Rapid Sequence Magnetic Resonance Imaging in the Assessment of Children with Hydrocephalus

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Key words
- HASTE MRI
- Hydrocephalus
- Radiation risk
- Rapid acquisition MRI
- Ventriculoperitoneal shunt

Abbreviations and Acronyms
CT: Computed tomography
HASTE: Half Fourier acquisition single shot turbo spin echo
MRI: Magnetic resonance imaging
RS-MRI: Rapid-sequence magnetic resonance imaging
TR: Repetition time

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Citation: World Neurosurg. (2013) 80, 6:e307-e312.
http://dx.doi.org/10.1016/j.wneu.2012.10.066

Journal homepage: www.WORLDNEUROSURGERY.org

Available online: www.sciencedirect.com

1878-8750/$ - see front matter
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■ OBJECTIVE: **Recent reports have shown the utility of rapid-acquisition magnetic resonance imaging (MRI) in the evaluation of children with hydrocephalus. Rapid sequence MRI (RS-MRI) acquires clinically useful images in seconds without exposing children to the risks of ionizing radiation or sedation. We review our experience with RS-MRI in children with shunts.**

■ METHODS: **Overall image quality, cost, catheter visualization, motion artifact, and ventricular size were reviewed for all RS-MRI studies obtained at Seattle Children's Hospital during a 2-year period. Image acquisition time was 12–19 seconds, with sessions usually lasting less than 3 minutes.**

■ RESULTS: **Image quality was very good or excellent in 94% of studies, whereas only one was graded as poor. Significant motion artifact was noted in 7%, whereas 77% had little or no motion artifact. Catheter visualization was good or excellent in 57%, poor in 36%, and misleading in 7%. Small ventricular size was correlated with poor catheter visualization (Spearman's $\rho = 0.586$; $P < 0.00001$). RS-MRI imaging cost ~$650 more than conventional computed tomography (CT).**

■ CONCLUSIONS: **Our study supports that RS-MRI is an adequate substitute that allows reduced use of CT imaging and resultant exposure to ionizing radiation. Catheter position visualization remains suboptimal when ventricles are small, but shunt malfunction can be adequately determined in most cases. The cost is significantly more than CT, but the potential for lifetime reduction in radiation exposure may justify this expense in children. Limitations include the risk of valve malfunction after repeated exposure to high magnetic fields and the need for reprogramming with many types of adjustable valves.**

INTRODUCTION

Shunt-dependent hydrocephalus is a common neurological disorder that often presents in infancy and may require frequent imaging for its treatment. Most of this imaging is in the form of computed tomography (CT) of the head and shunt series radiographs, two modalities that involve ionizing radiation. The risks associated with exposure to radiation, primarily a risk of inducing cancer (5, 12), are well known. The risks associated with CT scans are magnified in children in part because they have so many years of life ahead to actualize a potential cancer risk (3, 4).

Magnetic resonance imaging (MRI) is a radiation-free modality that provides multiple two-dimensional slice representation of a three-dimensional structure similar to CT. The utility of routine MRI protocols to evaluate children with hydrocephalus has been limited by the long acquisition time, which typically requires the child to be sedated. Long acquisition time and limited scanner availability are especially cumbersome in emergency situations, such as shunt malfunction; however, the recent introduction of rapid MRI sequences overcomes many of these limitations.

Half-Fourier acquisition single-shot turbo spin echo rapid-sequence MRI (HASTE RS-MRI) is one such rapid acquisition protocol that delivers T2-weighted images from a single pulse. The per-slice acquisition time can be as fast as 0.4 seconds, with a total sequence acquisition time of <20 seconds.

The protocol at our institution has been to obtain axial RS-MRI images after a requisite T1-weighted localizing image. The total study time is less than that to obtain a CT of the head (<20 seconds) and does not involve sedation. Other authors have reviewed the use of three-plane single-shot turbo spin echo (quick brain), a protocol similar to RS-MRI (6), and three-plane RS-MRI with three-plane turbo T1 (1). We review an imaging protocol of obtaining only axial RS-MRI images. This limits scan time (12- to 19-second acquisitions) while delivering images easily comparable with axial CT images.

We sought to evaluate the overall image quality and catheter visualization of axial

RS-MRI studies obtained in children with hydrocephalus. We hypothesize that axial RS-MRI is an appropriate substitute for CT scanning that allows appropriate clinical decision-making while avoiding exposure to ionizing radiation.

PATIENTS AND METHODS

After approval from the institutional review board, all patients with shunted hydrocephalus who underwent RS-MRI between May 2007 and May 2009 were identified. Their charts were reviewed for demographic information, including age at time of RS-MRI and sex. The numbers of lifetime head CTs and RS-MRIs also were recorded.

The MRI examinations were performed on a 1.5-Tesla (Siemens Avanto) or a 3-Tesla (Siemens Trio) system, depending on the availability of the scanner. A 12-channel phased array coil was used. The RS-MRI sequence was obtained on these scanners by the use of standard commercially available hardware and software. The HASTE RS-MRI sequence, which is a proprietary Siemens sequence, is a T2-weighted single-shot turbo spin echo sequence. The standard parameters used for the HASTE sequence were: 1.5-Tesla: repetition time (TR) 744 milliseconds, echo time 104 milliseconds, flip angle 150°, field of view 230 mm, matrix 256 × 156, number of acquisitions 1, slice thickness 4 mm with a skip of 1 mm and I-PAT factor of 2; 3-Tesla: TR 358 milliseconds, echo time 90 milliseconds, flip angle 150°, field of view 220 mm, matrix 256 × 156, number of acquisitions 1, slice thickness 4 mm with a skip of 1 mm and I-PAT factor of 2.

Minimal TR time for the sequence was selected and parallel imaging was used to reduce the scan time to the shortest interval possible. Only axial images were acquired, and this resulted in an imaging duration of 19 seconds for the 1.5-Tesla magnet and 12 seconds for the 3-Tesla magnet. The mean time for total in-magnet imaging was less than 3 minutes, which included positioning, localizers, slice planning, and the imaging duration for the axial RS-MRI sequence.

All RS-MRI studies were retrospectively and independently reviewed by a radiologist and a neurosurgeon blinded to the medical histories, location of shunts, and diagnoses. Overall image quality and catheter visualization were graded by both reviewers. The radiologist additionally graded the amount of motion artifact and ventricular size on all studies. Table 1 lists the scales used for grading the RS-MRI studies.

A Spearman's rank correlation test was then used to determine the correlation between the factors graded (overall image quality and motion artifact, overall image quality and catheter visualization, and ventricular size and catheter visualization). Particular interest was paid to exploring determinates of poor catheter visualization.

RESULTS

Fifty patients with implanted shunts (29 male; 21 female) underwent 119 RS-MRIs. Age at the time of imaging ranged from 12 days to 11 years (median, 1.3 years). Patients underwent an average of 2.38 RS-MRI imaging studies, with a maximum of 12 studies. A total of 502 head CT scans had been obtained in these 50 patients, with an average of 10.1 per patient. Sixty-six percent of these patients had more than five head CTs, whereas 38% had had more than 10 scans, and 10% had had more than 20 head CTs.

Image Quality

The radiologist rated 51.2% of the RS-MRI studies as "excellent" for overall image quality, 41.3% as "acceptable anatomic detail," and 7.5% as "significant obscuring of detail." No studies were rated as "not clinically useful." The neurosurgeon reviewing RS-MRI studies rated 76.5% of them as "excellent," 18.5% as "acceptable," and 4.2% as "significant obscuring" for overall image quality. One study (0.8%) was rated as "not clinically useful" by the neurosurgeon. Interrater reliability as determined by the ability to clinically rate the ventricular size as stable, smaller, or enlarged was 0.99.

Study ratings of "limited utility" were often the result of motion artifacts (Figure 1), with 4 of 6 images rated by the neurosurgeon as "limited" and 8 of 9 images rated by the radiologist as "limited" having

Table 1. Scales Used for Evaluating RS-MRI for Image Quality, Motion Artifact, Ventricular Size, and Catheter Visualization

Rating Scales	Score Indication
Overall image quality	1 — Poor, not clinically useful
	2 — Limited utility
	3 — Good, clinically useful
	4 — Excellent
Motion artifact	1 — Severe motion artifact, not clinically useful image
	2 — Moderate motion artifact with some loss of anatomic detail
	3 — Slight motion artifact with negligible loss of anatomic detail
	4 — No motion artifact
Ventricular size	1 — Slit-like
	2 — Normal ventricular size
	3 — Mild dilation
	4 — Mild-to-moderate dilation
	5 — Moderate dilation
	6 — Moderate-to-severe dilation
	7 — Severe dilation
Catheter visualization	1 — Misleading visualization of the location of the catheter tip
	2 — Unable to visualize catheter tip
	3 — Clinically useful visualization of catheter tip
	4 — Excellent visualization of the catheter tip

RS-MRI, rapid-sequence magnetic resonance imaging.

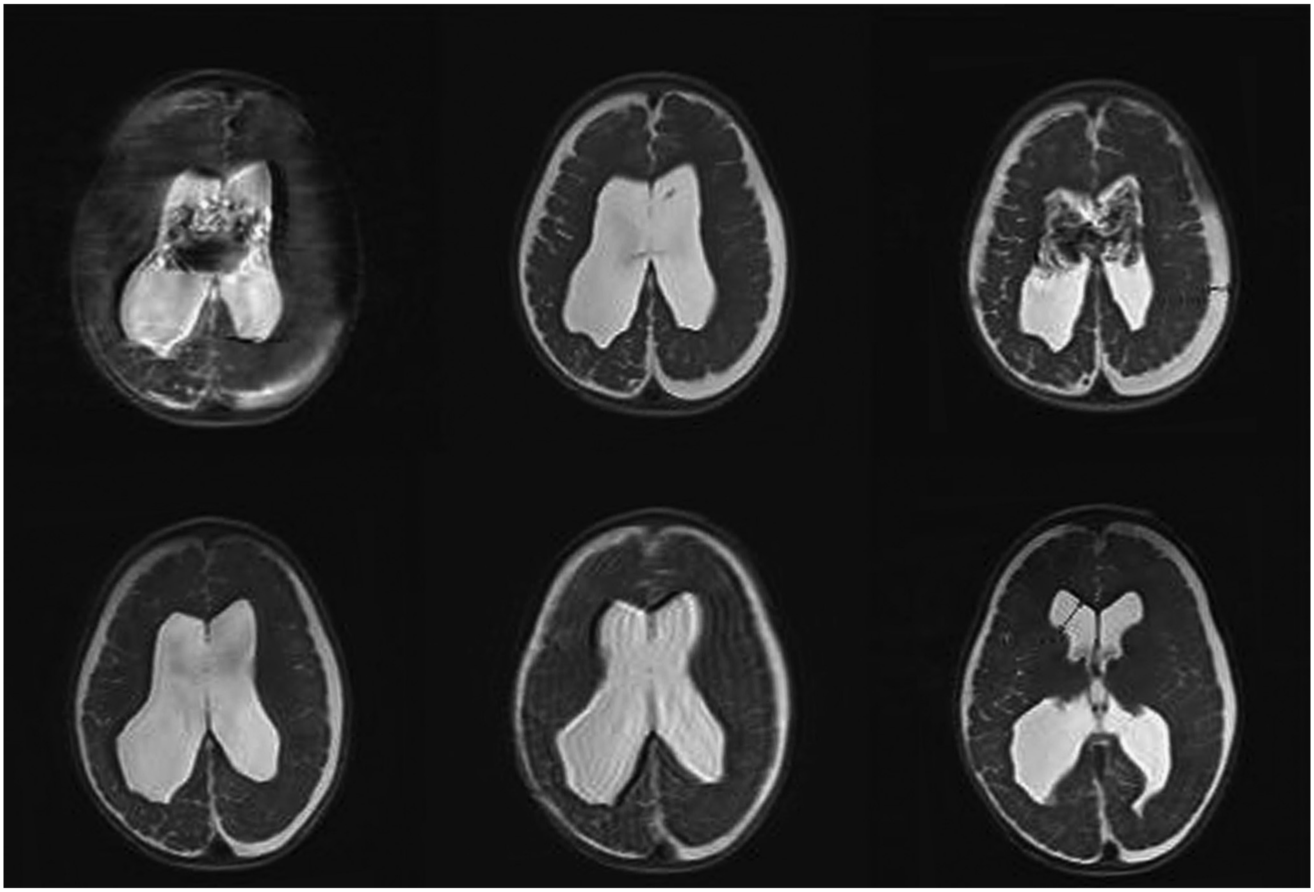

Figure 1. A routine follow-up RS-MRI scan obtained in a 2-year-old child with idiopathic hydrocephalus showing overall image quality of limited clinical utility (2) primarily because of severe (1) motion artifact. Moderate ventricular dilation and clinically useful (3) catheter visualization are also shown.

moderate to severe motion artifact. Overall, 76% of the RS-MRI studies had "slight" or "no motion artifact," 16% had "moderate motion artifact," and 8% had "severe motion artifact." The coefficient of correlation between image quality and motion artifact as determined by Spearman rho correlation test was 0.705 ($P < 0.00001$).

Catheter Tip Visualization

The radiologist rated 24.4% of the RS-MRI studies as providing "excellent catheter visualization" (Figure 2), 39.5% "clinically useful visualization," 35.3% "no catheter visualization," and 0.8% (1 study) "misleading visualization" that caused the reviewer to misjudge catheter location. The neurosurgeon found 42.9% of the RS-MRI sequences provided "excellent catheter visualization," 7.6% "clinically useful visualization," 38.7% "no visualization," and 13.5% "misleading visualization." Although the radiologist was misled by fewer RS-MRI studies, both reviewers found more than one-third of studies provided insufficient catheter visualization.

Catheter visualization was most commonly problematic in the setting of small ventricles (Figure 3). Among scans with slit ventricles, 68% had "no visualization" of the catheter tip, whereas the remaining 32% had "clinically useful" visualization. When the ventricles were enlarged (rated "mild" to "severe"), only 4% of catheter tips could not be visualized, 29% had "clinically useful" visualization, and the remaining 68% had excellent visualization. Spearman correlation for catheter visualization and ventricular size was 0.586 ($P < 0.00001$).

Catheter visualization correlated weakly with image quality (Spearman correlation 0.289, $P = 0.001$) and did not correlate with scan motion (Spearman correlation 0.149, $P = 0.105$).

The cost of RS-MRI was compared with the costs of noncontrast-enhanced head CT imaging. At our institution, the technical and professional fees for RS-MRI were $1800 and $170, respectively, and those for a head CT were $1200 and $123, respectively. RS-MRI was $647 more expensive per imaging session.

DISCUSSION

Our study is the first to evaluate RS-MRI in only the axial plane in children with shunted hydrocephalus. We adopted this protocol at our institution because it minimizes scan time (12- to 19-second acquisition time and less than 3 minutes total room session time) while providing good-quality images of the ventricular anatomy that are easily compared with an axial head CT.

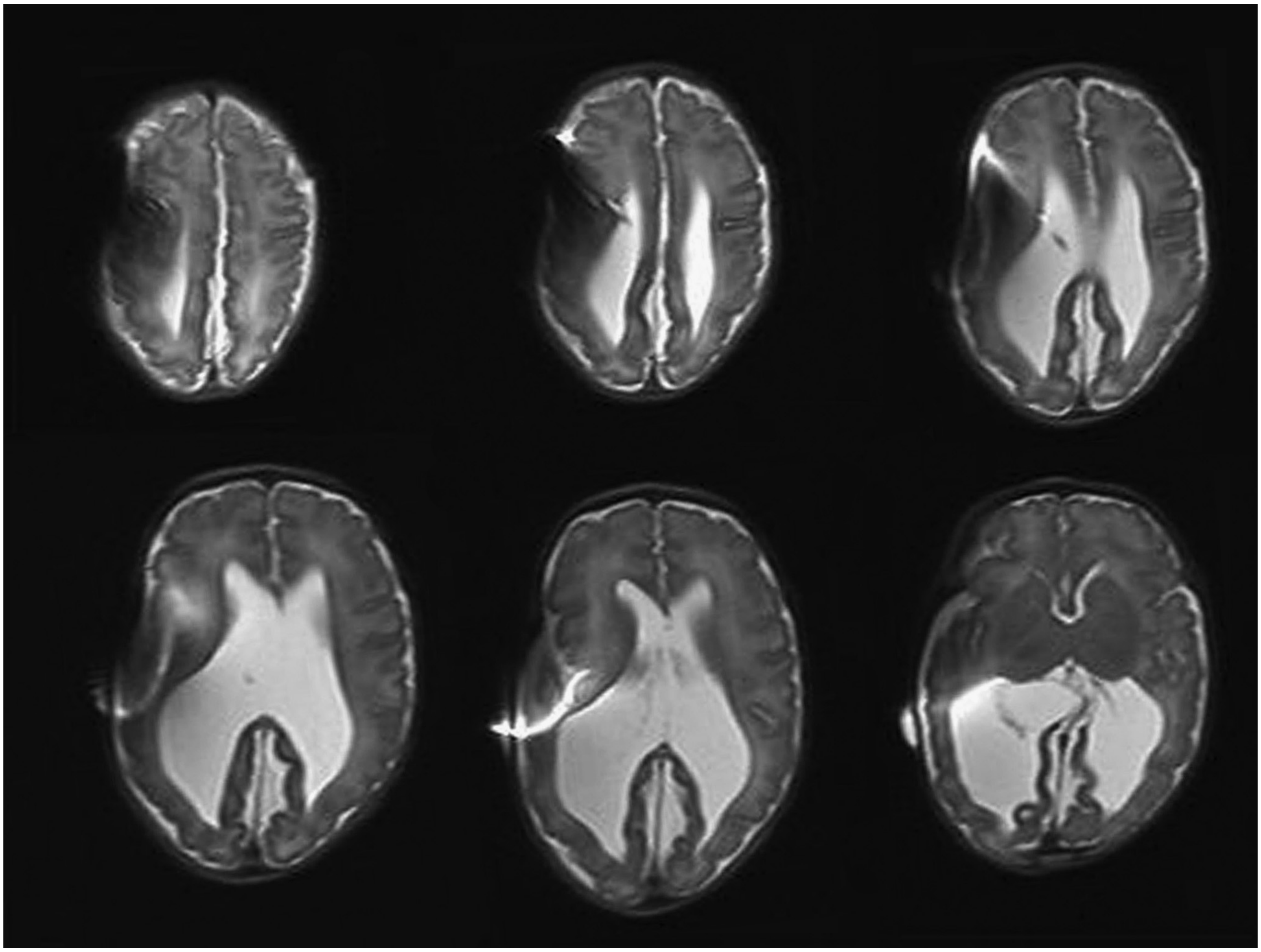

Figure 2. RS-MRI scan obtained in a 2-week-old child with aqueductal stenosis showing moderate ventricular enlargement with excellent (4) catheter visualization and good (3) overall image quality despite moderate (2) motion artifact.

The utility of RS-MRI has been espoused by the authors of two previous publications. In one, the authors reviewed the use of single-shot fast-spin echo acquired in three planes with an average imaging time of 3.4 minutes (6). A second study described the use of three-plane RS-MRI accompanied by three-plane turbo-fast low-angle shot T1, a protocol that took an average of 22 minutes per examination. Although this total study time is significantly longer than in the other studies, the authors were able to scan children of all ages without sedation thanks to the short acquisition time for each individual sequence, which were realigned in post-processing (1). By obtaining RS-MRIs in only the axial plane, our imaging protocol further limits total room scanner time to less than 3 minutes with actual image acquisition time of 12–19 seconds.

Image Quality

Overall image quality was good or excellent in the great majority of the RS-MRIs reviewed. Only one study was graded as poor, whereas 95% were graded excellent or very good. Ashley et al. (1) found similar results for overall image quality, with 88% of their RS-MRI studies rated as either good or excellent on overall image quality. Degradation in image quality was very closely related to motion artifact in our study, with a coefficient of correlation of 0.734, further emphasizing the importance of short acquisition time in obtaining quality images.

Although overall image quality (primarily focused on ventricular anatomy) was routinely graded as excellent in our study, catheter visualization proved more problematic. Forty-two percent of the reviews of catheter visualization were graded as either "no visualization" or "misleading." Ashley et al. (1) found similar results when reviewing their RS-MRI images, with 59% of reviews of catheter visualization rated as "poor." They found significantly better results with T1 images, with only 19% rated as "poor."

Catheter visualization was especially problematic in small ventricles (Figure 1). We found that 68% of the catheters could not be visualized on studies with slit ventricles, whereas only 4% of the studies on enlarged ventricles failed to clearly show the catheter. Excellent catheter

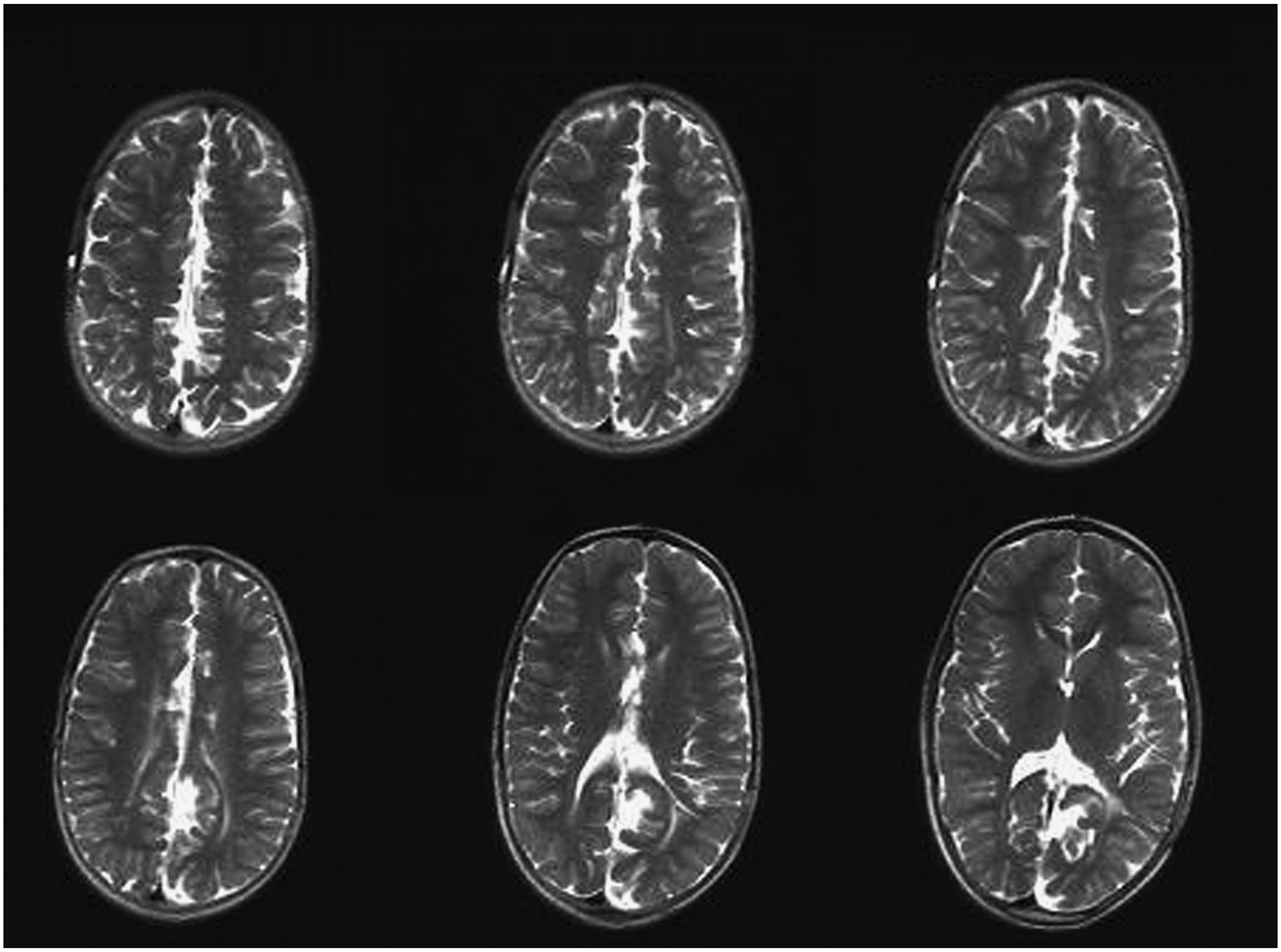

Figure 3. RS-MRI scan obtained in a 7-year-old child who was born prematurely at 26 weeks with posthemorrhagic hydrocephalus and one-day history of headache showing excellent (4) overall image quality, no (4) motion artifact, slit ventricles, and no visualization (2) of catheter tip.

visualization was reported in 68% of enlarged ventricles, 19% of normal-sized ventricles, and 0% of slit ventricles. When catheter tip visualization is necessary, the addition of a turbo T1 sequence or the choice of CT rather than RS-MRI may provide the needed visualization.

Risk of Radiation

The lifetime risk of multiple CTs of the head in young children is difficult to quantify. Because CT imaging was introduced more than 40 years ago, very few adults have had any CTs in childhood, especially in the quantities experienced in the first few years of life by the patients in our study. In a recent summary statement, the National Council on Radiation Protection and Measurements estimated that the U.S. population is currently exposed to seven times more ionizing radiation from medical imaging than it was in the first half of the 1980s (10). The 50 patients in our study had a total of 507 head CTs, an average of 10.1 per patient. Most of these patients were very young (averaging 1.3 years of age when undergoing RS-MRI) with the potential for many future radiation exposures.

Recent papers have raised the concern over radiation exposure in routine medical imaging (5, 12). Smith-Bindman et al. (12) calculated the lifetime adjustable risk of cancer in a 20-year-old woman after a single head CT with a mean effective dose of 2 mSv was 0.23 cancers per 1000 patients (range, 0.03—0.70). Much of what is known about the risk of medical imaging is extrapolated from long-term observation of the population exposed to radiation in the atomic bomb attacks on Hiroshima and Nagasaki. Estimates of radiation exposure from a head CT have been made with the use of phantoms and computer models. A single head CT scan with the scanner set at 200 milli-Angstroms in a neonate exposes the brain to 65 mGy of radiation. In a 1-year-old child, the brain receives 46 mGy, and by the age of 5 years, the dose is reduced to 33 mGy (3, 4, 7). Comparing the atomic bomb survivors with patients undergoing head CTs estimates the lifetime risk of a fatal cancer from a single head CT as 0.07%, or 1 in 1500, in a 1-year-old child (2). The risk after 15 head CTs by this estimate is 1%. The risk decreases significantly with increasing age. By the time the child is 5 years old, the risk is half that of a 1-year-old child. Our calculations taken from a routine head CT on a 3-year-old child at our institution demonstrated an effective dose of 3.16 mSv, which equates to 1.05 years of equivalent background radiation with a 0.12 additional lifetime associated risk of cancer and an additional lifetime associated risk of cancer mortality of 0.05% (9, 11).

Although any single imaging study surely offers more benefit to the patient than the small risk of a future malignancy, radiation exposure in children undergoing multiple medical imaging studies poses a significant public health risk. One review of the topic estimated that 2% of all cancers in the United States are caused by CT radiation exposure (3, 4). All of the estimates of radiation risk from medical imaging in children require several suppositions and lack direct data making these calculations rough approximations of the true risk.

A secondary benefit of RS-MRI is the speed at which pictures are obtained, which obviates the need for procedural sedation. Rare adverse events do occur during pediatric sedation, despite the expertise of experienced pediatric anesthetists. Hypoxemia was found to occur in 2.9% and adverse medication reactions in 3.6% of children undergoing sedation for MRI or CT in a study of more than 1000 children by Malviya et al. (8). Sedation was inadequate in 16% and failed in 7% of the children in their study. Despite sedation, 12% of the scans obtained had excessive motion artifact. Thirteen percent of children sent for imaging under sedation received general anesthesia (8). None of the patients undergoing RS-MRI at our institution were sedated for the procedure, avoiding one of the main risks of medical imaging in children.

Limitations

Limitations to this procedure for imaging include the potential risk of valve malfunction after repeated exposes to high magnetic fields and the need for post-MRI reprogramming with many types of adjustable valves. Magnetically adjustable valves undergo shear forces when placed in high static field magnetic environments. Although RS-MRI has been approved by the Food and Drug Administration, the exact number of exposures needed to cause valve failure is unknown. The second limitation is the need for post-MRI reprogramming of adjustable valves. A computerized tracking system at our hospital alerts the MRI technician if the patient has a programmable valve. Reprogramming visits are automatically scheduled at the time of the MRI request for routine follow-up RS-MRI; reprogramming occurs after the MRI in patients who undergo emergent RS-MRI. Even with these safety measures in place, it is important to educate the families and caregivers of these patients regarding the need for shunt reprogramming after any MRI.

CONCLUSION

Axial RS-MRI provides good visualization of ventricular anatomy without radiation exposure. Virtually all of the studies reviewed provided the necessary detail for appropriate clinical decision-making. Total study time was less than 3 minutes, with acquisition time of the axial RS-MRI less than 20 seconds. None of the children needed procedural sedation. Although the cost of RS-MRI is significantly more than that of CT, the routine use of axial RS-MRI to evaluate children with hydrocephalus could eliminate a large percentage of routine CT imaging studies, thereby reducing an individual child's lifetime ionizing radiation dose, and possibly avoid a future radiation-induced malignancy. The potential for valve failure with repeated MRIs should be discussed with families, and it is essential to establish a protocol for post-MRI valve reprogramming as part of the standard work at each institution implementing RS-MRI in routine practice.

ACKNOWLEDGMENTS

The authors thank Kristin Kraus, M.Sc., for editorial assistance.

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Received 11 June 2012; accepted 23 October 2012; published online 27 October 2012

Citation: World Neurosurg. (2013) 80, 6:e307-e312. http://dx.doi.org/10.1016/j.wneu.2012.10.066

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