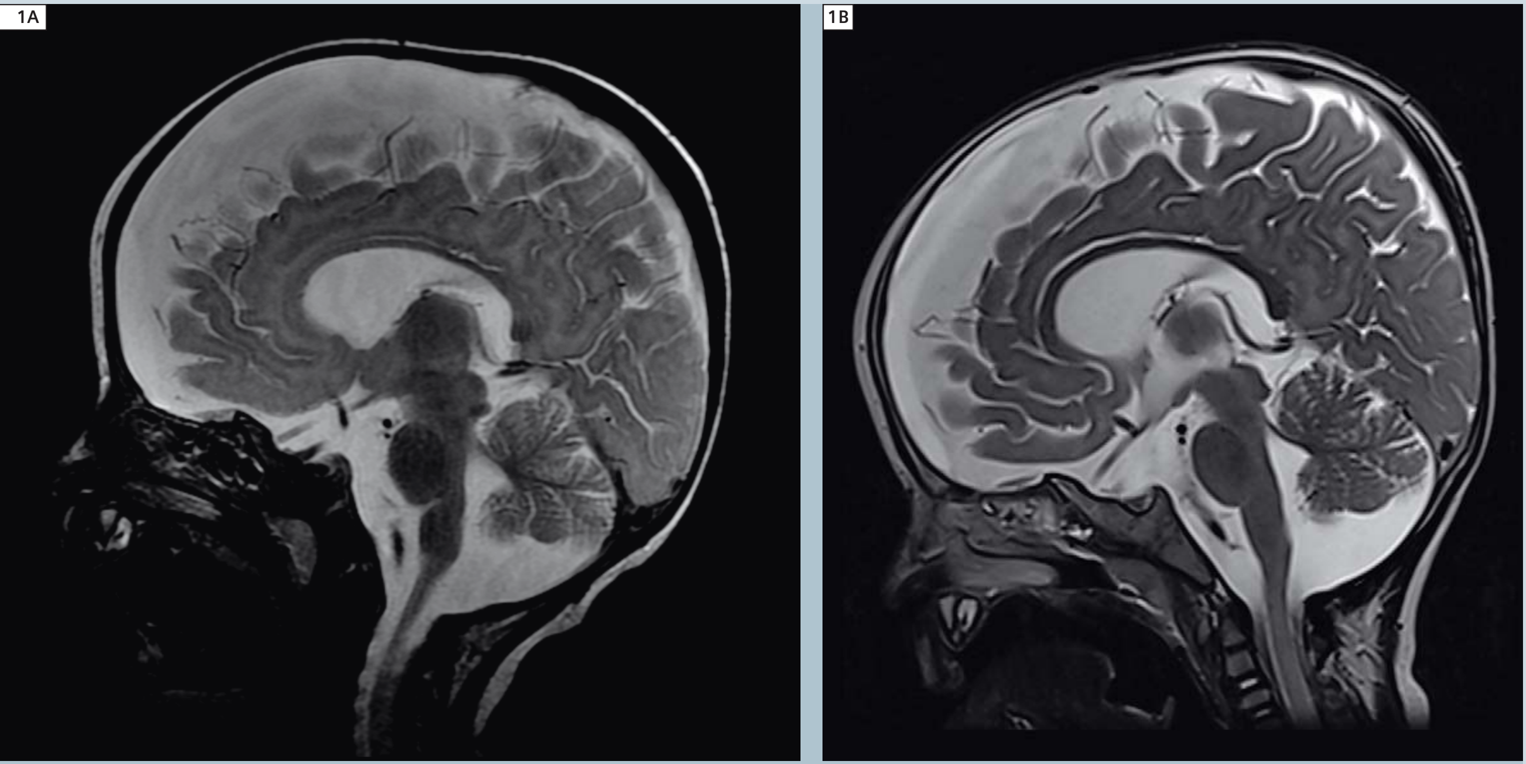

1 Longer TR and TE times are generally required when imaging very young children. The high water content in neonatal brains, coupled with the lack of fatty myelin results in a reduction in contrast-to-noise ratio (CNR) and grey/white matter differentiation. Restore pulses on T2w imaging can improve CSF contrast and allow shorter TR times to reduce scan time.

Techniques in Pediatric MRI – Tips for Imaging Children

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Magnetic resonance imaging (MRI) examinations of children require a particular set of skills and expertise in order to successfully obtain diagnostic images with minimal distress to the patients and their family. There have been many developments in MRI in recent years, which have lead to a dramatic increase in the number and types of referrals we are now seeing for pediatric MR examinations. This paper provides an overview of the challenges that pediatric patients raise in the MR setting, and some of the different techniques that may be employed to overcome these difficulties. While some technical modifications are described, the focus is on practical recommendations that can assist young children to comply with the MR procedure, and minimize the use of anesthesia with this vulnerable population. Pediatric MR imaging can be considered a series of subspecialties. Each area, neurology, cardiac, MSK, oncology, all have their own subtle nuances that alter as patients mature. In our facility we routinely scan patients from the early fetal* stages right through to young (and not so young) adults with complex congenital conditions. Each of these fields, and stages of development requires their own specialized skills, knowledge, and equipment to be performed appropriately, however, there is a number of common challenges and techniques that apply to imaging pediatric patients.

Challenges of scanning children

Safety

MRI of children poses a number of specific safety issues with patient heating being the primary concern. Neonates and infants in particular have immature thermoregulation mechanisms, and higher core body temperatures making them particularly sensitive to RF heating effects [1]. These mechanisms are further affected by sedation and anesthesia common in pediatric imaging [2], or when babies are swaddled for imaging [1]. Children also have a greater surface area to weight ratio than adults. This means for a given weight we often need to expose a greater surface area of the patients to the RF field. This can lead to increased heating in children, and decrease their ability to dissipate this heat. There is intrinsic uncertainty in current specific absorption rate (SAR) predictions based on extrapolated data from phantom models [3] particularly due to factors such as body shape, size, composition, and position within the MR scanner. While definitive data on safety risks are not yet available, close monitoring of children, particularly critically ill or compromised infants, is desirable when using higher field strengths and high SAR scan techniques [1].
Anesthesia is an important safety consideration in pediatric MRI. While serious complications such as death are rare, there are significantly higher rates of morbidity, particularly amongst neonates, when compared to adult anesthesia [2]. Aside from adverse events there are a number of common side effects including nausea, vomiting, drowsiness and agitation upon awakening, which affect about one third of pediatric patients [2]. The challenge of monitoring patients in the MR environment coupled with the reduced ability for the patient to communicate adverse events creates significant additional risks [4]. If sedation is required, the associated risks need to be taken into account when deciding to image young children.

Anatomy

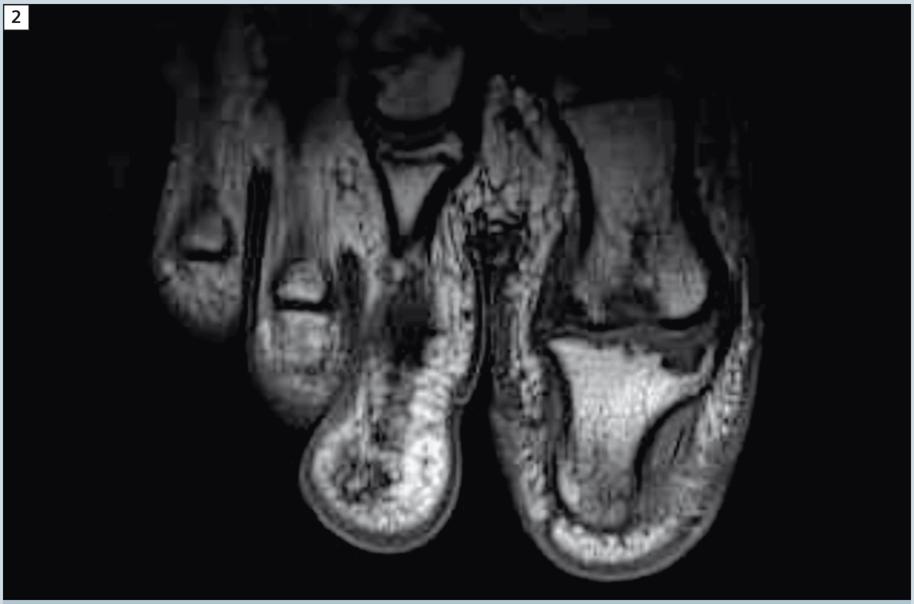
Normal structures in children are smaller than in the average adult. This creates a challenge both in terms of the available signal, and the limits of our scan resolution. Anatomy is further complicated by congenital anomalies and malformations as well as developmental changes [5].
At birth we are about 75% water and we dry out as we age to about 55–65% water for an average adult. This is best appreciated in the neonatal brain. The high water content, and lack of fatty myelin, requires an increase in TE on T2-weighted imaging to around 150–160 ms to improve contrast. With so much of the available hydrogen in loosely bound water, there often is not much to influence relaxation. The use of fast recovery (restore) pulses at the end of the echo train improves the signal-to-noise ratio (SNR) while allowing for shorter TRs to be used (Fig. 1).
T1 contrast can be particularly flat requiring an increase in TR to around 1,200 ms at 1.5 Tesla. The use of inversion recovery techniques, and magnetization prepared 3D imaging such as MPRAGE, are evident at many institutions, particularly at higher field strengths [5].

Pathology

Children are notoriously poor reporters of symptomatology, and their often vague and non-specific symptoms can belie the seriousness of their condition. Clinical examination is often very difficult, so MRI requests are seldom specific. There are many transient appearances on MR images that can be considered normal at some stages of development and abnormal at others. Recognizing the appearance of normal from abnormal development on MR images and determining the optimal sequences and factors to best display them presents a challenge to technologists with little pediatric experience.
An awareness of the conditions that are commonly found in the pediatric population is necessary to tailor scans appropriately.

Physiology

Pulse rate, blood flow, and respiration rates are considerably faster in children, with normal heart rates that can be in excess of 140 bpm and respiratory rates of 40/min [5]. Children typically find it difficult to satisfactorily hold their breath, creating significant challenges in cardiac,



2 Coronal PD-weighted image of an osteo-chondral defect (OCD) of the distal phalynx of the right toe.

chest and abdominal imaging. Increased flow rates lead to artifacts from blood vessels and cerebrospinal fluid (CSF) pulsations, creating difficulties with spine and Time-of-Flight (TOF) vessel imaging [5]. Differences and evolution in pediatric physiology may also lead wto changes in the mechanism of injury, or the types of injuries that occur in children, such as growth plate injuries and osteo-chondral defects (OCD) [6].

Behavioral

Sedation or anesthetic is commonly required for younger children or those with significant behavioral problems. Factors such as temperament, stress, pain, and illness play an important role in patient compliance, creating difficulties in establishing definitive age limits for identifying which children will require these procedures [7]. Encouraging children to co-operate for an MRI examination and identifying those who cannot are arguably the most significant challenges in pediatric MRI.

Techniques in scanning children without sedation

Preparation

At our institution we begin scanning without sedation from about five years of age, although some positive outcomes have been obtained with patients as young as three years. Adequate preparation of children for the MRI procedure has been vital in achieving these results. Our facility employs the services of educational play therapists who use a range of resources to assist children to comply with the procedure, such as brochures, MRI toys and storybooks, discussions with parents, and, most importantly, the 'mock MRI' procedure.

Simulation

The 'mock MRI' procedure involves children undergoing a simulated scan with the assistance of a play therapist prior to the actual diagnostic scan. It acts as both a screening tool, to assist in identifying children who are likely to be able to comply with the MRI procedure, and also helps to prepare these children, by familiarizing them with the environment, sounds, and equipment, while teaching them skills (such as breathing, relaxation, or distraction) to cope with the actual procedure (Fig. 2). Use of the 'mock' magnet has led to a marked reduction in the numbers of patients who have required anesthetic [7] and reduced the time required for the diagnostic scan [8]. Several pediatric facilities in various countries have introduced a mock procedure in their facilities in recent years [9].

Communication

Specialist staff and equipment are clearly helpful in assisting children to comply with an MR scan. However, for technologists, an awareness of how to talk to children and adolescents at different stages of development and the use of psychological techniques, such as distraction and relaxation, can be the critical factor determining whether a young person is willing, or able, to carry out the procedure. Many children are withdrawn or uncommunicative when nervous about a medical procedure, and taking the time to help the child to feel safe and secure in the environment is important. Compliance with preschool children may be facilitated by engaging in pretend play, where the child can be encouraged to frame the experience in familiar and non-threatening ways [10]. Nonverbal communication comprises a significant proportion of a child's interaction with the world at this stage, and young children can pick up on their parents' anxiety or the technologist's impatience through nonverbal clues. They may not understand these feelings and can interpret them as anger or fear of the examination. Professionals who work with children typically take steps to ensure that both their verbal communication and body

3

3 Mock MRI simulator – this procedure identifies patients that are able to comply with the requirements of an MRI examination, as well as prepare them for the clinical scan, saving unnecessary appointments and valuable scanner time.

Table 1: Communicating with children

Engage with the child	Get down on their level	Use simple language	Maintain eye contact
Frame the experience	Help them verbalize their experience	Involve the child's past experiences / play	Smile
Empower the child	Offer limited choices	Praise good behavior	Be positive "I know you can do this"

language are reassuring and convey calmness and confidence (Table 1). Positive reinforcement, where the child is praised for their efforts at each step, can be very helpful.
School age children are able to engage more actively in the procedure, and may respond well to efforts to increase their perceived control. Medical examinations often take the locus of control away from the patient, and this is particularly true in pediatrics where someone else usually makes the decisions for the patient. Empowering children by offering some choice in how they can have the scan can be helpful. This is particularly important during adolescence; a period of rapid social and physical changes [10], when increased autonomy is important, yet can be hampered by serious illness. Adolescents are less likely than children or adults to blindly follow instructions, and may be reluctant to accept or comply with the scan in the absence of a flexible approach, where the technologist is sensitive to their concerns.

Distraction and relaxation

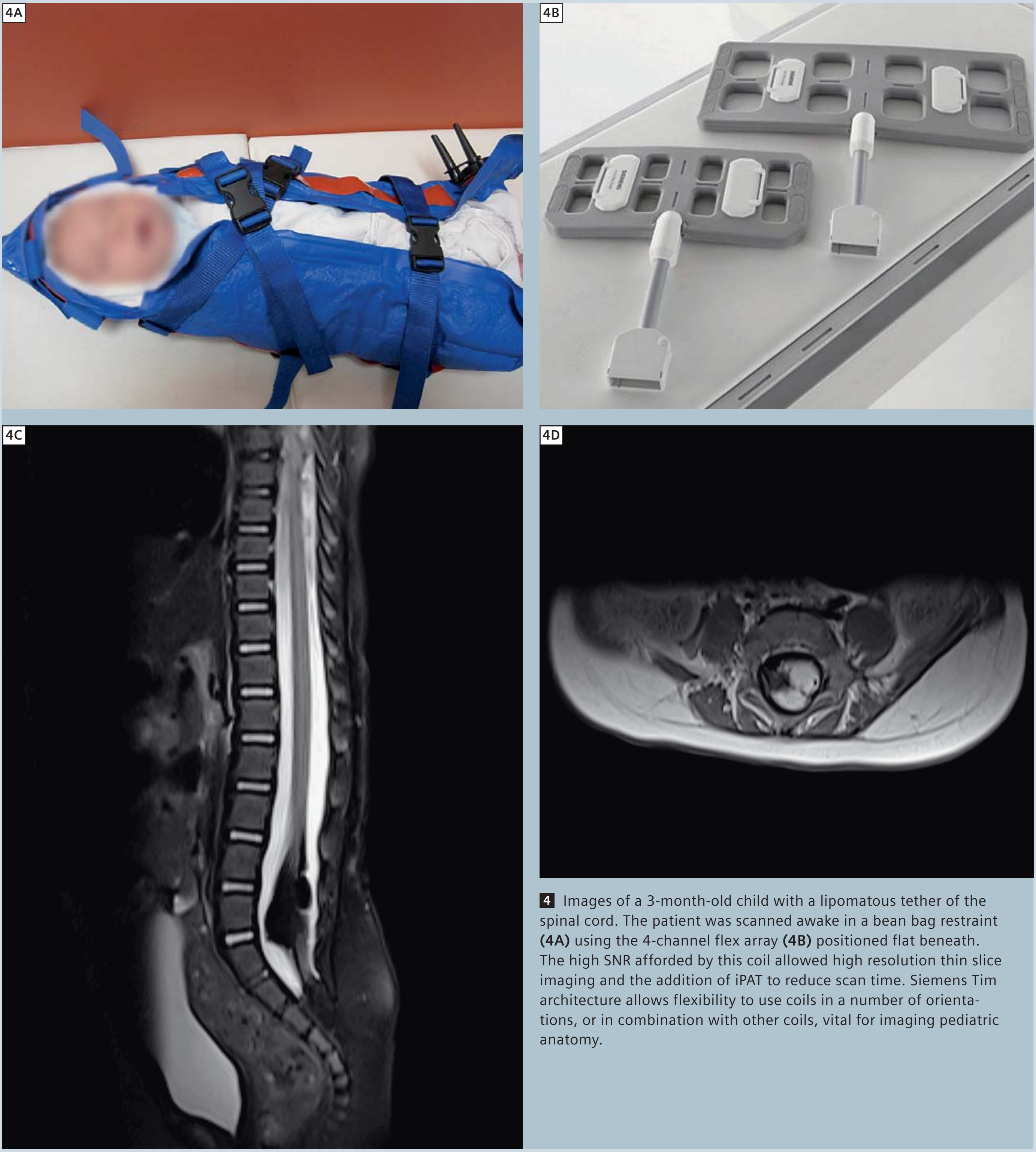
Distraction can be a powerful tool for reducing anxiety and increasing patient compliance. Distraction techniques can be either active or passive. Passive techniques such as audiovisual aids are useful during the scan when patients are required to lie still in the bore. Having a point of interest (such as a parent or video screen) is helpful in maintaining the patient in one position. Active techniques which require patient participation such as relaxation breathing, guided imagery, or complex puzzle tasks, are useful in relaxing children before MRI or performing interventions such as intravenous cannulation and general anesthetic (GA) inductions.

Successful use of intravenous (IV) contrast

IV cannulation is a major cause of anxiety in young patients presenting for MRI examination. Limiting the use of IV contrast in pediatric examinations can often mean the difference between a successful awake scan and a rebook for sedation. This requires the support of the radiologists to make decisions regarding whether the benefits of contrast are worth the potential distress to the patient. Where contrast is necessary, it is often helpful to separate the procedures of IV placement and the MR exam by either placing the cannula before the examination or offering a break between the pre and post contrast scans. Many children respond well to being able to choose an IV site. Active distraction techniques can be helpful, and there are several aids available to assist with the pain, such as local anesthetic creams, ice, or nitrous oxide.

Protocols and sequences

Protocol based scanning can be difficult in presenting pediatric patients, as the required sequences differ dramatically depending upon pathology, patient age, compliance, and the clinical questions being asked. It is often necessary for the technologist or radiologist to screen the examination as it progresses and tailor the sequences for the patient and pathology. A wide field-of-view scan can be helpful to obtain an overview to screen for other pathologies, particularly in children who are difficult to examine clinically. Children can be unpredictable in how long they will remain still, so it is important to prioritize sequences with the highest diagnostic yield such as T2, FLAIR, and diffusion. Scanning in multiple planes or using 3D sequences can help delineate disorders as well as minimize the chance of pathology being missed through partial voluming or interslice gap.
Often it is necessary to modify a protocol or sequence when imaging children of different sizes or capabilities. It is important to strike a balance between optimum image resolution and scan time.



4 Images of a 3-month-old child with a lipomatous tether of the spinal cord. The patient was scanned awake in a bean bag restraint **(4A)** using the 4-channel flex array **(4B)** positioned flat beneath. The high SNR afforded by this coil allowed high resolution thin slice imaging and the addition of iPAT to reduce scan time. Siemens Tim architecture allows flexibility to use coils in a number of orientations, or in combination with other coils, vital for imaging pediatric anatomy.

When modifying pulse sequences, the following suggestions may be helpful:

- Select pulse sequences that closely match the FOV required and the coil being used. The less changes you need to make to a sequence, the less chance for error.
- Concentrate on maintaining voxel size and signal-to-noise when changing field-of-view or matrix size, and consider using interpolation to maintain signal and resolution. The day optimizing throughput (Dot) engines on the newer Siemens scanners can be used to automate many of these decisions.
- Utilize recovery pulses, where available, to achieve reduction in TR times and to collect the images in multiple concatenations. When combined with interleaving this dramatically reduces the chance of crosstalk when using minimal slice gaps.
- Use the shortest TE that will maintain image contrast to boost signal and reduce image blur.

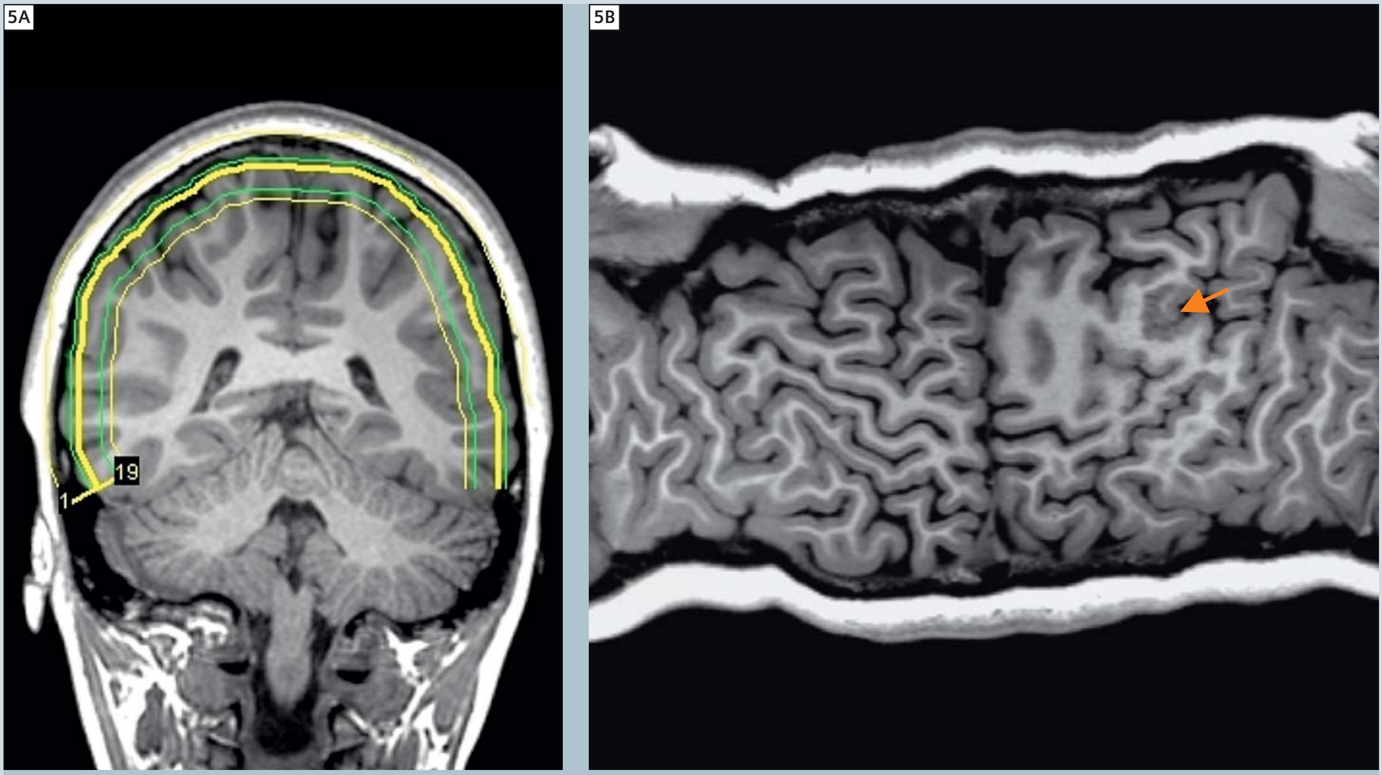
Scanning techniques

Coil selection

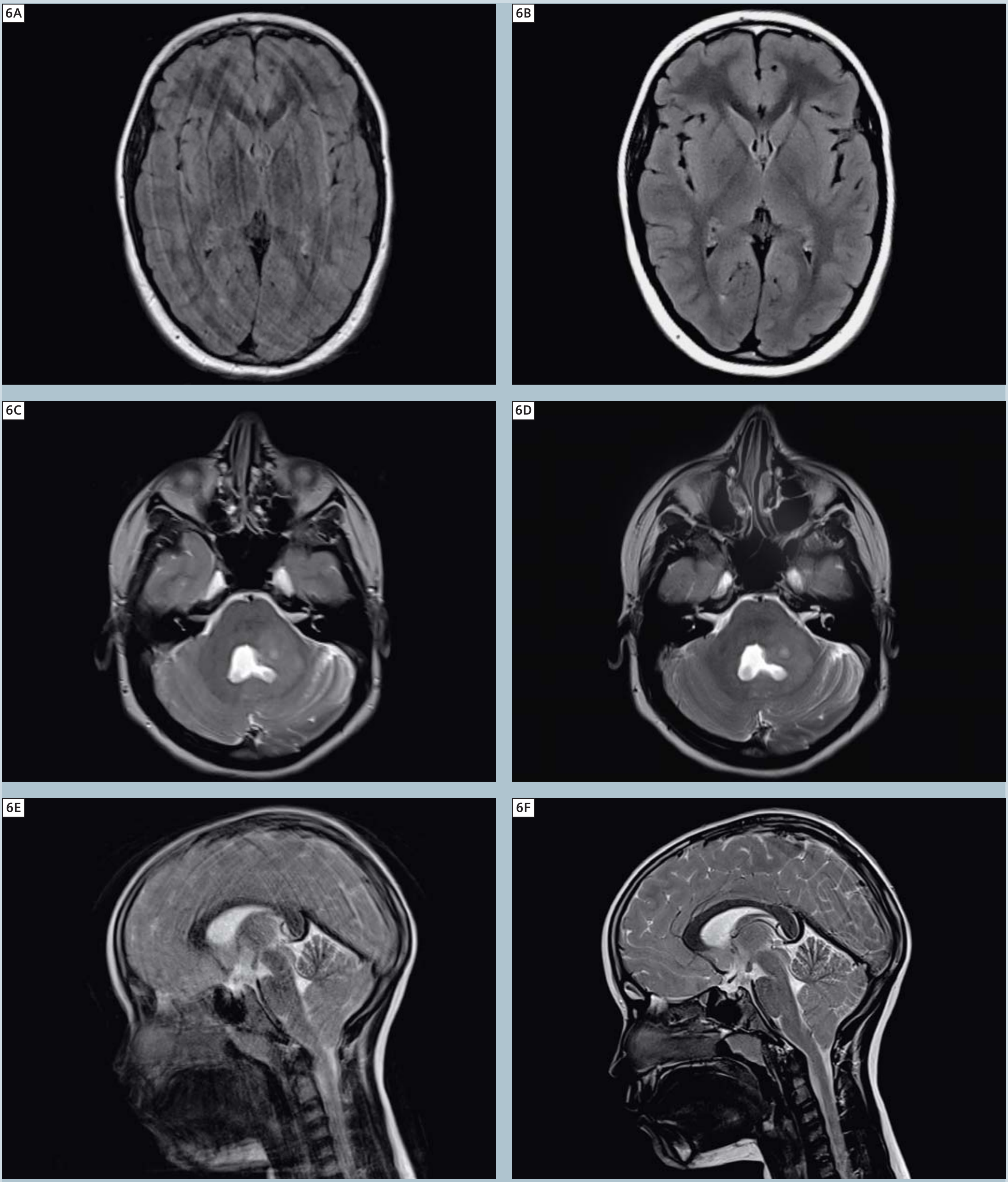
Novel uses of MR coils are possible and often necessary in pediatric imaging. Choosing a coil that closely matches the FOV you are imaging is important in extracting the maximum signal from your patients. Use of multichannel arrays is desirable when available to take advantage of parallel imaging techniques (Fig. 4).

Volume imaging

3D imaging can be utilized in all areas of the body. The use of 3D sequences permits reformatting, which can be helpful



5 Volume imaging: Reformatting of 3D imaging is useful in the investigation of complex congenital conditions. The curved reformat of the T1-weighted MPRAGE sequence allows appreciation of the disorganised left cerebral cortex, and helped in identification of a region of polymicrogyria which was the seizure focus in this 12-year-old girl.



6 Motion correction – *syngo* BLADE can be used to provide a limited study in uncooperative patients **(6A, 6B)**, but is particularly useful in imaging posterior fossa lesions in pediatric patients where complex and high flow from CSF and vascular structures cause artifacts that may obscure some lesions **(6C, 6D)**. High parallel imaging factors can also be utilised with multiple excitations to average out motion artifacts (**6E** None, **6F** PAT3).

in reviewing and diagnosing complex congenital conditions, and may reduce the number of 2D sequences performed. It allows for high resolution, no gap imaging which can be used to accurately measure lesion size, and monitor changes in follow up imaging (Fig. 5).

BLADE

Rotating k-space techniques are utilised in pediatric MR imaging to reduce artifacts from physiological motion in the brain, as well as other body areas such as the shoulder, chest, abdomen, and pelvis. It is particularly useful with younger patients scanned at 3T where complex and turbulent flow artifacts can mask pathology [11]. Recent studies show improvement in lesion conspicuity in the posterior fossa through reduction in pulsation artifacts [12]. Disadvantages of BLADE include increased scan time, altered image contrast, increased SAR, and reduction in sensitivity to some pathology, particularly haemorrhage [13]. Motion reduction with propeller sequences can be utilized to obtain limited diagnostic information in moving patients; however, their limitations restrict widespread use for correcting voluntary patient motion in pediatric patients (Fig. 6).

Parallel imaging

The advent of parallel imaging techniques and multiple element, phased array coils has transformed pediatric imaging in recent years, providing a boost in either signal or speed. Parallel imaging techniques combine signals from several coil elements to produce an image with increased SNR, or allow partial sampling to reduce scan time. The use of parallel image acceleration and multiple acquisitions can be used to average motion artifacts in pediatric imaging. Parallel imaging techniques can also be exploited to reduce the duration of breathhold imaging, allowing dynamic capture of fast moving pediatric anatomy. Parallel imaging also reduces inhomogeneity artifacts such as seen in diffusion-weighted imaging [14].

Time resolved angiography

When imaging arterio-venous malformations and vascular shunts it is important for treatment and management to identify feeder vessels as well as the direction of blood flow. Rapid heart rates and high flow rates in children often make imaging of complex vasculature difficult with traditional MR angiography techniques. Time resolved contrast-enhanced MR angiography (MRA) techniques can provide anatomical as well as functional assessment of these vascular conditions [14].

High field strength imaging (3T)

Higher field strengths offer the opportunity to address many of the difficulties encountered with pediatric MR imaging. The increased SNR allows for smaller voxels and increased resolution, or reduced averages for increased speed. Parallel imaging factors can be increased further reducing scan time. Prolonged T1 times facilitate better background suppression for MRA and improved visualization of paramagnetic contrast agents [5]. The advantages offered by higher field strengths have lead to the viability of several new techniques in pediatric MRI. Unfortunately, higher field strengths can also present a number of challenges. The increased field strength leads to greater RF deposition, resulting in increased heating (SAR), which can cause sequence limitation in pediatric imaging. B_1-field inhomogeneities, chemical shift, motion artifacts and susceptibility artifacts are more pronounced at higher field strengths. However, there are a number of new techniques, which offer potential to mitigate against these difficulties. Prolonged T1 relaxation at higher field strengths creates challenges in image contrast, particularly in the neonatal brain [5].

Emerging techniques in pediatric MRI

SWI

Susceptibility-weighted imaging is being increasingly utilized in pediatric patients for imaging trauma, vascular disease such as haemorrhage, telangiectasia, and cavernous and venous angiomas, tumors and epilepsy imaging, as well as investigating metabolic disorders (Figs. 7, 8). The use of the phase images can be used to differentiate calcification from haemhorrage in lesions [15].

Parallel transmit technology

The use of multiple coil elements to transmit part of the RF pulse results in shorter pulse durations, reductions in SAR, and corrections of patient-related inhomogeneities [16]. This addresses some major challenges of pediatric MRI, particularly at higher field strengths.

Diffusion Tensor Imaging

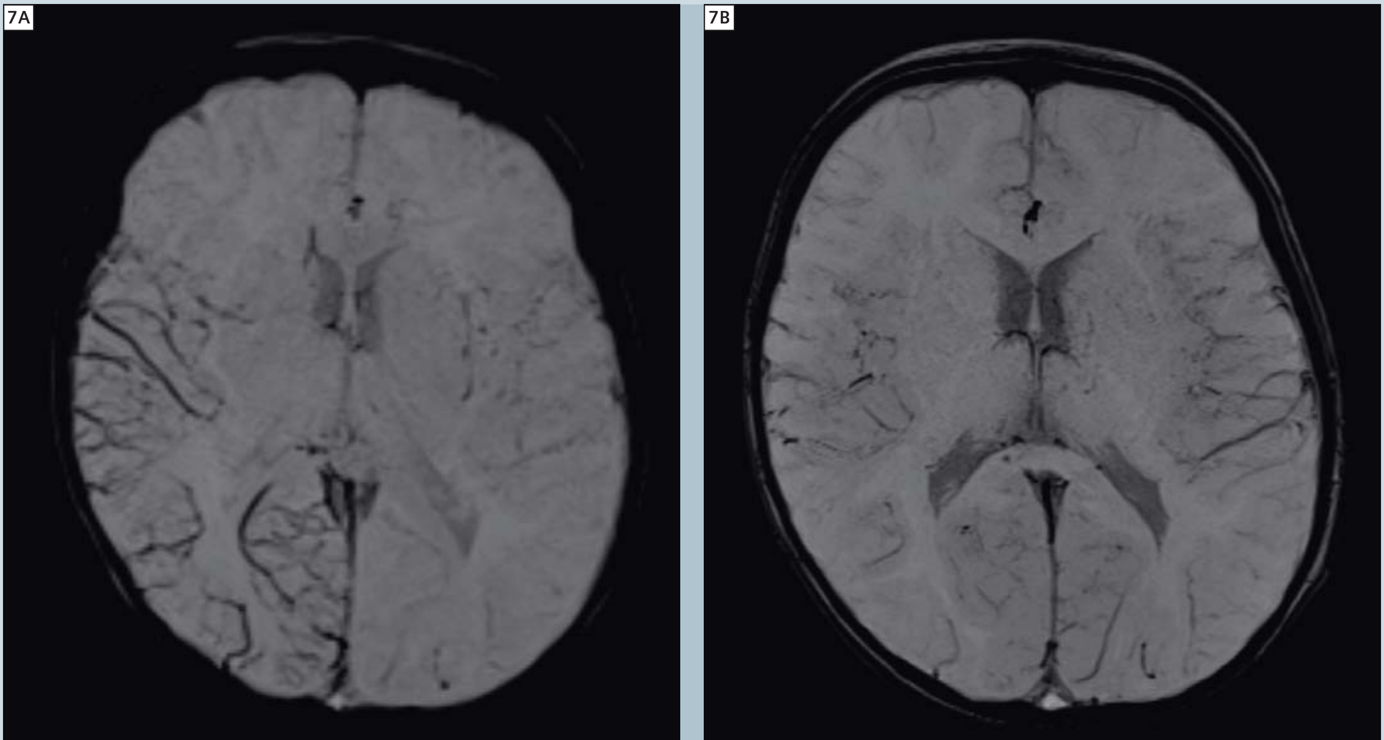
DTI has provided insights into connectivity and plasticity in the developing brain. It is now entering the clinical realm in the assessment of traumatic brain injury, epilepsy and white matter disease [14].

Arterial Spin Labeling

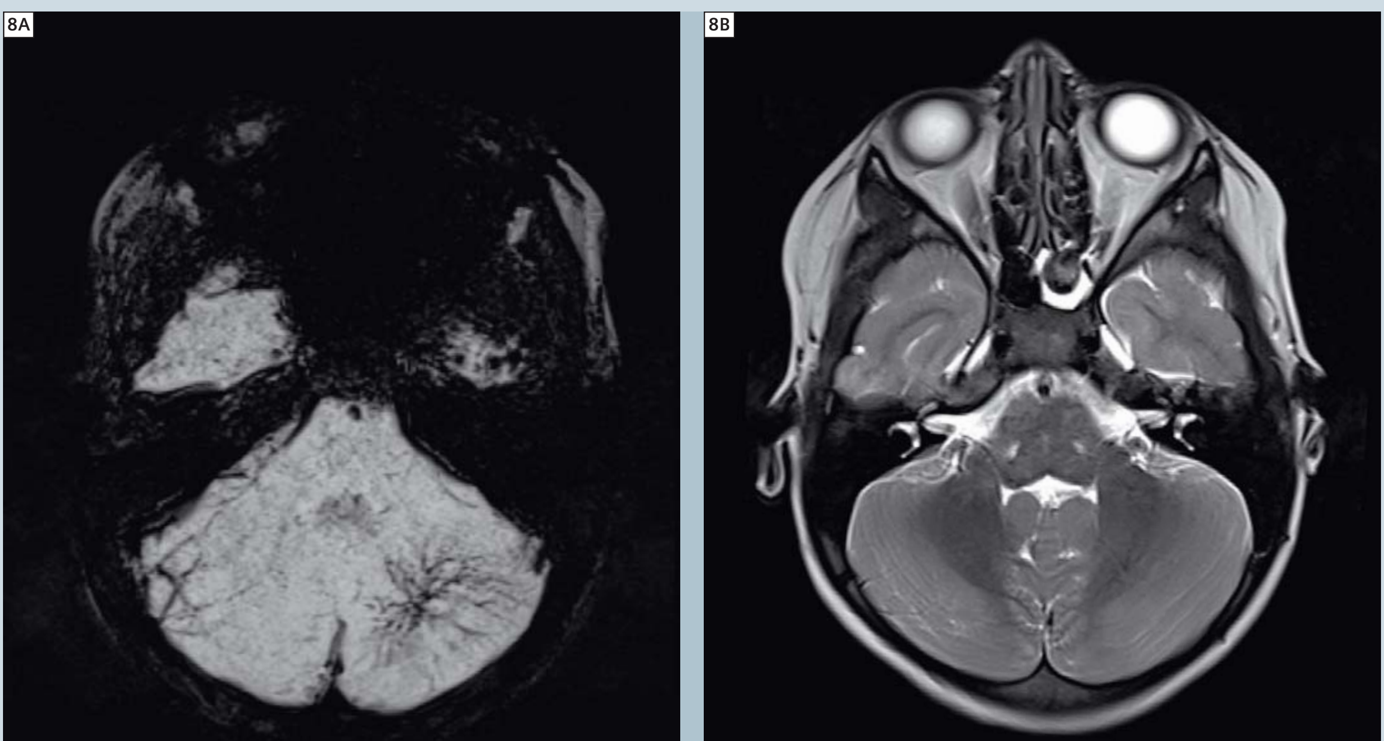
ASL provides functional information of blood perfusion by magnetically tagging inflowing blood upstream from the region of interest. Persistence of the 'tag' limits its use in adults; however, this is of less concern in pediatric patients, due to fast flows and relatively short perfusion distances [5]. This technique offers the potential to investigate regions of hypo- and hyper-perfusion, in conditions such as stroke or tumors, without the use of intravenous contrast media; however, further validation is required to demonstrate the clinical utility of this technique in pediatric patients [17].

MR urography

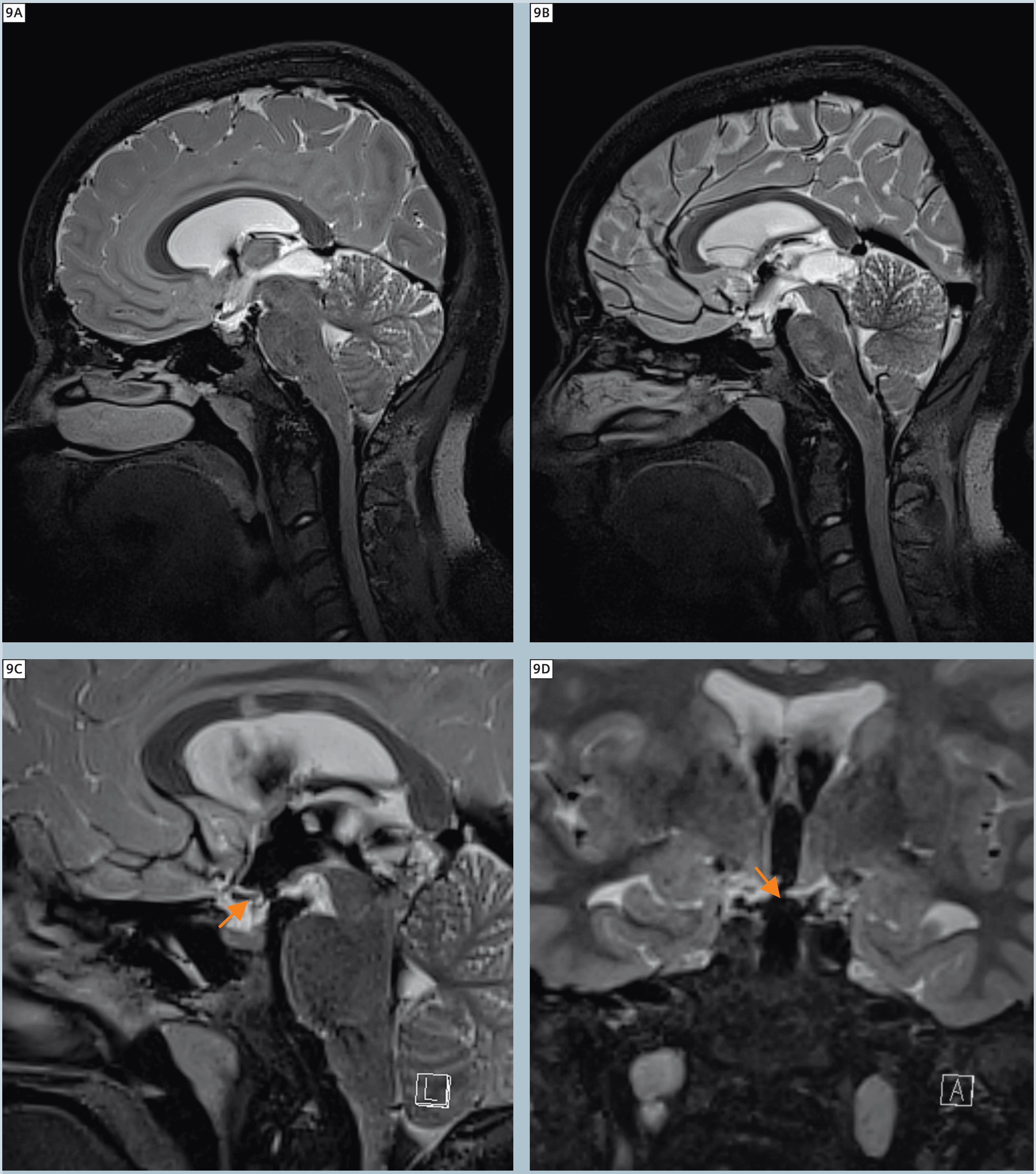
Magnetic resonance urography provides both anatomical and functional assessment of the kidneys and urinary collecting system. The multi-planar capabilities



7 Images of a 1-month-old who presented with acute seizures. T2w, T1w and diffusion-weighted imaging were unremarkable. Susceptibility-weighted imaging **(7A)** shows increased venous drainage in the right temporal-parietal region. **(7B)** The same patient imaged 48 hours later after seizure control with phenobarbital showing normalization of the cerebral flow. The sensitivity of *syngo* SWI is being increasingly utilized in the pediatric population.



8 Venous angioma as imaged on *syngo* SWI **(8A)** and T2w sequences **(8B)**. The ability to obtain this level of detail has allowed us to reduce our reliance on intravenous contrast agents to delineate these lesions.



9 These images are of a patient with a pineal cyst causing obstruction of the cerebral aqueduct with associated enlargement of the lateral and third ventricles. The sensitivity to flow of the T2w SPACE sequence can be used to demonstrate the obstruction in the pre surgical images **(9A)** as well as the increased retrograde flow through the foramen of Monro. The post surgical image **(9B)** shows the reduction in the size of the cyst as well as the restored flow to the cerebral aqueduct. The 3D sequence can be easily reformatted to show the site of the fenestration of the third ventricle **(9C, 9D** arrows**)**. Third ventricultomies have been traditionally difficult to demonstrate with standard 2D and phase contrast imaging, however, with a single 3D acquisition we can now easily answer all of the questions of the neurosurgeon.

of MRI are ideal for displaying complex congenital anomalies of the genito-urinary tract. This information can be used to predict outcome and select patients that are most likely to benefit from surgical intervention [18].

MR enterography

Crohn's disease is a serious and lifelong condition affecting the digestive system. It affects primarily the ileum and colon causing inflammation, ulceration and can lead to abscess formation or fistulae to other organs. Approximately 30% of patients with Crohn's disease will present before the age of 20. MRI provides the ability to diagnose and monitor this condition as well as complications such as peri-anal fistulae without exposing the patient to radiation [19].

Conclusion

Magnetic resonance imaging referrals for children continue to rise. The lack of ionizing radiation coupled with the high level of detail afforded by MR imaging has made it the examination of choice for a growing number of pediatric presentations. Most children who require magnetic resonance imaging will be examined in specialist pediatric centers or hospitals; however, heightened pressure on specialist centers has lead to many children being scanned in non-specialist facilities where technologists may have little experience in pediatric imaging. These referrals need to be treated differently to standard adult imaging requests in order to ensure diagnostic imaging with minimal distress and intervention to the patient. There is no 'one size fits all' approach to imaging children and pediatric MRI requires dedicated specialist knowledge, flexibility, and expert input from the technologist. An awareness of the challenges in pediatric MRI and experience in pediatric imaging techniques is vital to successful examination in this population. MRI in children can be extremely challenging physically, mentally, and emotionally, even for a seasoned pediatric technologist; however, these very challenges are also what make pediatric imaging such an interesting and rewarding field for MR technologists.

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*MR scanning has not been established as safe for imaging fetuses and infants under two years of age. The responsible physician must evaluate the benefit of the MRI examination in comparison to other imaging procedures.