A central factor that impacts lifetime risk of developing a malignancy is radiation exposure. Although background radiation is ubiquitous, the predominant source of radiation in contemporary society is medical imaging. Since 1990, there has been an explosion in medical imaging and a resultant increase in background radiation exposure. This has led to a substantial number of publications in the medical literature addressing radiation exposure risks and alternative methods to decrease these risks.3–5,23–25

Radiation exposure is particularly important in pediatrics because lifetime risk is cumulative and children have a long period of risk. This lifetime cumulative risk...
is of particular significance in subgroups such as patients with myelomeningocele because they require extensive imaging of different body systems from various medical services. Gaskill et al. documented cumulative radiation risks in patients with neural tube defects attributable to the radiation exposure from a CT scan in a 1-year-old child as 0.18% (abdominal) and 0.07% (head). They also observed that radiation risk is highest in the youngest children.

To eliminate the risk of radiation exposure, MRI is increasingly used. Traditional MR images require longer acquisition time and sedation, which can result in an increased risk from anesthetic administration. However, newer fast-sequence MRI (fsMRI) minimizes both components—duration and use of sedation—and has proven useful in imaging other organ systems. Birkemeier and colleagues demonstrated the utility of fast MRI of the chest as an imaging alternative in the preoperative evaluation of pectus excavatum. It proved to be an effective measure of chest wall deformity without exposing the patient to radiation. Dynamic MRI has also proven to be feasible in assessing velopharyngeal insufficiency in children without any sedation and radiation exposure.

Furthermore, recent evolution of MRI pulse sequences now allows for visibility of ventricular characteristics in the pediatric population. The T2-weighted single-shot fast spin echo demonstrates ventricular size and gradient recalled-echo visualizes the shunt catheter. Nevertheless, to date, only 3 investigations of the utility of fsMRI for hydrocephalus assessment have been performed, and 2 of these were feasibility studies nearly 10 years ago. We have incorporated an fsMRI protocol into our routine shunt surveillance and investigate its feasibility for evaluation of pediatric hydrocephalus in a nonacute setting.

Methods

The fsMRI protocol for routine surveillance was instituted in a single clinic at Children’s of Alabama starting in June 2008. Utilization has gradually increased as protocols have been refined. The MRI was performed in a 1.5-T system (General Electric). Sequences acquired for each child include an axial, coronal, and sagittal T2-weighted half-Fourier acquisition single-shot turbo spin-echo (HASTE) images.

After obtaining institutional review board approval, we conducted a retrospective chart and imaging review of all cases treated from June 1, 2008, to November 15, 2012. The review included cases in which an fsMRI protocol was used for either mild symptomatic or asymptomatic routine surveillance of patients with shunt-treated hydrocephalus. Patients were excluded if they were older than 19 years, if imaging was performed for indications other than routine hydrocephalus follow-up, if imaging was not performed according to defined fast-sequence protocol, or if an intravenous contrast agent was used.

Information regarding demographics—including sex and date of birth, duration of examinations, use of sedation, imaging-related complications, and fsMRI quality—was collected and analyzed. The duration it took to scan the patient was determined from differences in image time between the start of first and the last sequences obtained. Overall fsMRI quality was evaluated based on visibility of 5 different parameters, including ventricular size, ventricular configuration, ventricular wall sharp demarcation (as a surrogate for transependymal flow), absence of motion artifact, and visualization of ventricular catheter. Each visibility parameter was graded as 1 (present) or 0 (absent). The presence of 4 or 5 of these parameters translated into an excellent quality for the exam. If only 3 parameters were present, the quality of the exam was considered good. If only 2 or fewer of these parameters were present, the quality was determined to be poor.

The 2 raters for the interrater reliability part of this study included 1 pediatric neurosurgeon and 1 neurosurgical resident. Each fsMRI study was assessed independently by the raters, and each rater was blinded to the assessment of the other. Each fsMR image was evaluated for the 5 aforementioned parameters.

Descriptive statistics for the study population, including frequencies and means (± SD), were evaluated for statistical significance using chi-square tests and t-tests, respectively. Interrater agreement between pairs of observers was calculated using Kendall’s tau-b coefficient and intraclass coefficient (ICC). The interrater reliability for each individual visibility parameter assessed on a nominal scale was calculated using either Cohen’s kappa or prevalence-adjusted and bias-adjusted kappa (PABAK). PABAK is a method for addressing the paradox that can occur with Cohen’s kappa when a very low or high prevalence of a finding is associated with a very high observed proportion of agreement between the 2 raters. This can result in an un-representatively low calculated kappa statistic. The nominally assessed individual parameters for ventricular size, ventricular configuration, and transependymal flow exhibited this paradox and were assessed for interrater reliability using PABAK methodology. All statistical analysis was performed using SAS v9.3 (SAS Institute, Inc) with the exception of the ICCs, which were computed using SPSS v21.0 (SPSS, Inc.).

Results

A total of 200 fsMRI studies in 200 patients were obtained for either asymptomatic routine assessment or mild symptomatic workup. There were 122 males (61%) and 78 females (39%) (Table 1). The mean age of patients was 5 years and 7 months (SD 4 years and 8 months). Since it is difficult to perform imaging due to the movements of very young children, we further divided this group of patients those ≤ 60 months and those ≥ 60 months. Of the 200 patients, 101 (50.5%) were ≤ 60 months and 99 (49.5%) were ≥ 60 months (Table 1). When baseline characteristics were grouped by imaging quality, no statistically significant difference in sex was noted among excellent-, good-, and
poor-quality fsMR images. However, there was statistically significant difference in age breakdown in the different categories of overall quality of fsMR images. Although 100% of the patients were younger than 60 months of age in the category of poor-quality fsMRI scans, 95.7% of patients in the good-quality fsMRI category and only 42.0% of those in the excellent-quality fsMRI category were younger than 60 months (Table 1). Furthermore, the mean time it took to obtain the fsMR images was greater in the poor-quality image category than it was in the excellent- and good-quality image categories (4:10 minutes vs 3:35 and 3:39, respectively) (Table 1).

### Sedation and Duration of Imaging

Although 101 (50.5%) of the children were < 60 months of age, no sedation or general anesthesia was used for any of the imaging examinations. The average duration of examinations was 3.37 ± 1.06 minutes. Out of the 200 examinations, 123 (61.5%) of the studies required 3–5 minutes and 61 (30.5%) required < 3 minutes (Table 2, Fig. 1). Only 16 (8%) of the studies required > 5 minutes for acquisition.

### Quality of Images

Quality of the fsMRI studies was evaluated based on the aforementioned 5 different parameters: 1) ventricular size, 2) ventricular configuration, 3) ventricular wall sharp demarcation (as a surrogate for transependymal flow), 4) absence of motion artifact, and 5) visualization of ventricular catheter. The presence of 4 or 5 of these parameters was equivalent to an excellent score, 3 to a good score, and 1 or 2 to a poor score in terms of image quality. The summary of results showed that fsMR images were

<table>
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<tr>
<th>TABLE 1: Baseline characteristics grouped by imaging quality*</th>
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<tr>
<td>Mean age in yrs</td>
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<tr>
<td>Mean age in mos</td>
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<tr>
<td>Age, dichotomized†</td>
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<tr>
<td>&lt;60 mos</td>
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<td>≥60 mos</td>
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<tr>
<td>Mean duration of fsMRI in mins</td>
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<tr>
<td>Visibility of parameters†</td>
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<tr>
<td>Ventricular size</td>
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<td>Ventricular configuration</td>
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<td>Wall demarcation</td>
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<td>Catheter visible</td>
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<tr>
<td>Absence of motion artifact†</td>
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<td>Imaging quality†</td>
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<td>Excellent</td>
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<td>Poor</td>
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<td>Overall quality of fsMRI†</td>
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* Mean values are presented ± SD.
† Values are presented as the number (%) of patients.

<table>
<thead>
<tr>
<th>TABLE 2: Duration of fsMRI and need for sedation</th>
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<tr>
<td>Duration of Exam</td>
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<td>&lt;3 mins</td>
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<td>3–5 mins</td>
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<td>&gt;5 mins</td>
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<tr>
<td>Mean 3.37 mins*</td>
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<td>Use of sedation or general anesthesia</td>
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* The average time for standard MRI is approximately 30 minutes.
usually excellent or good (Fig. 2). Of the 200 imaging examinations, 169 (84.5%) exhibited 4 or 5 parameters, representing excellent quality. Also, 23 examinations (11.5%) were of good quality, having at least 3 parameters. Only 8 (4%) examinations were of poor quality (having 1 or 2 parameters). No image-quality failures or scores of 0 were identified.

Further analysis of each of the parameters (Fig. 3) revealed that all 200 studies (100%) provided excellent visualization of ventricular size and 188 (94%) showed detailed ventricular configuration. Visualization of the transependymal flow, as evaluated by sharp demarcation of the ventricular wall, was present in 190 (95%) of the imaging examinations (Fig. 3). Nevertheless, absence of motion artifact and visualization of ventricular catheter were two parameters that were missing in examinations.

Although 31.0% of the fsMRI examinations were poor quality due to the presence of motion artifact, 22.5% of the examinations presented difficulty visualizing the catheters (Fig. 3). Official radiology reports (as dictated by the attending radiologist) supplemented chart review when necessary to clarify catheter visualization.

**Interrater Reliability**

For the overall quality assessment of fsMRI, the interrater reliability according to Kendall’s coefficient was 0.82 (p = 0.002). Upon further analysis of each individual visibility parameter, the prevalence-adjusted kappa was 1.00 for ventricular size, configuration, and wall demarcation. The 2 raters were in perfect agreement for these 3 parameters. However, the kappa for absence of motion artifact was 0.84 (p = 0.04) and that for visibility of catheter was 0.76 (p = 0.009). Although the agreement for these 2 domains was not perfect, it was substantial and present in more than 75% of the examinations. More importantly, the ICC was extremely high at 0.87 (95% CI 0.72–0.94) (Table 3).

**Discussion**

Intracranial imaging plays an important role in the assessment of hydrocephalic patients with shunts. In the symptomatic patient, visualization of enlarged ventricles with or without transependymal flow confirms a clinical suspicion of shunt failure and enables rapid, efficient intervention. The role of so-called surveillance imaging in the asymptomatic patient is less clear cut and more controversial but still pursued by some pediatric neurosurgeons. At a minimum, surveillance imaging while the patient is asymptomatic serves to provide a baseline of ventricular size and morphology that may be used as a basis for comparison if the same patient presents with signs of shunt failure in the future. We acknowledge that it is not routine in all practices to perform surveillance imaging in the...
When multiplied by the 2.7 million scans obtained by demonstrating subtle though important changes in ventricular size or ventricular configuration that may precede the onset of symptomatic failure. Traditionally, the main radiographic modality for evaluating shunt function has been CT scanning because of its speed, diagnostic accuracy, and virtually uniform availability in Western cultures. Despite its many advantages, CT imaging still utilizes ionizing radiation, and the practice is being inuced neoplasia. Authors of previous studies have documented the use of limited-sequence MRI in a much larger series of patients for the follow-up of shunt-treated patients with hydrocephalus. Pediatric patients with shunted hydrocephalus need to be monitored closely for shunt malfunction, and some neurosurgeons indicate that surveillance imaging contributes by demonstrating subtle though important changes in ventricular size or ventricular configuration that may precede the onset of symptomatic failure. Traditionally, the main radiographic modality for evaluating shunt function has been CT scanning because of its speed, diagnostic accuracy, and virtually uniform availability in Western cultures. Despite its many advantages, CT imaging still utilizes ionizing radiation, and the practice is being increasingly challenged due to its inherent potential of inducing neoplasia. Authors of previous studies have documented a small, but notable, risk of cancer from one CT scan. When multiplied by the 2.7 million scans obtained each year in children, the scope of the potential problem takes on significant public health implications.

Our study reveals fsMRI scans have significant advantages over other diagnostic imaging in the nonacute evaluation of hydrocephalic patients. In our series the vast majority of fsMRI scans provided high-quality images for evaluation of shunt function in a wide age range of patients in whom the need for sedation was completely absent. No examination failures were identified. The imaging allowed consistent and accurate evaluation of ventricular size, ventricular configuration, ventricular wall demarcation, and catheter position with an absence of motion artifacts in most cases. Our interrater reliability scores support the contention that fsMRI produced a clinically useful product that resulted in reliably similar clinic impressions. In this study’s conditions, the Kendall’s coefficient was 0.82 and was statistically significant, suggesting excellent reliability and agreement in the image assessment based on the 5 visibility parameters. Furthermore, the ICC, designed to compare the variability of raters’ rating of the same patient to the total variation across all ratings, was 0.87 (95% CI 0.72–0.94; p < 0.0001) and was considered to have excellent interrater reliability according to the values proposed by Enderlein and Fleiss. The significance of the interrater reliability lies in the fact that the two previous studies regarding the use of fsMRI demonstrated difficulty in observation of the 5 visibility parameters, particularly visualization of ventricular catheter and wall. The high interrater reliability proves that our 5 visibility parameter scale is reliable and demonstrates high concordance in the ratings given by judges. These results suggest that the fsMRI protocol utilization may provide a highly reliable tool for surveillance of shunted hydrocephalus in pediatric patients.

Our results are consistent with earlier findings of others. Iskandar et al. performed a retrospective review of 72 patients and indicated that so-called quick-brain MRI offered an adequate demonstration of neuroanatomy necessary for proper evaluation of shunt function. A year later, in 2005, Ashley et al. investigated 67 patients at St. Louis Children’s Hospital and showed that 80% of rapid-sequence MR images exhibited good visualization for evaluation of shunted hydrocephalus. These 2 early studies collectively indicated the utility and feasibility of fsMRI in evaluating shunt function. More recently, Niederhauser and colleagues documented the use of rapid-sequence MRI in a much larger series of patients for diagnosis and follow-up of various intracranial etiologies, including shunted hydrocephalus. Recently Pindrik and colleagues reported a technique of limited-sequence CT studies that successfully imaged the ventricles in a cohort of children with shunted hydrocephalus; these studies, compared with conventional CT scans, substantively reduced the children’s radiation exposure. These prior published studies, as well as our preliminary experience, enabled us to identify 5 specific challenges inherent in fsMRI of patients with hydrocephalus: motion artifact, visualization of the ventricular catheter, study duration, need for patient sedation, and cost.

**Motion Artifact**

Some motion artifact was present in 31% of the fsMRI scans in the present series. This can be largely attributed to the young age of our patients (average age 5.7 years). At this age and within the challenging environment of the scanner, it is difficult or impossible for patients to follow instructions. Additionally, many patients who harbor ventricular shunts are challenged with cognitive and behavioral delays that may further decrease their compliance with limiting their movement. The presence of motion artifact on a single slice or two rarely prevented the scan from enabling assessment of shunt function because ventricular anatomy was still readily visible on the vast majority of fsMRI scans despite the motion artifact. No cases required conversion to CT or to standard MRI with sedation (Figs. 4 and 5).

**Visualization of the Ventricular Catheter**

The ventricular catheter was readily visualized in
more than two-thirds of patients (Fig. 3). This number is inferior to that visualized with CT imaging, which uniformly delineates the ventricular catheter. A significant advantage is conferred to CT imaging in the manufacturing process of the ventricular catheters because they are impregnated with barium. If fsMRI becomes more widely used, it is conceivable that similar agents (for example, weakly ferromagnetic agents) will be incorporated into future ventricular catheters to improve their visibility even further on MRI. Furthermore, the shunt catheter’s exact depiction is not absolutely necessary for evaluation of shunted hydrocephalus or adequate diagnosis of shunt malfunction.

Study Duration and Need for Sedation

The results of this retrospective study demonstrate that fsMRI can be performed very quickly (average time 3–4 minutes) with nearly the same speed as conventional head CT scanning (2-minute acquisition). Although comprehensive general MRI scans have longer acquisition time, fsMRI scans are far more rapid. In fast spin echo sequences, the interval of time after the first echo is used to receive the echo train, to fill the other k-space lines in the same slice. Because of the reduced number of repetitions required, the k-space is filled faster and slice acquisition time for each slice is reduced. Due to rapid acquisition of images in fsMRI, the need for sedation was eliminated, in our experience. No sedation or general anesthesia was used in acquiring any of the scans. The elimination of the need for sedation decreases the risk of serious adverse events such as hypoxemia and paradoxical reactions from sedation that are seen at a higher incidence in pediatric populations.

The time in the scanner was investigated through review of the radiology reports for approximately 60 patients. We noted that there was no significant difference between the scan time and time in the scanner. Therefore, we chose to report scan time, which was accurately available for all 200 patients. We acknowledge that some patients might have required strategies to calm them, but none required sedation or general anesthesia. Furthermore, no patient in this series required repetition of fsMRI.

Cost

At our medical center for the study period of this report, costs fsMRI were comparable to those of CT scanning without administration of a contrast agent. During the study period, the average cost for a CT scan of brain without contrast was $1650, whereas that for an fsMRI scan was $1600. For the same period, the cost of a complete non-Gd MRI study of the brain was $2850.

Limitations of the Study

The fsMRI examination, the protocol used, and the retrospective nature of this review each has limitations. Fast-sequence MRI is insensitive to T2 changes, and as such makes it difficult to view blood products from hemorrhages, pneumocephalus, or implanted devices. In addition, it is not easy to study communication between ventricular and cystic loculations since contrast material is not used.

Also, fsMRI has potential hazards in patients with programmable shunts because exposure to a magnetic field has the potential to change the shunt setting and might require reprogramming. In our study, there were only 4 programmable shunts that were affected by the magnetic field of the fsMRI. Our routine practice is to check the setting of the programmable shunts after any known exposure to a magnetic field and adjust it if change has occurred. We do not routinely place programmable shunts in our practice, although we do follow pediatric patients in whom programmable shunts were placed at other facilities. To date there have not been any cases in which the programmable shunts became nonadjustable, causing symptoms and requiring revision. However, we acknowledge that the impact of repetitive MRI on valve functions is uncertain and requires further investigation.
Future institution of the fsMRI protocol requires an understanding of these limitations.

This protocol only incorporated nonsymptomatic or minimally symptomatic patients undergoing surveillance imaging of shunts. This design is intentional and reflects progressive experience at our center. The feasibility and efficacy of fsMRI were unproven at the outset of our study. Therefore, only patients who were clinically well or exhibited minimal clinical signs of shunt dysfunction were included. It would be difficult to justify utilization of an unproven imaging modality to evaluate the symptomatic shunt-treated patient for whom timely accurate imaging is of great importance. Over time and with greater experience, fsMRI has been increasingly used for shunted hydrocephalus in more clinically urgent scenarios. Furthermore, fsMRI is increasingly performed to assess other pathologies with sufficient anatomical detail, including patients treated with endoscopic third ventriculostomy and patients with complex ventricular system loculations and septae. In these cases, fsMRI was sufficient for follow-up evaluation of shunted hydrocephalus and standard MRI sequences were not used unless there was requirement of contrast-enhanced imaging detail.

Our study’s further limitations include its retrospective nature, subjective chart review, and narrow focus for study indication. The subjective nature and its associated bias are mitigated by the inclusion of 2 raters and the excellent interrater reliability. We sought to assess and report our initial fsMRI results with respect to feasibility, utility, and reliability in shunt-treated hydrocephalus patients with mild or no symptoms. Fast-sequence MRI is being increasingly used at our center and probably at other pediatric imaging centers. However, there is very little evidence in the neurosurgical or radiology literature to support the utility of this increasingly used modality.\(^{15,20,21}\) Despite the limitations detailed above, this study provides some evidence supporting the use of fsMRI for screening and assessing pediatric patients with hydrocephalus and ventricular shunts.

**Conclusions**

Results in this cohort of asymptomatic or minimally symptomatic pediatric patients with ventricular shunts indicate that fsMRI yields reliable visualization of ventricles and excellent anatomical detail while eliminating radiation exposure and the need for sedation. Although this protocol might be implemented at a few other institutions, there are no recent reports regarding its use for evaluation of shunted hydrocephalus. Due to lack of institutional efforts and interspecialty collaboration at most facilities, noncontrast head CT scanning is still being performed for the evaluation and follow-up of shunted hydrocephalus. Fast-sequence MRI should replace conventional CT as the diagnostic modality of choice for examining patients with shunted hydrocephalus in the nonacute setting because it offers significant advantages and it is effective, efficient, and reliable.

**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: Blount. Acquisition of data: Patel, Pate. Analysis and interpretation of data: Blount, Patel, Johnston. Drafting the article: Blount, Patel. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Blount. Statistical analysis: Patel. Administrative/technical/ material support: Blount, Pate. Study supervision: Blount, Johnston.

**References**

Fast-sequenve MRI for surveillance in pediatric hydrocephalus


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