patients (age ≤ 21 years) with a ventricular shunt who presented to the Boston Children’s Hospital ED and underwent either cranial CT or rapid cranial MRI at the recommendation of the attending neurosurgeon for evaluation of possible ventricular shunt malfunction. The 42-month study period extended from March 1, 2010 (when rapid cranial MRI first became clinically available in the ED at our institution) to August 31, 2013. The Boston Children’s Hospital Institutional Review Board approved our research protocol.

Case Identification

Study cases were identified by using a computer-assisted natural language text search tool of existing ED medical records and radiology databases. All coding was created using ActivePerl version 5.8.8.820 (ActiveState Software, Inc.). To ensure complete case identification, we also reviewed all radiology orders placed for either rapid cranial MRI or CT in patients with ventricular shunts during the study period. We subsequently performed manual record review of all identified ED encounters to determine study eligibility.

Inclusion and Exclusion Criteria

We included children with any type of ventricular shunt: ventriculoperitoneal, ventriculoatrial, or ventriculopleural. We excluded children who needed neuroimaging for reasons other than shunt malfunction (eg, infection) or who were referred after neuroimaging was performed at an outside institution or before the ED encounter. Children with multiple ED visits for possible shunt malfunction were included as long as each ED visit was ≥ 7 days after the last ED encounter meeting study inclusion criteria or ≥ 48 hours after surgical shunt revision.

Data Collection

Once eligible ED encounters were identified, 2 researchers (T.P.B., B.M.F.) manually abstracted data from the medical record using the REDCap electronic data collection tool. We recorded patient demographic information, historical and clinical factors, triage vital signs and Emergency Severity Index score, neurosurgical provider, and clinical outcome. We defined “seizure” as either new-onset or worsening seizure pattern and “mental status change” as history of or current lethargy, irritability, or altered mental status. We abstracted the type of diagnostic neuroimaging (cranial CT or rapid cranial MRI), with the clinical radiologist interpretation, as well as the modality of baseline comparison studies. Additionally, we reviewed all return visits to the study institution within 72 hours of the index ED visit to identify children with a ventricular shunt malfunction needing operative repair.

We abstracted the following times from the electronic tracking system: ED arrival, placement of neuroimaging order, neuroimaging completion, ED disposition, and operative intervention. We defined the following study time periods: time to imaging order (ED arrival to placement of neuroimaging order), time to imaging (ED arrival to completion of neuroimaging study), ED length of stay (ED arrival to ED disposition), and time to operating room (ED arrival to arrival in operating room) for patients undergoing operative intervention.
Classification of Neuroimaging

For each ED visit, we reviewed the preliminary and final clinical radiologist neuroimaging report. We classified imaging studies as “normal” if the ventricular size was unchanged or decreased and “abnormal” if the size was greater than in the most recent baseline study. “Ambiguous” results included reports of “slight,” “possible,” or “minimal” changes in ventricle size or both increase and decrease in different areas of the ventricular system. To dichotomize imaging results, the study radiologist (M.J.P.), blinded to the clinical scenario and the clinical radiologist interpretation, reviewed and classified all ambiguous neuroimaging studies as either “normal” or “abnormal.” A second neuroradiologist (S.P.) provided a secondary blinded review for cases that were difficult to classify (n = 4). Fig 1 shows a baseline and abnormal (ie, increased ventricle size) rapid cranial MRI and CT scan for 2 different study patients.

Outcome Measure

Our primary outcome measure was the presence of a ventricular shunt malfunction as documented in neurosurgical operative notes. We defined a ventricular shunt malfunction as a patient who needed operative revision for relief of mechanical causes of altered shunt flow within 72 hours of initial ED evaluation.1,8,9,21 Children who underwent neurosurgical intervention for reasons other than altered shunt flow (eg, infection) or whose ventricular shunt valve was adjusted were classified as not having a ventricular shunt malfunction. Two investigators (T.P.B., L.E.N.) reviewed medical records for all children who underwent operative intervention to assess for a ventricular shunt malfunction. In cases of disagreement, the study neurosurgeon (J.R.M.) reviewed records and assigned a final outcome (n = 2).

Statistical Analysis

The primary unit of analysis was the ED encounter. First, we performed a bivariate analysis to compare the demographic and clinical characteristics of ED visits where cranial CT or rapid cranial MRI was obtained. We compared proportions with the \( \chi^2 \) test or the Fisher's exact test as appropriate. We compared medians with the Mann–Whitney \( U \) test. We used the Pearson's correlation coefficient to test linearity between providers and imaging modality. We then calculated the sensitivity, specificity, and overall accuracy with 95% confidence intervals (CIs) of rapid cranial MRI and CT for diagnosing ventricular shunt malfunction using standard methods.

Our primary analysis was to test for noninferiority of the accuracy of rapid cranial MRI to CT. Our a priori non-inferiority margin was a clinically significant 10% difference in accuracy between CT and rapid brain MRI for
diagnosing a ventricular shunt malfunction. Assuming a CT accuracy of 80%,\(^9\) we required 275 ED visits using each imaging modality to detect a 10% difference in accuracy with a power of 0.90 (\(\alpha = 0.05\)). To assess non-inferiority, a 95% CI was computed on the difference of the proportions between CT and rapid cranial MRI groups. If the upper limit of the CI was less than the threshold of 10%, non-inferiority was concluded. To adjust for clinical differences between patients and study time period and for clustering by patient, we used a generalized linear model to compare the accuracy between rapid cranial MRI and CT scan for ventricular shunt malfunction.

All data analysis was performed using IBM SPSS Statistics version 21.0 (IBM SPSS Statistics, IBM Corporation).\(^2\)

RESULTS

We identified 1254 potentially eligible ED encounters during the study period, of which 698 ED visits (55% of identified cases) met study inclusion criteria (Fig 2). A total of 286 children accounted for the included ED encounters (131 children had 1 ED visit, 65 had 2 visits, and 90 had \(\geq 3\) visits). For all ED encounters, the median patient age was 10.0 years (interquartile range [IQR] 6.0–15.6 years), and 395 (57%) were male. The ventricular shunts were initially placed for the following reasons: intraventricular hemorrhage of prematurity (\(n = 76, 27%\) of study patients), congenital hydrocephalus (80, 28%), spina bifida (45, 16%), neumormalignancy (42, 14%), postmeningitis (9, 3%), and other causes (34, 12%).

In 698 included ED visits, children underwent 336 (48%) CT scans and 362 (52%) rapid cranial MRI scans. Use of rapid cranial MRI increased over the study period (odds ratio = 1.08 per month; 95% CI, 1.06 to 1.09) (Fig 3). Attending neurosurgical provider and neuroimaging modality were highly correlated (\(x^2 = 93.9, P < .001\)).

Clinical neuroimaging reports were based on comparisons with most recent baseline neuroimaging studies. Of 336 cranial CT scans, 288 (86%) used a comparison cranial CT, 91 (27%) a cranial MRI, and 53 (16%) a rapid cranial MRI. Of 362 rapid cranial MRI scans, 131 (36%) had a comparison cranial CT, 138 (38%) a cranial MRI, and 184 (51%) a rapid cranial MRI.

We compared the clinical characteristics of patients who had a cranial CT with those who had a rapid cranial MRI (Table 1). Children who underwent CT were more likely to present with mental status change, new or worsening seizure frequency, pupillary abnormalities, and bradycardia. The prevalence of ventricular shunt malfunction was similar between neuroimaging modalities (70/362 [19%] rapid cranial MRI vs 70/336 [21%] CT, \(P = .62\)). Fewer children who had a rapid cranial MRI needed sedation for neuroimaging (2/362 [0.6%] rapid cranial MRI vs 24/336 [7%] CT, \(P < .001\)).

Of the 698 study ED visits, 427 (61% of visits) resulted in admission and 153 (22%) in a neurosurgical intervention within 72 hours of ED arrival. Of operative cases, 140 (92%) had a ventricular shunt malfunction. Most ventricular shunt malfunctions were diagnosed during the index ED visit (76% initial ED visit vs 24% subsequent diagnosis). Of the 14 children who went to the operating room but did not have a malfunction, 6 had a normal neurosurgical exploration and 8 needed revision for reasons other than malfunction (eg, possible infection, subdural hematomas from overdrainage). Three patients had shunt valve adjustments as a therapeutic maneuver (1 for ventriculomegaly and 2 for overshunting).

The clinical radiology interpretation changed between the preliminary and final interpretation in a minority of cases (1.5% of CT and 1.2% rapid cranial MRI scans). We identified 142 ED visits
(20% of study visits) with ambiguous final radiology reports (51% CT and 49% rapid cranial MRI). After blinded neuroimaging review, 27 CT and 21 MRI scans (34% of ambiguous images) were classified as abnormal, 45 CT and 48 MRI scans (65%) were normal, and 1 CT scan (0.7%) was unable to be classified reliably (1 ventricle increased, another decreased). The single ED visit with unclassifiable neuroimaging was excluded from the accuracy analysis.

We then compared the test characteristics of rapid cranial MRI with CT for diagnosing ventricular shunt malfunction (Table 2). Neither the accuracy nor the specificity of rapid cranial MRI was inferior to that of CT, but we were underpowered to compare sensitivity. After adjustment for characteristics that differed between patients who had a rapid cranial MRI versus a CT (patient gender, altered mental status, seizure, abnormal pupils, bradycardia, neurosurgical provider type, and study month) and clustering by patient, the accuracy of rapid cranial MRI remained noninferior to that of CT, with an adjusted risk difference within our non-inferiority margin of 10% (adjusted risk difference 2.0%, 95% CI, –4.2% to 8.2%) (Fig 4).

Finally, we compared the study time intervals between imaging modalities (Table 3). The time to obtain neuroimaging was longer for the ED visits with a rapid cranial MRI than a CT. The majority of the observed difference was the time from placement of the imaging order to obtaining the neuroimaging. Additionally, ED length of stay and time to operating room were longer for the ED visits with a rapid cranial MRI.

**DISCUSSION**

We performed a large single-center study of ED visits for children with possible ventricular shunt malfunction to compare the test characteristics of rapid cranial MRI and CT for the emergent diagnosis of ventricular shunt malfunction. We demonstrated that the accuracy and specificity of rapid cranial MRI were not inferior to those of CT for diagnosing ventricular shunt malfunction, although we were underpowered to compare sensitivity. The times to obtain neuroimaging and to neurosurgical intervention were
longer for ED visits with a rapid cranial MRI than for a CT scan.

The current practice standard for imaging children with possible ventricular shunt malfunction is cranial CT. The published accuracy of cranial CT is ∼75% to 83%, sensitivity between 54% and 80%, and specificity of 80% to 90%.8–10 The test characteristics of CT in our study were similar to published estimates. Previous evaluation of rapid cranial MRI in children with ventricular shunts has focused on image quality or radiographic characteristics.15–17,23 Our study is the first to demonstrate that the accuracy of rapid cranial MRI is non-inferior to that of CT, suggesting rapid cranial MRI is a viable diagnostic alternative for the emergent evaluation of a possible ventricular shunt malfunction. In our study population, clinicians selected CT in ED visits in which patients were more symptomatic, as manifested by their clinical findings or vital sign abnormalities.

Clinicians must be aware of several important factors regarding rapid cranial MRI when determining the appropriate diagnostic imaging modality for a child with possible ventricular shunt malfunction. First, there may be a price difference between the imaging modalities. At our institution, the patient charge for rapid cranial MRI ($1428) is slightly more than that of CT ($1364). However, the small difference in charge is arguably balanced by the long-term benefits of reduced ionizing radiation exposure in this vulnerable population.24 Second, rapid cranial MRI may have limited availability, especially in general EDs or at night. For an institution to adopt a rapid cranial MRI protocol, both MRI technologists and radiologists may need specific training in the acquisition and accurate interpretation of these images. Finally, children with some programmable shunt valves are at risk for unintentional valve adjustment by the scanner’s magnetic field and must undergo reprogramming by a trained provider.25

As rapid cranial MRI is adopted and more available universally, practical limitations in the ease of obtaining imaging may need to be addressed. We found that the time from ED arrival to obtaining neuroimaging was longer for ED visits when a rapid cranial MRI rather than a CT scan was obtained. At our study institution, the CT scanner is located in the ED, with exclusive use by ED patients. The MRI scanners are located outside the ED in the radiology suite and are shared with other hospital clinical areas. When an MRI scanner has available imaging time, the patient must be transferred to a distinct clinical area and complete a required safety check. Although time from ED arrival to the operating room was also longer for patients undergoing rapid cranial MRI, this probably reflects differences in the severity of the ventricular shunt

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**TABLE 2 Test Characteristics of Rapid Cranial MRI Versus CT for the Diagnosis of Ventricular Shunt Malfunction**

<table>
<thead>
<tr>
<th>Test Characteristic</th>
<th>Cranial CT n/N (%) (95% CI)</th>
<th>Rapid Cranial MRI n/N (%) (95% CI)</th>
<th>Difference of Proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>46/70 (65.7) (54.0 to 75.8)</td>
<td>36/70 (51.4) (40.0 to 62.8)</td>
<td>14.3 (–2.0 to 29.5)</td>
</tr>
<tr>
<td>Specificity</td>
<td>229/265 (86.4) (81.8 to 90.0)</td>
<td>290/292 (89.0) (84.9 to 92.1)</td>
<td>1.4 (–4.1 to 7.1)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>278/335 (82.4) (78.0 to 86.1)</td>
<td>296/362 (81.8) (77.5 to 85.4)</td>
<td>0.6 (–5.1 to 6.3)</td>
</tr>
</tbody>
</table>

**FIGURE 4**
Noninferiority analysis of crude and adjusted accuracy of rapid cranial MRI versus CT for diagnosing ventricular shunt malfunction.

**TABLE 3 Comparison of Median Study Time Intervals Between ED Visits With Rapid Cranial MRI Versus CT**

<table>
<thead>
<tr>
<th>Times (h)</th>
<th>Rapid Cranial MRI n (IQR), N = 362</th>
<th>Cranial CT n (IQR), N = 336</th>
<th>Difference Between Medians</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED arrival to image completion</td>
<td>2.3 (1.5–4.0)</td>
<td>1.7 (1.1–2.9)</td>
<td>0.5 (0.3–0.7)</td>
</tr>
<tr>
<td>ED arrival to image order</td>
<td>1.0 (0.7–1.6)</td>
<td>0.9 (0.5–1.7)</td>
<td>0.1 (0.0–0.2)</td>
</tr>
<tr>
<td>Image order to completion</td>
<td>1.2 (0.4–2.4)</td>
<td>0.7 (0.5–1.1)</td>
<td>0.4 (0.2–0.8)</td>
</tr>
<tr>
<td>Image completion to ED disposition</td>
<td>3.2 (2.0–4.8)</td>
<td>3.0 (1.9–4.9)</td>
<td>0.1 (0.2–0.5)</td>
</tr>
<tr>
<td>ED length of stay</td>
<td>6.0 (4.6, 7.7)</td>
<td>5.3 (5.9, 7.1)</td>
<td>0.8 (0.4, 1.1)</td>
</tr>
<tr>
<td>ED arrival to operating rooma</td>
<td>14.6 (5.4, 23.1)</td>
<td>5.2 (3.3, 17.0)</td>
<td>9.4 (1.4, 9.9)</td>
</tr>
</tbody>
</table>

* For children who went to the neurosurgery operating room within 72 h (N = 76 ED visits for rapid cranial MRI, N = 78 for CT).
malfunction as much as delays specific to obtaining neuroimaging. To support this difference in severity, the median difference in time to the operating room for ED visits with rapid cranial MRI was 4.3 hours, but only 30 minutes of the additional time can be explained by the time to obtain the neuroimaging study.

Diagnosing ventricular shunt malfunction remains challenging for clinicians. First, shunts fail for reasons that do not result in radiographic ventriculomegaly. Second, a substantial minority of children with a ventricular shunt who present with signs of elevated intracranial pressure and a confirmed shunt obstruction at neurosurgery had no evidence of ventricular dilation on serial neuroimaging. Ultimately, diagnosing shunt malfunction in a child with hydrocephalus continues to require integration of the clinical presentation and neuroimaging results by evaluating ED and neurosurgical clinicians.

Our study has several limitations. First, our study was retrospective and thus limited to the clinical information available in the medical record. However, we had minimal missing data for important clinical predictors and used an objective outcome measure. Second, the selection of neuroimaging modality varied by severity of the patient’s clinical symptoms, neurosurgical provider, and month. Additionally, children who returned to the ED multiple times during the study interval were included more than once, although the test performance of the radiologic study will not be independent. However, the accuracy of CT and MRI for ventricular shunt malfunction remained non-inferior after adjustment for clinical and provider differences and clustering by patient. Third, we calculated test performance by using the clinical radiologist’s final interpretation, with additional review by study radiologists, although only the radiology trainee report may have been available to the treating clinician at the time of ED evaluation and differed in a minority of cases. Fourth, we assumed that a 10% difference in accuracy between imaging modalities would be a clinically acceptable difference to providers because our study was not powered to detect smaller differences. Fifth, although we did not define valve adjustment as a ventricular shunt malfunction, the small number of these patients is unlikely to bias our results. Finally, we were unable to determine whether a child discharged from the ED had a delayed diagnosis of a ventricular shunt malfunction if the patient returned to another institution for diagnosis and treatment. We assume this occurred very rarely because these children were followed by neurosurgeons at the study institution.

CONCLUSIONS

The use of rapid cranial MRI to evaluate possible ventricular shunt malfunction increased dramatically over the study period. Rapid cranial MRI accuracy was not inferior to that of CT for diagnosing ventricular shunt malfunction and has the advantage of sparing ionizing radiation exposure in children with shunted hydrocephalus. However, the time to obtain neuroimaging was slightly longer for ED visits where rapid cranial MRI was performed. As increased familiarity extends use of rapid cranial MRI to a wider spectrum of patients with potential shunt malfunction, sensitivity of rapid cranial MRI for this diagnosis and neuroimaging time should be revisited.

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