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Clinical Study

Fast-brain MRI in children is quick, without sedation, and radiation-free, but beware of limitations ☆

Katya Rozovsky [a,*], Enrique C.G. Ventureyra [b], Elka Miller [a]

[a] Department of Diagnostic Imaging, Children's Hospital of Eastern Ontario, Ottawa, Canada
[b] Division of Pediatric Neurosurgery, Children's Hospital of Eastern Ontario, Ottawa, Canada

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ABSTRACT

Fast-brain MRI is a promising technique for young children who require anesthesia for conventional MRI; however, poor contrast resolution and the use of one type of pulse sequence only has limitations. We aimed to review and document pitfalls of fast-brain MRI in non-sedated children. Fifty fast-brain MRI studies (Fast Imaging Employing sTeady State Acquistion [FIESTA] protocol; 1.5-Tesla Signa Excite HD, GE HealthCare, Milwaukee, WI, USA) performed between January 2008 and August 2010 in 30 non-sedated patients aged 1 day to 5 years of age (mean: 18 months) were reviewed retrospectively and compared to the most recent MRI or CT scan. The indications were: ventriculoperitoneal (VP) shunt insertion or revision or follow-up (20/50, 40%), postoperative follow-up (9/50, 18%), macrocephaly, ventriculomegaly or congenital malformation (15/50, 30%), complications of prematurity (6/50, 12%). The VP shunt position and size of fluid-filled structures were satisfactorily assessed in all patients. Undetected findings in 7/50 studies (14%) were: venous sinus thrombosis (one patient), subdural hematoma (three), failure to differentiate blood products (two), and limited evaluation of extra-axial collections (one). FIESTA fast-brain MRI provides satisfactory assessment of shunt position and the size of fluid-filled structures, but radiologists should be aware of limitations for depiction of venous sinus thrombosis, and bleeding. Modification of fast-brain protocols appears to be indicated.

1. Introduction

Fast-brain MRI was introduced initially for children with shunt-dependent hydrocephalus,[1–4] who usually undergo serial imaging studies. The main choice for these patients is between serial brain CT scans and MRI. CT scans involve exposure to radiation, which is potentially harmful, especially for young children.[5] The substitute for the CT scan is MRI, but brain MRI is time consuming, and sensitive to movement artifacts. In most young patients, MRI studies require sedation or general anesthesia, which have their own risks of complications.[6,7] Fast MRI sequences can avoid the need for sedation or anesthesia, and are thus especially useful for young and uncooperative patients.

Since 2000, fast MRI has gradually become more popular and fast protocols are used increasingly for non-hydrocephalic indications such as macrocephaly, intracranial cysts, screening for some structural congenital anomalies, and postoperative follow-up.[8] The most common protocols are T2-weighted MRI with very short (20–40 s) acquisition times, which are designed to answer specific clinical questions. Although of poor contrast resolution, these sequences allow evaluation of the size and configuration of the ventricular system and extra-axial cerebrospinal fluid (CSF) spaces. The advantages of this method – including the lack of exposure to ionizing radiation, sedation, or anesthesia – have been described in the neurosurgical literature. However, the use of a single type of pulse sequence and the poor contrast resolution inherent with these protocols carry potential pitfalls that should be kept in mind when interpreting these short MRI studies.

At our institution fast-brain MRI is obtained using a Fast Imaging Employing Steady-sTate Acquisition sequence (FIESTA) pulse sequence. During reviews of these studies, we encountered both advantages and disadvantages to these protocols. We aimed to discuss pitfalls and limitations of fast-brain MRI in non-sedated children.

2. Materials and methods

2.1. Patients

Institutional Review Board approval was obtained and informed consent was waived for this retrospective study.

☆ All authors contributed to the preparation of this manuscript.

* Corresponding author. Present address: Department of Radiology, Hadassah–Hebrew University, Medical Center, Jerusalem 91120, Israel. Tel.: +972 2 677 6901; fax: +972 2 643 7531.
E-mail address: ROZ@hadassah.org.il (K. Rozovsky).

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We searched our radiology database to identify children aged 0 to 5 years who underwent FIESTA MRI of the brain in 2 or 3 planes between January 2008 and August 2010. Studies performed for assessment of shunt position and of the size and configuration of fluid-filled structures, without gadolinium administration and without general anesthesia or sedation, were included. We excluded MRI performed in patients older than 5 years, those performed under general anesthesia or sedation at any age, and FIESTA studies performed for clinical indications other than assessment of the ventricular system and extra-axial CSF spaces.

2.2. Imaging protocol

All MRI were performed using a 1.5-Tesla MRI (Signa Excite HD, GE Healthcare, Milwaukee, WI, USA). The routine short FIESTA protocol included 3-plane acquisition in axial, coronal, and sagittal views; 22-cm field of view; 5-mm slice thickness, 1-mm gap; matrix 2.24×3.20; two excitations; echo time $\geqslant 1.8$ ms; 70° flip angle; and 83.33 MHz bandwidth. The total number of slices for a 3-plane study was 60 to 72, depending on patient size. Acquisition time was approximately 15 s for a single plane of the entire brain and less than 2 minutes for the 3-plane acquisition.

The FIESTA protocol on GE MRI systems is analogous to balanced Fast Field Echo (FFE) protocols on Phillips MRI systems, true Fast Imaging with Steady-state Precession (FISP) or Multiple-Echo Data Image Combination (MEDIC) protocols on Siemens systems, true Steady State Free precession (SSFP) studies on Toshiba MRI, and BAlanced SarGe (Spoiled steady state Acquisition Rewinded Gradient Echo) (BASG) sequences on Hitachi MRI systems.

2.3. Image interpretation

FIESTA examinations were reviewed in detail by a clinical fellow (K.R., with 5 years' experience in pediatric radiology) and a pediatric neuroradiologist (E.M., with 10 years' experience in pediatric radiology and 4 years' experience in neuroradiology). Radiologists had knowledge of the clinical indications for each study but were blinded to previously reported findings. Their interpretations were subsequently compared to findings reported in Picture Archiving and Communication System (PACS) image record. All studies were compared to the most recent MRI or CT study, which served as a reference standard. Disagreements between readers and between the new interpretation and original report were resolved in consensus.

In all patients, the size and configuration of fluid-filled structures, including the ventricles and cisterns as well as fluid-filled lesions, were noted. In children evaluated following ventriculoperitoneal (VP) shunt insertion, shunt position was evaluated. Images were also reviewed to identify any structural abnormality or signal changes that could be interpreted as unusual or pathological findings, and these findings were recorded.

2.4. Literature review

In addition, we conducted a search of the literature using PubMed and Medline databases, with the keywords "short" or "fast" or "quick" or "rapid" or "ultrafast" or "FIESTA brain MRI", or "MR" or "imaging" or "magnetic" or "magnetic resonance imaging"; "without sedation" or "non-sedated" or "nonsedated" or "unsedated" or "without anesthesia"; "pediatric" or "children" or "infant" (birth to 23 months) or "preschool child" (2 to 5 years).

3. Results

The search of hospital records identified 50 FIESTA studies performed in 30 non-sedated pediatric patients that met the inclusion criteria.

The 30 children undergoing the FIESTA studies without sedation included 21 males and nine females, of ages ranging from 1 day to 5 years (mean: 18 months). The studies included in this analysis were ordered by the neurosurgeons for very specific indications, including status after shunt insertion/revision ($n = 11$), follow-up of shunt-dependent hydrocephalus ($n = 9$), non-shunt-related postoperative follow-up ($n = 9$), complications of prematurity ($n = 6$), macrocephaly ($n = 6$), congenital structural malformation ($n = 4$), and follow-up of isolated ventriculomegaly ($n = 5$).

In all cases, the FIESTA study provided a satisfactory answer to the clinical question. The size and configuration of the ventricular system, extra-axial collections and cysts were successfully evaluated in all 30 children. In five of six patients with macrocephaly, the FIESTA study was sufficient to exclude hydrocephalus and gross pathological abnormalities; in one of six cases fast-brain MRI diagnosed a vein of Galen malformation and the patient was referred for further imaging evaluation. Adequate follow-up and assessment of fluid-filled structures were provided in patients with known isolated ventriculomegaly (five patients), with ventriculomegaly as a complication of prematurity (six cases), and with congenital malformations (four patients) such as arachnoid cyst, vein of Galen malformation, achondroplasia, or borderline narrowing of the aqueduct. FIESTA studies also enabled assessment of the size of fluid-filled structures in non-shunt related postoperative patients (nine patients).

Shunt position and ventricular size were adequately assessed in 20/20 patients with shunt-dependent hydrocephalus.

There were additional undetected or underestimated pathological findings in eight studies of seven children, including six of 11 children evaluated from 1 to 60 days after VP shunt insertion or revision and one child in follow-up after craniotomy and subdural hematoma (SDH) evacuation due to traumatic brain injury (TBI) (Table 1).

In a 2-month-old premature male (36 weeks gestation) with aqueductal stenosis and multiple sites of bleeding post shunt insertion, FIESTA MRI failed to detect a thrombosis in the transverse sinus on two consecutive studies performed 3 days and 7 days after shunt insertion (Patient 1, Fig. 1).

FIESTA MRI underdiagnosed SDH in two children, including a 10-month-old term female with Chiari 1 malformation who was 12 days post VP shunt insertion (Patient 2, Fig. 2), and a 10-month-old term male with Costello syndrome and Chiari 1 malformation who was 3 weeks post shunt insertion.

In two children (Patients 4 and 5), there was limited evaluation of extra-axial space dilatation, with failure to differentiate blood products from CSF. Both children were premature, of 28 weeks and 26 weeks gestation, and were imaged at ages 5 months and 4 months corrected age, respectively. Both studies were after shunt insertion. No clinical or imaging follow-up was available for Patient 4. In Patient 5, CT scans and MRI performed during a 2-month period after the FIESTA study demonstrated bilateral SDH of different ages.

In a 6-month-old premature female (26 weeks gestation, Patient 6) with a history of Grade 4 intraventricular hemorrhage and VP shunt insertion, FIESTA brain MRI obtained 8 weeks post shunt insertion showed bilateral subdural collections of different signal intensity. However, the study did not enable evaluation of the age of extra-axial bleeding.

In a 3-month-old full term male who was 8 weeks post craniotomy and evacuation of SDH, FIESTA MRI provided only limited evaluation of a growing extra-axial space dilatation, with failure to differentiate blood products from CSF (Patient 7, Fig. 3).

4. Discussion

We present a series of 50 fast MRI FIESTA studies performed in 30 children, including 21 studies of patients without previous

Table 1
Clinical and imaging findings in patients with underestimated findings on fast-brain MRI

Patient no.	Age, gender	Clinical background	Indication	Findings	Limitations
1	2 m, M	Ex 36 weeks GA prematurity, VPS for aqueductal stenosis. CT 1st day after shunt: parenchymal bleeding	AVPSp 3 and 7 days post VPS insertion	No change in VM. Two areas of heterogeneous signal in the left parietal lobe, suspicious for bleeding.	Failure to visualize left transverse sinus vein thrombosis in two consecutive 3-plane FIESTA studies 4 day interval. Sinus vein thrombosis diagnosed on F/U CT study.
2	10 m, F	Term, Chiari 1 malformation, hydrocephalus, VPS	AVPSp 12 days post VPS insertion	Improvement of VM, increase of extra-axial CSF spaces. Left temporoparietal extra-axial collection?	Failure to visualize left temporoparietal SDH. Chronic SDH seen on F/U complete MRI 2 weeks later.
3	10 m, M	Term, Costello syndrome, hydrocephalus, Chiari 1 malformation, VPS	Assess ventricular size 27 days post VPS insertion	Mild reduction of VM. Prominence of extra-axial CSF spaces.	Failure to visualize small frontal SDH seen on T1w MRI, same day.
4	5 m, M	Ex preterm 28 weeks, IVH grade 4, VPS	AVPSp 7 days post VPS insertion	Decreased VM. Large bilateral extra-axial subdural fluid collections. Slight right midline shift.	Limited evaluation of extra-axial collections. Failure to differentiate blood products from CSF in space dilatation. No clinical, imaging F/U.
5	4 m, M	Ex 26 weeks GA prematurity, IVH grade 4, VPS	AVPSp1 day post insertion	Decreased VM. 2 small extra axial collections adjacent to falx.	Limited evaluation of extra-axial collections, failure to differentiate blood products from CSF in space dilatation. F/U CT and complete MRI 2 months later demonstrated bilateral SDH of different ages.
6	6 m, M	Ex 26 weeks GA prematurity, IVH grade 4, VPS	AVPSp 6 m post insertion	Improvement of VM. Different signal intensity of bilateral subdural collections.	Limited evaluation of aging of extra-axial bleeding. F/U CT scan 6 days later demonstrated SDH of different ages.
7	3 m, F	Term, TBI, right decompressive craniotomy and evacuation of SDH	F/U surgery 2 m postop	Increase in size and bulging of extra-axial spaces and parenchyma at the craniotomy site, worse than in CT scan obtained 45 days earlier.	Limited evaluation of extra-axial collections, failure to differentiate blood products from CSF in space dilatation. F/U complete MRI from the same date negative for bleed.

AVPSp = assess VPS position, CSF = cerebrospinal fluid, Ex = history of, FIESTA = Fast Imaging Employing Steady sTate Acquistion, F/U = follow-up, GA = gestational age, IVH = intraventricular hemorrhage, m = months, M = male, postop = postoperative, SDH = subdural hematoma, T1w = T1-weighted, TBI = traumatic brain injury, VM = ventriculomegaly, VPS = ventriculoperitoneal shunt.

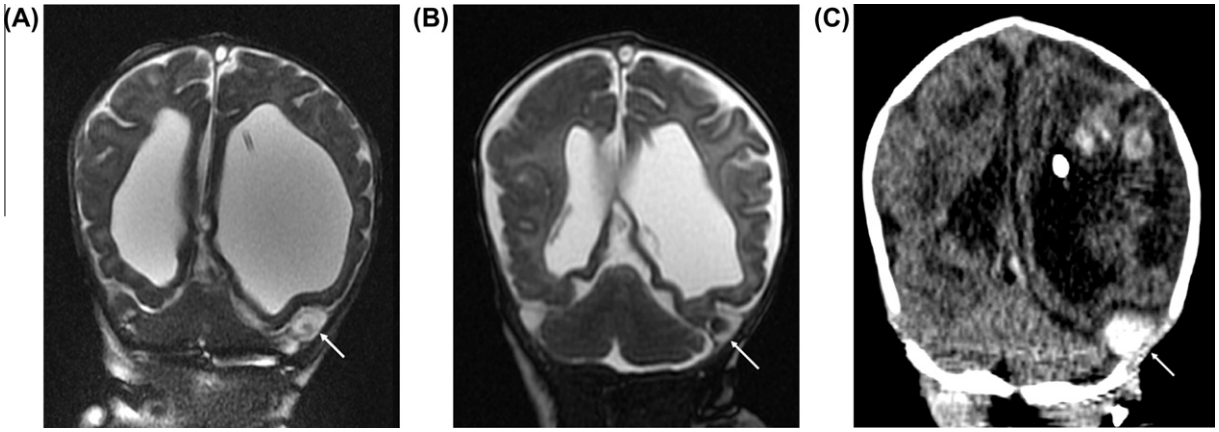

Fig. 1. Images of a 2-month-old male, premature, 36 weeks gestation, with aqueductal stenosis and multiple sites of bleed post shunt (Patient 1). (A) Coronal Fast Imaging Employing Steady sTate Acquisition (FIESTA) brain MRI 3 days post ventriculperitoneal (VP) shunt insertion; retrospectively, there was suspicion of thrombosis in the left transverse sinus (arrow). (B) Coronal FIESTA brain MRI 7 days post VP shunt insertion; retrospectively, there was suspicion of left transverse sinus thrombosis (arrow). (C) Axial non-contrast CT scan 7 days post VP shunt insertion showing thrombosis of the left transverse sinus (arrow) and parenchymal bleeding.

history of surgical intervention, nine studies of children with shunt-dependant hydrocephalus, 11 studies performed for evaluation of recently inserted VP shunts, and nine studies for follow-up after surgical procedures not related to shunt placement. For patients with recent surgery, FIESTA studies provided good assessment of VP shunt and ventricle status; however, in eight studies performed in seven patients aged 2 months to 10 months, potentially important pathological findings were underestimated or missed with our fast MRI protocol. The primary limitations were an inability to differentiate between blood products and CSF in patients with enlarged extra-axial space dilatation, inability to determine the age of intracranial hemorrhage, and failure to detect venous sinus thrombosis.

Fast-brain MRI has become an important part of clinical practice in many pediatric centers. Initially, it was used for hydrocephalus and shunt assessment[1–4,9] Review of the literature showed that it is now also commonly used for non-hydrocephalic indications, such as macrocephaly, intracranial cysts, follow-up of congenital

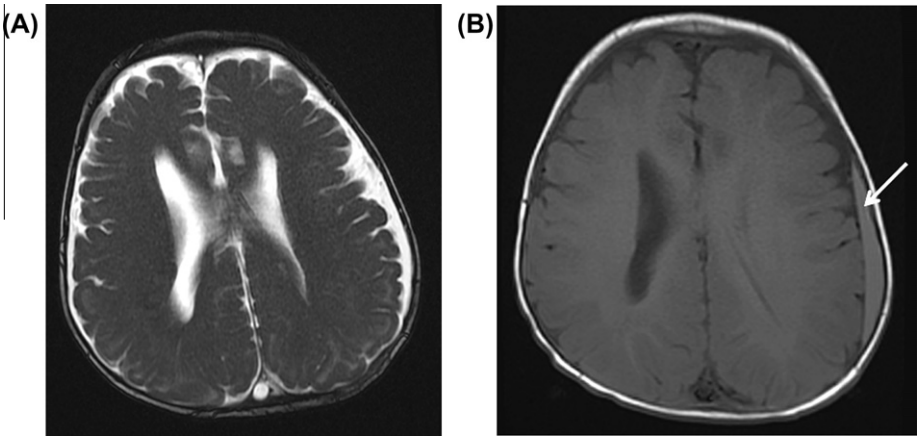

Fig. 2. Axial images of a 10-month-old term female with Chiari 1 malformation, 12 days post ventriculperitoneal (VP) shunt insertion (Patient 2). (A) Fast Imaging Employing Steady sTate Acquistion (FIESTA) brain MRI showing prominent extra-axial cerebrospinal fluid spaces, especially on the left side. (B) T1-weighted MRI performed 2 weeks later showing chronic left temporoparietal subdural hematoma (arrow).

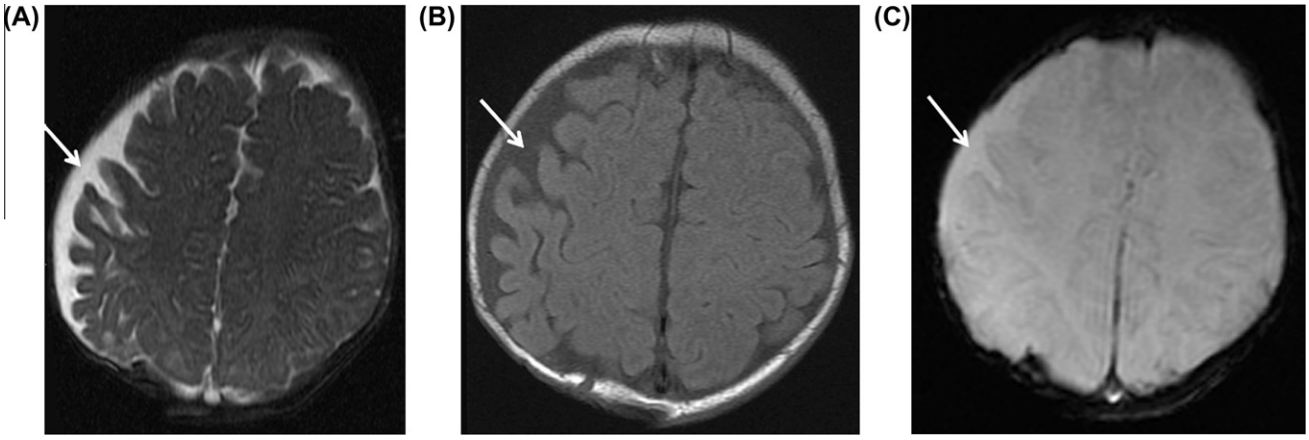

Fig. 3. Axial images of a 3-month-old female with a history of traumatic brain injury, 2 months after right decompressive craniotomy and evacuation of a subdural hematoma (Patient 7). (A) Fast Imaging Employing sTeady State Acquistion brain MRI showing dilatation of extra-axial cerebrospinal (CSF) spaces at the craniotomy site (arrow). The CSF spaces were increased in size in comparison to a previous study (not shown); however, we were unable to rule out or confirm new bleeding. (B) T1-weighted MRI performed on the same date showing no evidence of bleeding (arrow). (C) Gradient echo sequence on the same date showing that a blooming artifact, suggestive of blood products, is not seen (arrow).

structural anomalies, screening prior to lumbar puncture (to exclude increased intracranial pressure), and postoperative follow-up.[8]

The advantage of performing fast-brain MRI is the very short acquisition time, usually less than 1 minute, obviating the need to obtain a CT study and, therefore, reducing the exposure to radiation in young children. It is also a promising protocol as it avoids sedation, which is often required for a complete MRI study in pediatric patients.

Several "fast MRI" protocols have been described; the most popular are modifications of T2-weighted MRI, including Half-Fourier Acquisition Single-shot Turbo Spin Echo (HASTE),[9] Single Shot Fast Spin Echo (SSFSE),[3,8] and Periodically Rotated Overlapping Parallel lines with enhanced reconstruction (PROP) FSE.[2] Ashley et al.[1] used a combination of HASTE T2-weighted and Turbo-Fast Low-Angle SHot (FLASH) T1-weighted MRI for evaluation of shunt-dependent hydrocephalus. Miller et al.[4] reported on improved delineation of ventricular shunt catheters using a combination of single-shot TSE T2-weighted MRI and fast, post-excitation refocused Steady-State Gradient-Echo sequence (SS-GRE) imaging.

At our institution, a short MRI has become a routine part of our clinical practice and is important in evaluating pediatric neurosurgical patients. Mostly the study indications specified by referring neurosurgeons are ventricular size assessment and evaluation of VP shunt position. Our results, as well as reports from others,[1–4,9] have confirmed the usefulness of FIESTA image protocols for these indications.

We also began to receive referrals to fast MRI for other clinical indications, including young patients with macrocephaly, in which ultrasound is insufficient due to a small or closed fontanelle and CT scans would be the next imaging of choice. In our series, in five of six children, this short MRI without sedation was sufficient to exclude hydrocephalus and gross pathological abnormalities, giving the clinician adequate information and avoiding the need for more imaging, and in one patient short MRI diagnosed a vein of Galen malformation. This patient was referred for a full MRI study under anesthesia.

The FIESTA fast MRI protocol also provided good follow-up in patients with known isolated ventriculomegaly (five patients). It was useful for follow-up of some congenital structural malformations (four patients) such as arachnoid cyst, vein of Galen malformation, achondroplasia, and borderline narrowing of the aqueduct, in which the clinical interest was to assess ventricular size or size of the fluid-filled intracranial cyst.

In all these patients the initial diagnosis was made using full-protocol brain MRI. Radiologists cannot expect that fast sequences can confirm or exclude congenital cortical malformations, migration anomalies, or brain neoplasm.

Our institutional protocol includes a 3-plane FIESTA MRI, which provides good anatomic resolution and allows quick assessment of fluid-filled intracranial structures. But this sequence provides poor contrast resolution, especially for evaluation of blood products or unexpected findings like cerebral venous thrombosis. These limitations are common in most ''fast-brain'' protocols; hence our interest in creating awareness of potential undetected or underestimated pathological findings. The most common problem using a single type of short sequence is poor differentiation of CSF from blood products.

In a comparison of T2-weighted MRI such as conventional FSE, SSFSE, and Single-Shot T2-GRAdient-Spin-Echo (SS-GRASE), Ba-Ssalamah et al.[10] consistently noted limited evaluation of blood products. They found better results using the SS-GRASE technique. Iskandar et al.[3] discussed limitations of fast-brain T2-weighted MRI, and mentioned its relative insensitivity to blood products, air, calcifications, and implanted devices. They proposed that fast-brain MRI should be complemented with CT scans to rule out hemorrhage or hydrocephalus in patients with evidence of postoperative neurological deterioration.

Ashley et al.[1] used a combination of short turbo-flash T1-weighted and HASTE T2-weighted MRI. They found that the T1-weighted MRI were better suited for catheter visualization, whereas T2-weighted MRI were more sensitive for ventricular assessment. Singh et al.[11] used axial and coronal T2-weighted SSFSE and axial T1-weighted echo planar imaging for detection of a range of brain anomalies, and stated that ultrafast imaging is very limited in showing SAH; however in three of three patients, parenchymal bleeding was successfully detected.

In view of our findings and other reports, the recommendation for patients who are post shunt insertion or post surgery should be to add a short T1-weighted MRI in at least one imaging plane to better differentiate between blood and CSF. Alternatively, a short gradient sequence could be implemented.

To our knowledge, the English literature does not describe the pitfalls of using these sequences, except for Missios et al.,[8] who reported missed findings in two patients out of 457. Complete MRI of the brain revealed a small subdural hemorrhage and a cerebral vein thrombosis that were not recognized in the fast-brain studies.

In our series, in all but one, it was difficult to recognize or classify extra-axial fluid collections in subdural or subarachnoid spaces. The poor differentiation of subdural versus subarachnoid space dilatation and the limited evaluation of signal characteristics are two clinically important limitations of the FIESTA sequences. The proper and prompt diagnosis of subdural bleeding can potentially change clinical management.[12] Very young infants are especially prone to develop SDH, probably due to the immaturity of arachnoid villi in pretoddlers.[13]

Subdural CSF collections tend to appear 3 to 28 days (mean: 7 days) after surgery and are not necessarily appreciated immediately after the intervention. This complication is also more frequent in young infants.[14] The differentiation between these two conditions was extremely difficult or impossible with only the short FIESTA sequence.

In one infant we found cerebral venous sinus thrombosis associated with bleeding that was difficult to diagnose with FIESTA, even when retrospectively reviewed. That the finding was overlooked by two experienced pediatric radiologists emphasizes the importance of awareness of very subtle findings with potential for significant morbidity,[15,16] when interpreting these short sequences.

Prematurity is another risk factor that should be taken into account when reading these images, as premature infants are prone to increased postoperative complications.[17] In our study, four of seven patients with undetected or underestimated pathological findings on FIESTA MRI were born prematurely (Table 1).

It is difficult to adequately evaluate the clinical significance of missed findings in our patients. In most cases, knowledge of venous sinus thrombosis and acute or chronic extra-axial hematoma, as well as the timing of bleeding, should change follow-up frequency and in some cases can significantly change the treatment plan.

The limitations of our study include a small patient population, use of only one type of short MRI, the lack of a consistent reference standard for this retrospective evaluation, and lack of follow-up in one patient with unclear findings on the FIESTA study.

In conclusion, short MRI in pediatric patients are a very useful tool, especially in young children who would require sedation for a complete MRI, and to avoid the radiation burden of a CT scan. In our experience, fast-brain FIESTA studies provided good assessment of VP shunt position as well as size and configuration of fluid-filled structures; however, they did not allow differentiation between CSF and blood products. In children with risk of intracranial bleeding, fast-brain studies should be used with caution. Our recommendation is to combine a fast T2-weighted (FIESTA or HASTE) MRI with a fast-shot gradient or T1-weighted study in at least one imaging plane, especially in infants born prematurely and postoperative patients, to rule out hemorrhage and thrombosis. Protocols should be optimized in these patients, and clinicians and radiologists ordering fast MRI studies should be aware of their limitations.

Conflicts of interest/disclosures

The authors declare that they have no financial or other conflicts of interest in relation to this research and its publication.

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