3T MRI in Pediatrics: Challenges and Clinical Applications

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1. Introduction

The primary reason for increasing the magnetic field strength in magnetic resonance imaging (MRI) is to take advantage of the linear relationship between field strength and the signal-to-noise ratio (SNR). By increasing the signal that is obtained in MRI there is improvement in either the spatial or temporal resolution or both [1–4]. In pediatrics* there are a number of unique challenges which improved spatial and/or temporal resolution assist in overcoming. The challenges of high field MRI remain relevant in the pediatric setting. These include the altered T1 contrast, artefacts and safety issues, including specific absorption rate (SAR). These challenges also create opportunities with improvement in MR angiography (MRA), arterial spin labelling (*syngo* ASL), functional MRI (fMRI), susceptibility-weighted imaging (*syngo* SWI), and MR spectroscopy (MRS), all of which have distinctive applications in pediatrics.

This review will try to address basic considerations for pediatric 3T MR imaging, list the frequent and potential future applications, and discuss the challenges and restrictions.

2. What are the challenges of imaging children?

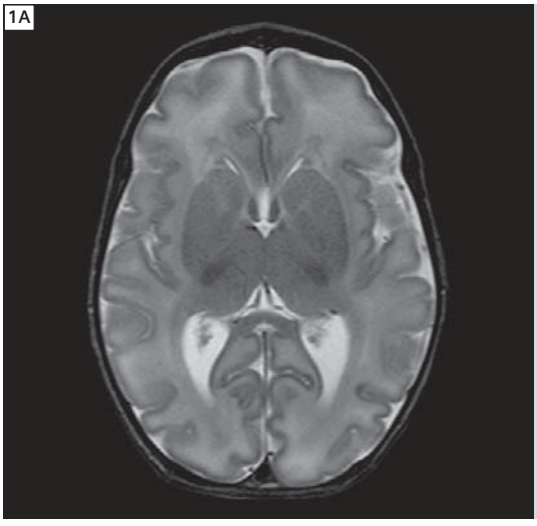
The four main challenges in imaging children are: (1) anatomical challenges, (2) developmental issues, (3) physiological challenges and (4) behavioural challenges.

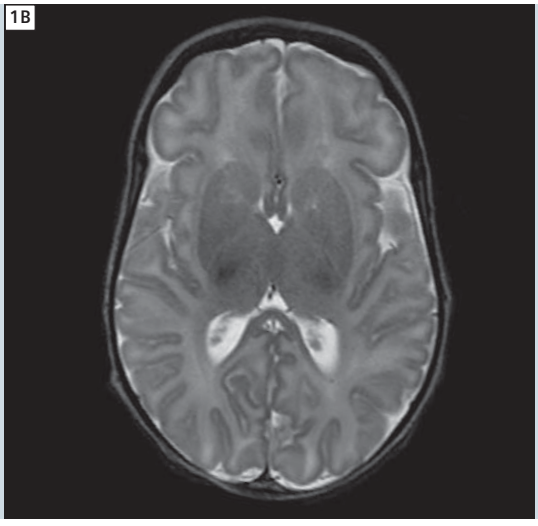
2.1. Anatomical challenges

In children, normal structures are smaller than in adults. However, we often forget how small they are compared to the average adult. An average term neonate weighs 3.5 kg, with brain 25% of the adult size [5]. A premature neonate at 24 weeks gestation may weigh as little as 0.5 kg, with a very small brain. Other anatomical structures that we image such as the inner ear, cranial nerves, brachial plexus, biliary tree, peripheral joints and blood vessels are very small in children. The improved SNR at higher field strength allows the acquisition of thinner slices and improved spatial detail of these structures.

2.2. Developmental issues

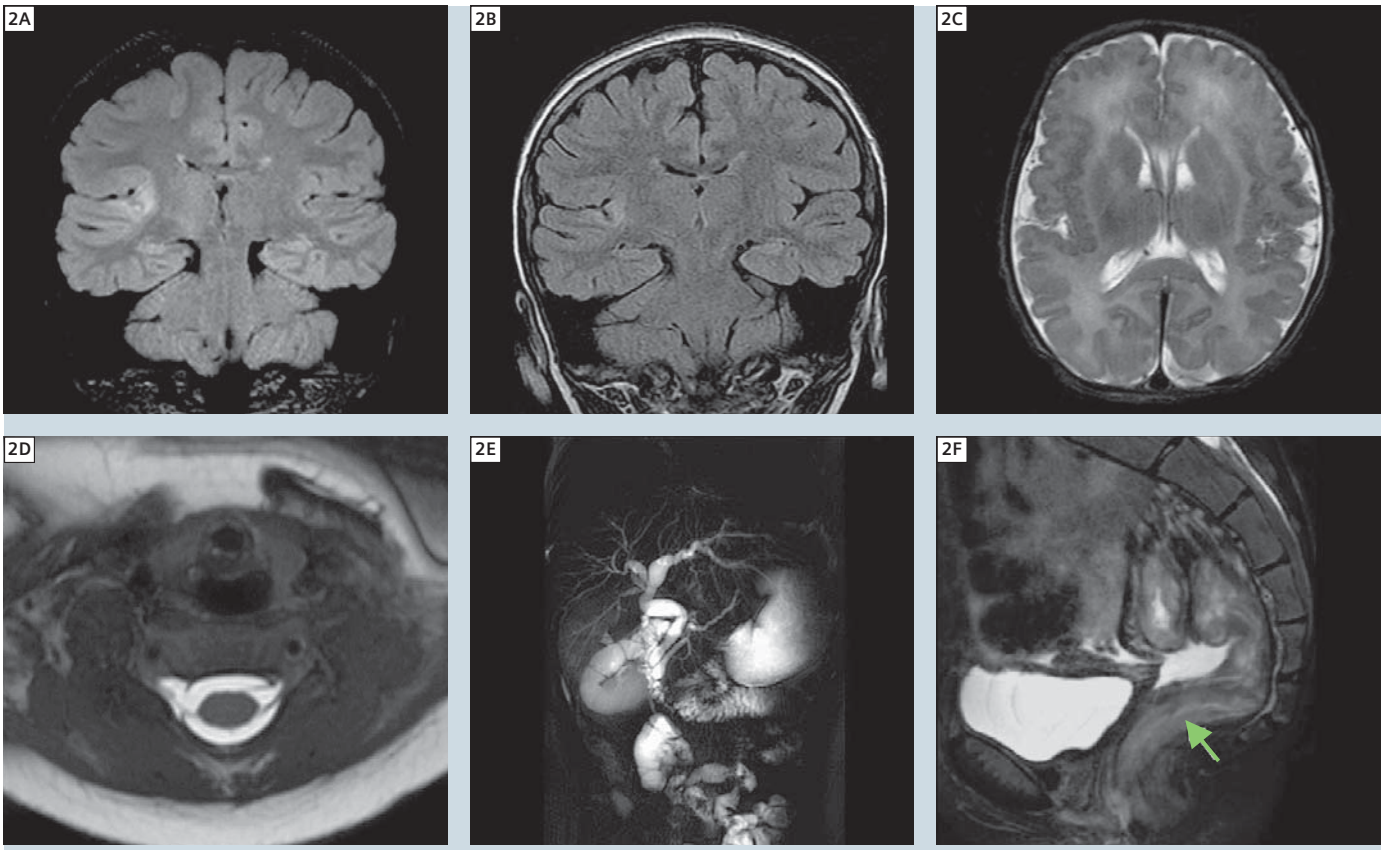
With development and maturation, in addition to growth, there are changes in the appearance of many structures. This is especially true for the brain, bones and cartilage. The brain sulcation and myelination of the white matter tracts develop rapidly in the neonatal period, the changes being more dramatic in the premature (Fig. 1A and B). In the joints, with maturation there is conversion of the epiphyseal and apophyseal cartilage to bone. These changes are better visualised with improved spatial resolution as the structures involved are often small and the changes subtle.





1 Axial T2 images from serial 3T MRI brain studies of a premature infant (34 weeks gestation) obtained 7 days **(A)** and 6 weeks **(B)** after birth demonstrate temporal maturation of the sulcal pattern, and progressive myelination in the posterior limbs of internal capsules and ventro-lateral thalami.

*The safety of imaging fetuses / infants has not been established.



2 Histologically confirmed cortical dysplasia: coronal T2 FLAIR images from MRI brain study performed at 3T **(A)** demonstrates ill-defined increased signal in the right insular cortex and adjacent white matter, much better appreciated than on **(B)** the earlier study performed at 1.5T, **(C)** axial T2 image of a term neonate with polymicrogyria, **(D)** axial T2 TrueFISP MRI of the cervical spine in a 3-month-infant demonstrates avulsed right C6 ventral nerve root and traumatic pseudo-meningocoele due to obstetric brachial plexus palsy, **(E)** MRCP of a patient with a choledochocele and **(F)** sagittal T2 TSE images demonstrate recto-sigmoid wall oedema and thickening due to inflammatory bowel disease.

2.3. Physiological challenges

In children the blood flow, pulse and respiratory rates are considerably faster. The normal heart rate in a neonate can be as high as 140/min, and the respiratory rate up to 40/min. Children are also unable to hold their breath satisfactorily until they are about 8 years of age [6]. These parameters are significant for cardiac, chest and abdominal imaging and benefit from the shorter scan times as a result of the improved temporal resolution.

2.4. Behavioural challenges

One of the greatest challenges in children is getting them to cooperate adequately for a diagnostic MRI study. Younger children usually require sedation or general anaesthesia for a successful scan. This involves some inherent risk, requires specialised staff, MR compatible anaesthetic and monitoring equipment. It is also slow and expensive [7]. The need for anaesthesia can be reduced by the use of bean bags, timing the scan with feeds and sleeping, education and practice sessions with dedicated educational play therapy staff, MRI toys and where possible a practice MRI unit [6]. The chance of these succeeding is greater if the scan times are shorter which can be achieved at higher field strength due to the improved temporal resolution.

3. How good is 3T at imaging children?

3.1. Can it do the basics?

With continuing hardware advances such as the availability of dedicated receiver coils, new pulse sequences and parallel imaging techniques, the 3T MRI unit can be used for imaging of all the organ systems evaluated on the 1.5T system [3,8]. Many pediatric MRI applications benefit from the increased signal at 3T (Fig. 2A–F; Table 1). Others, involving anatomic regions such as the heart, chest and abdomen are inherently prone to 3T artefacts, which must be controlled – these are discussed later in the article.

3.2. Is the SNR doubled?

The primary benefit of imaging at high field strength is the increased SNR. This is a direct consequence of the increase in MR signal resulting from greater number of protons aligned with the main magnetic field [2]. The signal increases four-fold when going from 1.5 to 3T. However, the noise is also doubled. So theoretically, the SNR should increase two-fold at 3T, when compared to 1.5T. However, this assumes fully relaxed T1

conditions and a constant bandwidth and flip angle [9].
The observed SNR gain is influenced by numerous factors including receiver coil design, B_0 and B_1 field homogeneity and radiofrequency (RF) flip angle limitations governed by increased RF power deposition [10]. In practice, in controlling for chemical shift, susceptibility and SAR at 3T, the bandwidth is usually increased and the flip angle reduced. In addition, at 3T the relaxation times are altered, and the T1 of tissues is longer [11,12]. If the TR is kept constant, there will be a reduction in SNR. Increasing the TR to compensate for the longer T1 will increase the acquisition time [2]. Therefore, the signal-to-noise gain is always less, (typically 1.7–1.8-fold), and this gain varies for different tissues [10,13].

3.3. How fast?

The improvement in SNR can be used to reduce the scan time. However, as discussed above, the observed SNR gain is less than two-fold, so it is not possible to image at twice the speed. Nevertheless, imaging is faster at 3T. In our practice this has not allowed us to reduce the need for general anaesthesia routinely at 3T. In isolated instances, however, this has been possible. However, it has allowed us to perform sequences more routinely than is possible at 1.5T, due to the inherently longer scan times. This has been particularly true for MR spectroscopy (MRS) [2], whole body MRI and diffusion-weighted imaging (*syngo* DWI), including diffusion tensor imaging (*syngo* DTI) and 3D imaging, including 3D dynamic vascular imaging – these are discussed in detail later.

3.4. What resolution can be achieved?

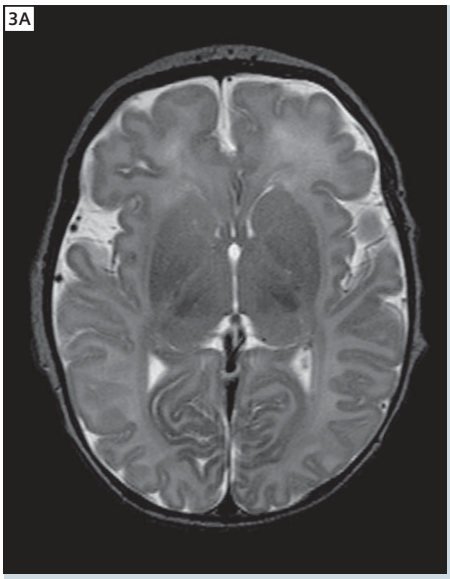
The SNR gain can also be used to increase spatial resolution. This has improved the imaging quality of small structures in children (Table 1).We have also been able to diagnose subtle abnormalities, which were earlier missed at

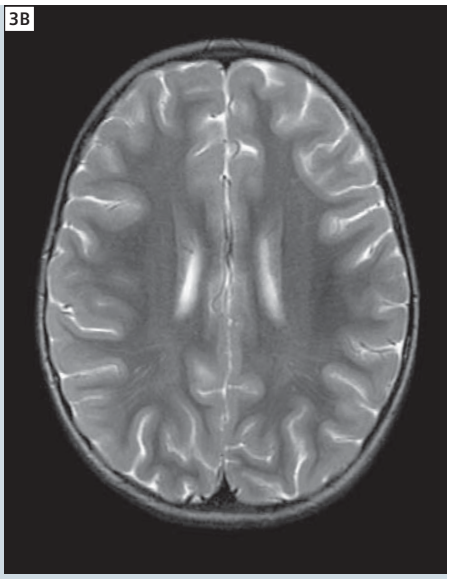
Table 1: Pediatric applications that benefit from the improved spatial and temporal resolution.

	Application	Examples of specific diseases
Neonate	All structures	
Nervous system	Brain Inner ear Cranial nerves Brachial plexus	Cortical dysplasia, migrational abnormalities Congenital sensory neural hearing loss Neuritis, e.g. bells palsy Birth trauma
Abdomen	Biliary tree	Sclerosing cholangitis, post liver transplant assessment
Musculoskeletal system	Small joints Polyarthropathy	Post reduction of dislocated hips in DDH, pre operative congenital deformity correction Haemophilia
MR angiography	Vasculitis Vascular malformations Congenital heart disease	Takayasu's arteritis, Moya Moya, Kawasakis disease Characterising type of vascular malformation Pulmonary arterial and aortic abnormalities, anomalous pulmonary venous return
Whole body MRI	Neoplasia Bone infarction Multifocal diseases Osteoporosis (compression fractures)	Neuroblastoma, lymphoma, leukaemia, ewings sarcoma Sickle cell disease, post chemotherapy and steroid therapy Chronic recurrent multifocal osteomyelitis, polymyositis Metabolic bone disease, steroid therapy

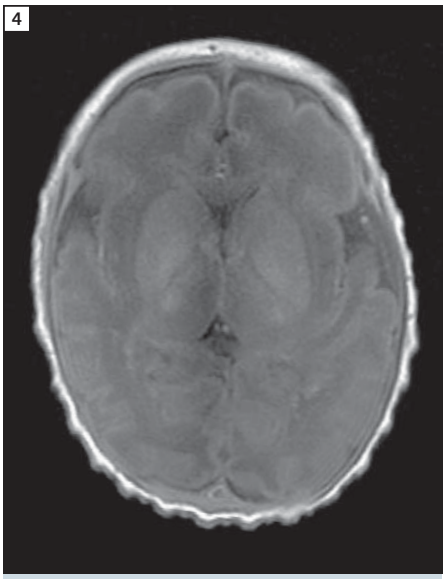
Table 2: How the opportunities of high field MRI can be applied in different organ systems.

Opportunity	Central nervous system	Musculoskeletal system	Cardiovascular system
SNR	Improved DWI, DTI, fMRI	Small joints, cartilage structure	Improved temporal resolution
Longer T1	Improved MRA	Improved MRA	Improved MRA, ASL, myocardial tagging
Susceptibility	Improved fMRI, SWI	Improved detection of calcification	Potential BOLD imaging
Chemical shift	Improved MRS	Improved MRS and fat saturation	Potential MRS





3 Axial T2 TSE MRI brain images obtained at 3T: the claustrum **(A)** is well demonstrated in this term neonate, **(B)** the perivascular spaces are routinely visualised at 3T.



4 Axial T1 image from MRI brain study of a neonate. The image contrast is less due to the prolonged T1 time, and the high water content of non-myelinated white matter.

1.5T (Fig. 2A and B). As with the differences in image contrast when compared to 1.5T, it is also important to familiarise oneself with the normal structures that are routinely visualised at 3T, e.g. the claustrum and multiple perivascular spaces on brain studies (Fig. 3A and B).

4. What are the challenges and opportunities at 3T?

The improved signal at 3T confers indisputable advantages. However, further improvements with newer sequences and dedicated coils for imaging neonates and premature infants are routinely required to realise the full potential of 3T. In addition, the increased energy deposition raises important safety concerns. The primary challenges are due to longer T1 relaxation times, the effect on T2 and T2*, and the greater chemical shift. Each of these factors play a different role depending on the region studied, and also create opportunities in the form of important clinical applications as discussed below and in Table 2.
T1 or the longitudinal relaxation time varies for different tissues; but is generally longer at higher field strength for a specific tissue type. The T1 times of different tissues increase to varying degrees (Table 3). For instance, the T1 relaxation time of brain parenchyma is increased by up to 40% when compared to imaging at 1.5T. Other tissues with significant magnetisation transfer also demonstrate increments of 20–40%, whereas for cerebrospinal fluid, the change is negligible (Table 3). For some tissues the T1 is even higher, for example an increase of up to 73% is reported for the kidneys [3].

4.1.1. Challenges due to longer T1

The increase in tissue T1 time will usually cause a decrease in image SNR [3]. In addition, the T1 values of different tissues tend to become more uniform at higher field strengths [14–16], with the result that the T1 images show less contrast between tissues. The pulse sequence parameters used at 1.5T require modification when applying to 3T [17]. These adaptations help minimise the intrinsic 3T image contrast losses. Knowledge of T1 values of different tissues at 3T will help select TR, TE, flip angle and inversion time to optimise image contrast [2] (Tables 3 and 4). The longer relaxation times affect T1 imaging of the neonatal brain. The neonatal brain inherently has high water content, especially in the white matter, making grey–white differentiation difficult. This is compounded at 3T due to the decreased T1 contrast (Fig. 4). It is less of a problem in older children, after myelination is complete. The decreased grey–white contrast can be improved by appropriate use of TR, TE and flip angle and the use of sequences such as T1 FLAIR.

4.1.2. Advantages of longer T1

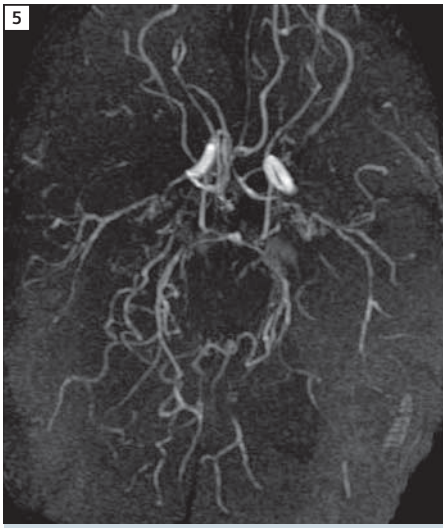
a) MRA: The longer T1 relaxation times allow better background suppression for MRA techniques, with a larger signal difference, or greater contrast, between blood vessels and the surrounding tissues [17]. This improves vessel visualisation both with time of flight (ToF) (Fig. 5) and contrast enhanced MRA (ceMRA). With ceMRA, the signal difference between blood and unenhanced tissue is further increased as the relaxivity of paramagnetic MR contrast agents is only slightly reduced at 3T [17]. Improved MRA has reduced the need for conventional angiography at our institution.

b) Post contrast imaging: For post contrast imaging in general, the improved contrast resolution at 3T and the rela-

Table 3: Increase in T1 times of different tissues at 3T vs. 1.5T [4, 8, 27, 32, 33]

Tissue type	% T1 increase	Examples of tissue T1 times (ms) at 1.5T	at 3T
Brain – grey matter	Up to 62%	960	1331
Brain – white matter	Up to 42%	700	832
CSF	Negligible change	Negligible change	Negligible change
Myocardium	43%	1030	1471
Blood	34%	1200	1500
Bone marrow	30%	290–550	370–590
Skeletal muscle	Up to 40%	860–1130	900–1420
Cartilage	10%	1020–1060	1170–1240
Synovial fluid	27%	2850	3620
Fat	20%	290–340	370–380
Liver	Up to 41%	493	641
Spleen	20%	790	950
Kidney	73%	652	774

tively less marked change in the relaxivity of paramagnetic contrast agents when compared to the surrounding parenchyma can permit a reduction of gadolinium doses and potentially enable earlier detection of inflammatory and neoplastic diseases [18–20].



5 MoyaMoya disease. MIP of time-of-flight MR brain angiogram demonstrates marked irregularity, narrowing of several vessels of the circle of Willis, with collateral neovascularisation.

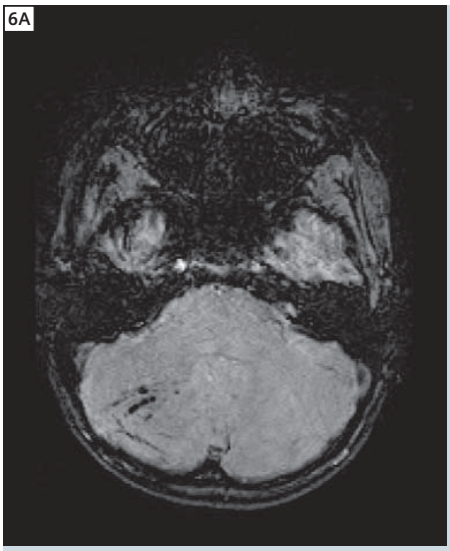
c) Arterial spin labelling: ASL enables perfusion imaging without contrast and is potentially a very useful technique in children. Blood is labelled magnetically and then followed into the brain. At 3T the label lasts longer due to the longer T1 tissue relaxation times [21] and there is a potential three-fold increase in the SNR with this technique. In addition, the rate of blood flow is faster in children so that the label can also pass further through the vascular bed before fading. ASL has enormous potential in vasculitic conditions such as Moya Moya disease. Moya Moya disease manifests with progressive irregularity, stenoses and obliteration of intracranial arteries and neo-vascularisation by collaterals that have a 'puff-of-smoke' appearance on angiography (Fig. 5). Treatment is surgical creation of burr-holes to promote collateral formation via intra- to extracranial anastomoses. The timing of surgery is important to ensure the best possible outcome as collateralisation is optimal in the presence of a degree of tissue ischaemia, but delay can result in stroke. Serial imaging is used for assessment of the intra-cranial vasculature. ASL potentially has an important role in identifying parenchyma that is at risk of ischaemia, and to determine the optimal timing of surgery.

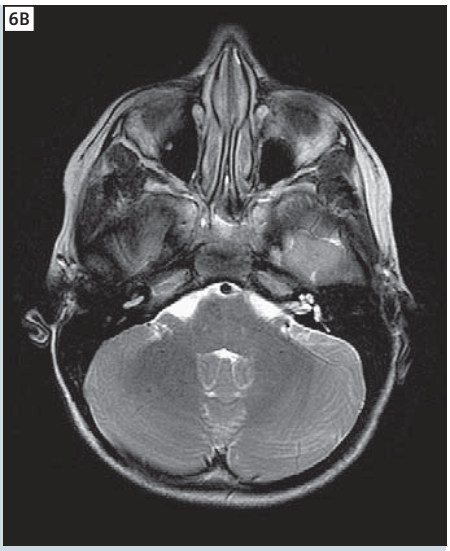
4.1.3. Effect on T2 and T2*

Tissue T2 values tend to decrease with field strength. However, tissue contrast on T2 images is not as significantly affected as T1 images [8]. Some recent reports suggest up to 10% decrease in T2 relaxation times at 3T, compared to 1.5T [16, 22, 23]. This further reduces the SNR gain for long TE sequences [17]. T2* decay, on the other hand, is considerably shorter at 3T due to microscopic field inhomogeneities which increase linearly with field strength.

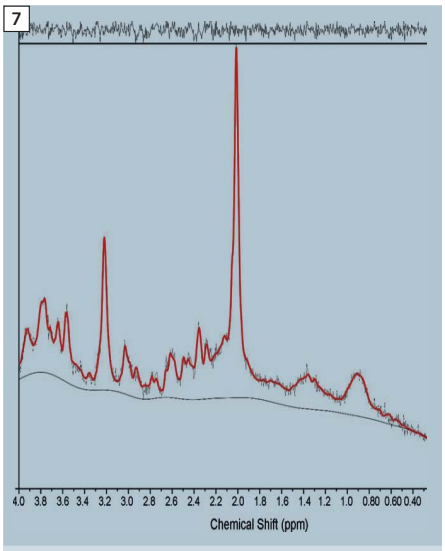
Table 4: Adapting (1.5T) parameters to circumvent important 3T specific challenges.

	Effect	Compensation	Effect of compensation (trade off)
↑T1 value	↓T1 tissue contrast	Increasing TR Parallel imaging techniques IR or MT sequences	↑Scan time ↓SNR
↓T2* values	Change T2* contrast	↓TE	↓SNR
↑Chemical shift	Artefact at fat–soft-tissue interfaces and MRS mis-registration	Doubling the readout bandwidth ↓FOV Fat suppression ↓Voxel Size	↓SNR, permits↑, number of slices acquired for given TR ↓SNR Allows imaging at low readout bandwidth, SNR remains high
↑SAR	↑Body temperature	SAR monitor (legal limits) Special RF pulses ↓FOV Longer sequence duration ↓Flip angle ↓Number of slices Longer TR	 ↓SNR
↑Magnetic susceptibility	Image distortion, dark bands	Frequency encode parallel to long axis of implant Remove cause ↓Voxel size ↓Slice thickness ↓TE ↑Receiver bandwidth ↑Spatial resolution ↑ETL (TSE better than SE) Parallel imaging Shimming GRE sequence most affected	 ↓SNR ↓SNR ↑SAR ↓SNR
B_1 inhomogeneity	Bright central region, signal loss	B_1 insensitive (Adiabatic) pulses Shimming Dielectric pads	
↑Signal	↑Flow artefact	Saturation band Phase encode direction other than AP Gradient moment nulling Cardiac gating	





6 **(A)** Foci of profound signal loss due to haemosiderin on the susceptibility-weighted image on follow-up MRI brain study after trauma **(B)** these are only identified in retrospect on the axial T2 images.



7 3T proton MRS (TE 30 PRESS) from the parietal white matter of a child with guanidinoacetate methyltransferase (GAMT) deficiency demonstrating a dramatic reduction in the creatine peak.

4.1.4. T2* related artefacts or susceptibility artefacts

The susceptibility effect is a materials' tendency to distort the applied magnetic field, and increases linearly with field strength. It occurs at air, bone or soft-tissue interfaces; and can cause areas of signal loss, inhomogeneous fat saturation and geometric distortion [24] (Figs. 6A and 8D). It is commonly seen near the paranasal sinuses in brain imaging, due to bowel gas in abdominal imaging, and with metallic implants, especially dental hardware in teenage children. The effect can be quite marked at 3T and was initially considered a major limitation to the clinical utility of high field MRI. The detrimental effect of susceptibility from macroscopic structures can be controlled at 3T by a number of techniques. The cause should be removed if possible. Appropriate shimming directly reduces field inhomogeneity. Decreasing the voxel size and TE and increasing the bandwidth can reduce this artefact, but with a concomitant decrease in SNR. Parallel imaging also reduces susceptibility, with a reduction in SNR [2] (Table 4). This decrease is adequately compensated by the increased signal at 3T.

4.1.5. T2* applications

The increased susceptibility at 3T has a number of advantages:

a) Functional MRI: fMRI relies on the ability to detect the blood deoxyhaemoglobin levels (BOLD effect), a T2* dependent technique. The greater susceptibility at high field strengths produces increased sensitivity for fMRI. fMRI has important applications in pediatric neuroimaging, especially in the preoperative assessment of children with intractable epilepsy and brain tumors, to minimise the resection of functional parenchyma.

b) Susceptibility-weighted imaging: The increased susceptibility at 3T increases the sensitivity to haemorrhage and calcification, which is exploited with *syngo* SWI. *syngo* SWI is very sensitive in identifying haemorrhagic foci in the brain (Fig. 6A and B). Specific pediatric applications include non-accidental injury, birth trauma and diffuse axonal injury due to vehicular accidents. Calcification is also easier to detect and is useful for characterising masses such as dysembryoplastic neuroepitheleal tumors.

SWI is also useful in children with haemosiderosis. Abnormal tissue iron deposition at an early age is most commonly due to recurrent transfusions in thalassemia major. Myocardial iron deposition can be fatal due to arrythmias and cardiomyopathy. This is prevented by judicious use of chelating agents, which have significant side-effects. Imaging at 3T can potentially increase the sensitivity for myocardial and liver iron quantification. This is useful to guide therapy – specifically, to optimise the dose of chelating agents and the timing of initiation of therapy.

4.2. Chemical shift

The chemical shift effect is increased two-fold at 3T compared to 1.5T [8, 25], and can result in pronounced artefacts, however, it can also be exploited for MRS.

4.2.1. Chemical shift artefact

Chemical shift artefact is caused by spatial mis-registration of fat and water, and causes a dark band at fat–soft tissue interfaces. It causes problems with MRS (discussed in detail later) and in abdominal imaging, where it can obscure subtle bowel wall changes in early inflammatory disease. This artefact is controlled by doubling the bandwidth [8, 26], or by decreasing the FOV [26]. Both of these

reduce SNR (SNR∝1/√BW), however, this loss is adequately compensated for by the increased signal at 3T [26]. The artefact can also be reduced by fat saturation, decreasing the voxel size and altering the TE.

4.2.2. MR spectroscopy

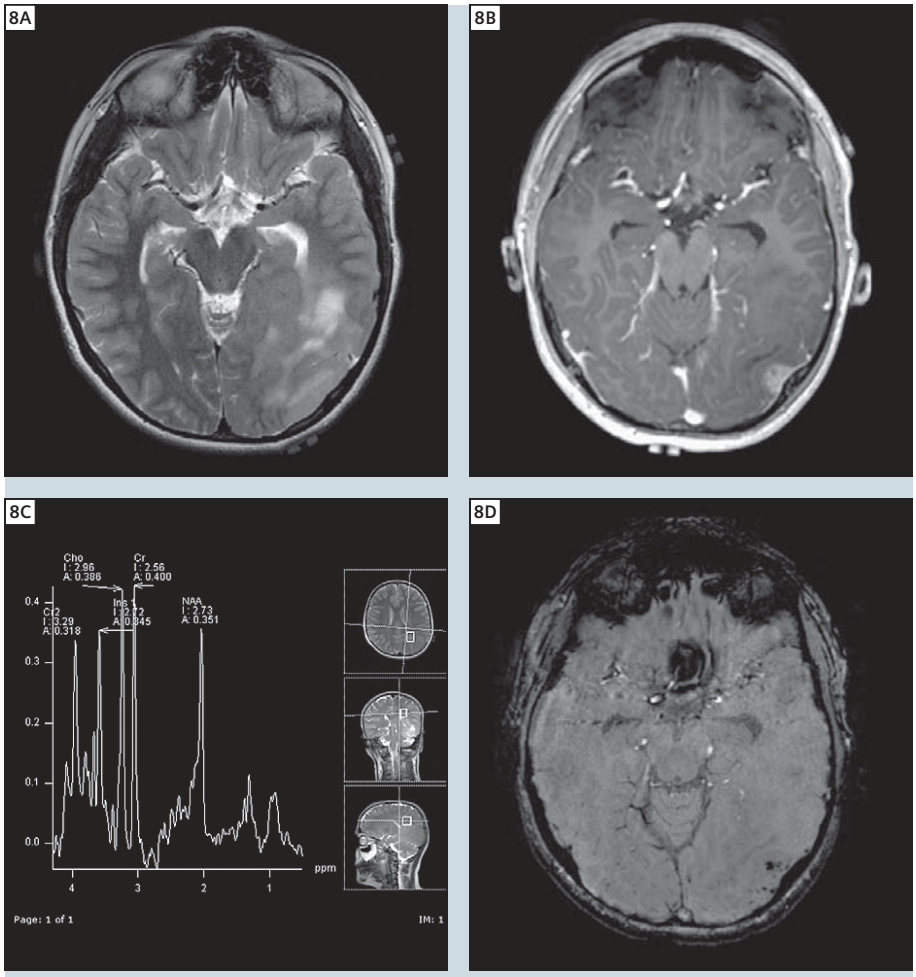
In the pediatric setting MRS is performed as a problem-solving tool, to answer specific questions. It is important for the work up of metabolic disorders. With significant overlap in the presentation of different conditions, MRS provides valuable information for the individual patient when considered in the appropriate clinical context. It can be diagnostic in certain entities, such as creatine deficiency syndromes (Fig. 7), useful to indicate disease activity, as in Leigh's disease and also to monitor response to treatment. It is also helpful to characterise space-occupying lesions and to determine the extent of infiltrative spread (Fig. 8).
In neonates and pre term infants, MRS is performed for assessment of biochemical changes with brain maturation related to location and development, in order to detect brain injury (Fig. 9), and to distinguish hypoxic insults from metabolic/ neurodegenerative conditions.

4.2.3. MRS: 3T advantages

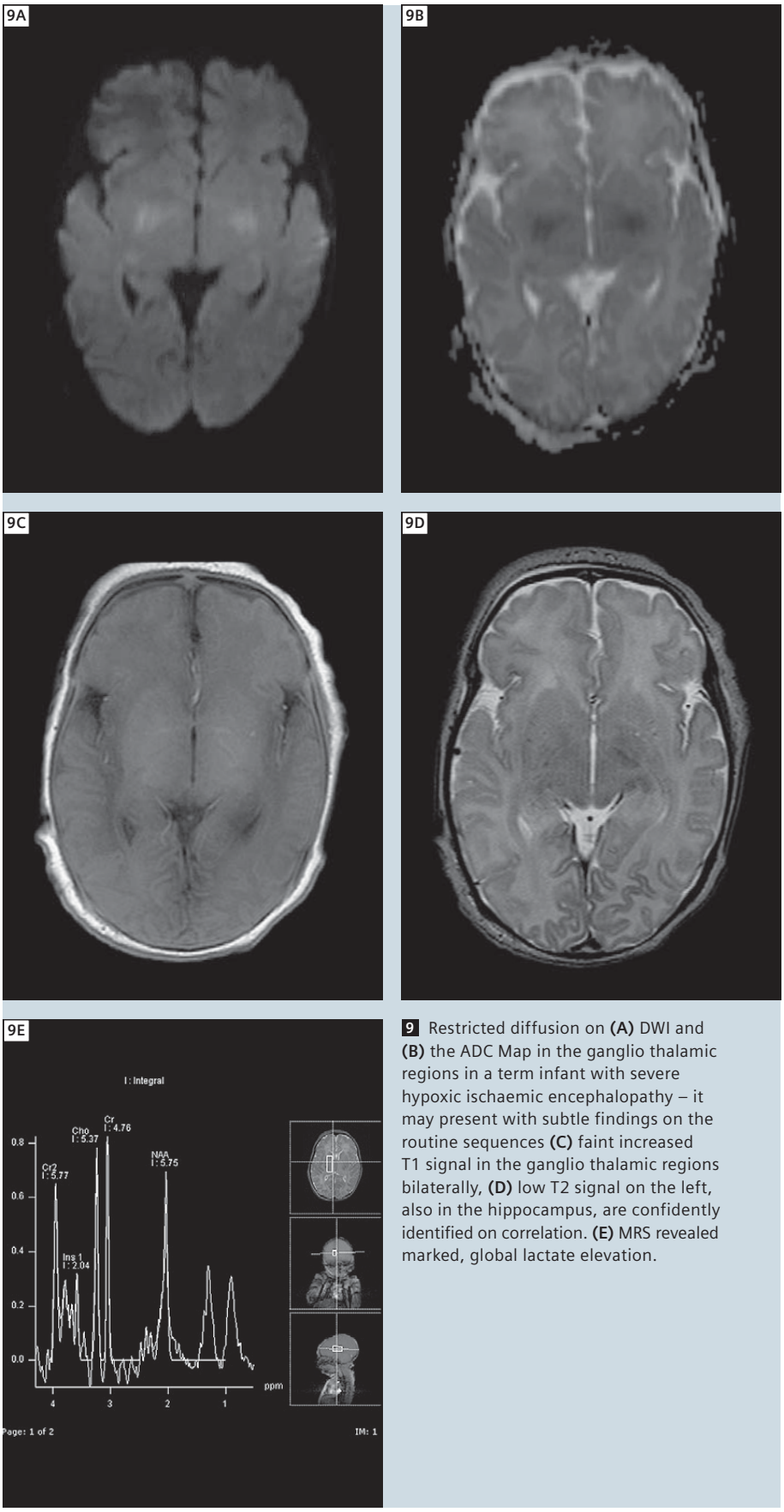
Greater chemical shift is the basis of improvement in MRS at 3T, with increased frequency spread of individual peaks resulting in improved metabolite identification. In addition, the amount of signal derived from each metabolite is increased, so the metabolite peaks are easier to differentiate from background noise. The increased signal also enables faster acquisition times [8] which makes it more realistic in children, and especially neonates, who may not tolerate a longer sequence. The voxel size can also be reduced both with single voxel and multi voxel MRS, reducing the likelihood of contamination from subcutaneous/retro orbital fat in peripherally located lesions.

4.2.4. MRS: 3T challenges

Performing MRS at high field strength has quite a few advantages – but at the same time, there are several issues to consider when applying the 1.5T parameters and experience at 3T. The increased chemical shift also causes specific constraints for 3T MRS, whether using single or multi voxel techniques. Specifically, problems with misregistration (which results in poor lactate inversion at 3T, discussed later); and artefacts from increased susceptibility near bony structures, air sinuses and soft-tissue interfaces [25] are more pronounced than at 1.5T.
The greatest gain in SNR occurs at MRS using short TE – the latter is also the most useful in the assessment of metabolic diseases, as it is possible to detect metabolites with short T2 relaxation times, and there is little need for T2 correction. However, the general disadvantages of short TEMRS are also relevant at 3T, i.e., the overlap of lipid and lactate peaks, and distortion of the baseline due to the effect of eddy currents [27]. Hence, spectra are usually obtained at two TE values.
3T MRS at intermediate TE suffers from variable lactate inversion, which complicates the distinction of lactate from lipids – an important consideration, especially in the neonatal period as an additional sign of hypoxia. At long TE MRS the signal benefit at 3T compared to 1.5T becomes negligible [27] and the baseline is smoother, which limits detection



8 Glioblastoma Multiforme: Axial images from MRI brain study performed for right homonymous hemianopia demonstrate **(A)** gyral thickening, ill-defined increased T2 signal and indistinct grey-white differentiation in the left parieto-occipital region. **(B)** Cortically based enhancement **(C)** MR spectroscopy demonstrates marked elevation of choline away from the small central enhancing area – this is useful to delineate tumor extent, and distinguish infiltrative spread from peri lesional oedema. **(D)** Foci of signal dropout from blood degradation products. Note the skull base susceptibility artefact.



9 Restricted diffusion on **(A)** DWI and **(B)** the ADC Map in the ganglio thalamic regions in a term infant with severe hypoxic ischaemic encephalopathy – it may present with subtle findings on the routine sequences **(C)** faint increased T1 signal in the ganglio thalamic regions bilaterally, **(D)** low T2 signal on the left, also in the hippocampus, are confidently identified on correlation. **(E)** MRS revealed marked, global lactate elevation.

of smaller metabolite peaks. However, in the hypoxic setting, it is the preferred second acquisition as lipids in the voxel are neutralised, and confident assessment of lactate levels is possible.

4.3. B_1 inhomogeneity

B_1 inhomogeneity produces regions of reduced signal in the centre of the imaged object. This effect is caused by a combination of (A) variable and reduced RF penetration depth as the magnetic field strength increases and (B) dielectric tissue properties cause resonance phenomena that appear as standing waves when half the wavelength is in the order of the object size.
This is an important 3T artifact, is unpredictable and depends on the body shape and organ size. It is less of a problem in smaller children, as the tissue depth for RF penetration is less and the organ size smaller. It can affect abdominal MR images of older children. Appropriate shimming is helpful to move these dark bands away fromthe region of interest. Dielectric pads can help with this artifact and newer B_1 insensitive (Adiabatic) pulses have been developed with the latest MRI machines.

4.4. Safety issues

4.4.1. Specific absorption rate

SAR reduction is a very important factor that permits the clinical use of 3T MRI. It is a measure of the amount of energy deposited by an RF field in a given mass of tissue, and is constrained by FDA guidelines. As the power required for excitation increases with increasing frequency (and thus field strength); the SAR increases with field strength. This is according to the formula SAR∝Bo2 [10]. Therefore, using equivalent parameters, there is a four-fold increase in SAR at 3T compared to 1.5T.
The SAR increase is greater in fast spin echo sequences due to the multiple refocussing pulses and with RF intense pulse sequences such as FLAIR [25]. It also increases with gradient echo sequences that have a very short TR (e.g. TrueFISP). SAR is related to the flip angle according to the formula SAR∝(flip angle)2 [2]. Fast contrast

enhanced 3D angiography using a high flip angle; and fully rephased gradient echo techniques which yield optimum signal at high flip angle excitation with short TR easily reach SAR limits at 3T. The SAR can be reduced by using special RF coil designs such as transmit/receive array coils, by reducing the number of slices, by having a delay between sequences, or by the use of parallel imaging techniques. The choice of sequence can also reduce SAR, by using a smaller flip angle or echo train length, or an increased bandwidth or TE. However, reducing the flip angle or increasing the bandwidth alters tissue contrast. Specialised RF pulses that vary the flip angle throughout the sequence (e.g. hyperecho [28]) can reduce the SAR by up to four-fold (Table 4).
SAR potentially can create issues with temperature control, especially in neonates. They are kept wrapped in the scanner to keep them warm, however, the greater energy deposition has the potential to further increase body heat. Temperature monitoring (either skin or rectal) is therefore useful, but requires MR compatible probes. Although this is a potential issue at 3T, in practice it has not been anymore problematic when compared to scanning at 1.5T.

4.5. Specific applications that benefit from high field strength: whole body MRI, DWI & DTI and 3D imaging

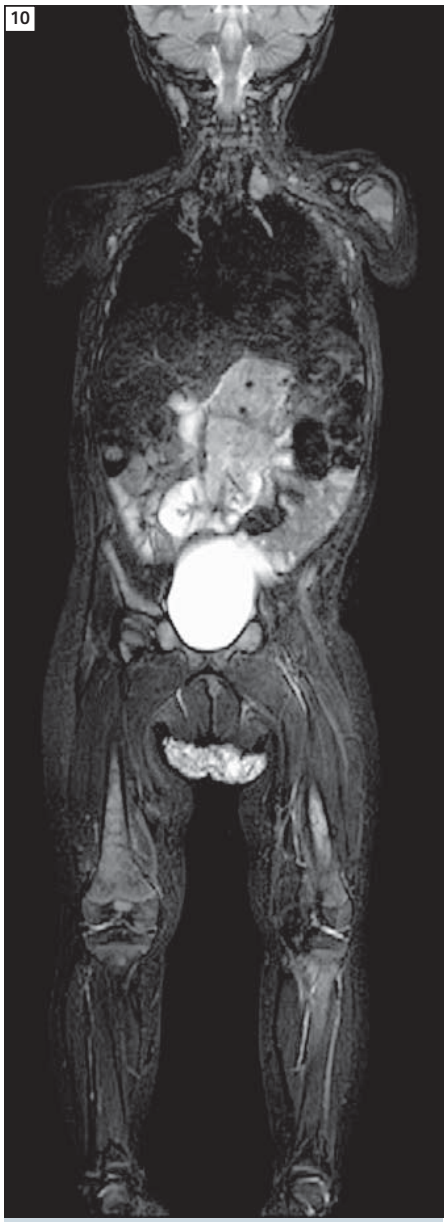
The reduced scan times enable wider coverage while maintaining adequate SNR, and these advantages make whole body MRI and *syngo* DTI feasible at 3T.

4.6. Whole body MRI

There is an inherent advantage of the smaller patient size in pediatric whole body MR imaging, as the total number of acquisitions required is less than for adults. Whole body MRI in children is primarily used for oncologic screening to assess the skeletal spread [14], by obtaining overlapping STIR coronal sections (Fig. 10). An estimate of the total tumor burden, including soft-tissue involvement can be performed. It has a role in pediatric haematologic malignancies such as leukaemia and lymphoma [29], round cell tumors especially neuroblastoma, and skeletal tumors such as Ewings sarcoma [30]. Myelofibrosis, and also the response to therapy can be assessed. Non-oncologic applications include multifocal muscle disease, screening the osteoporotic skeleton for fractures, multiple bone infarcts, assessment of total body fat stores or whole body MR angiography (e.g. Takayasu's arteritis) [31].

4.6.1. Diffusion weighted (DWI) and diffusion tensor imaging (DTI)

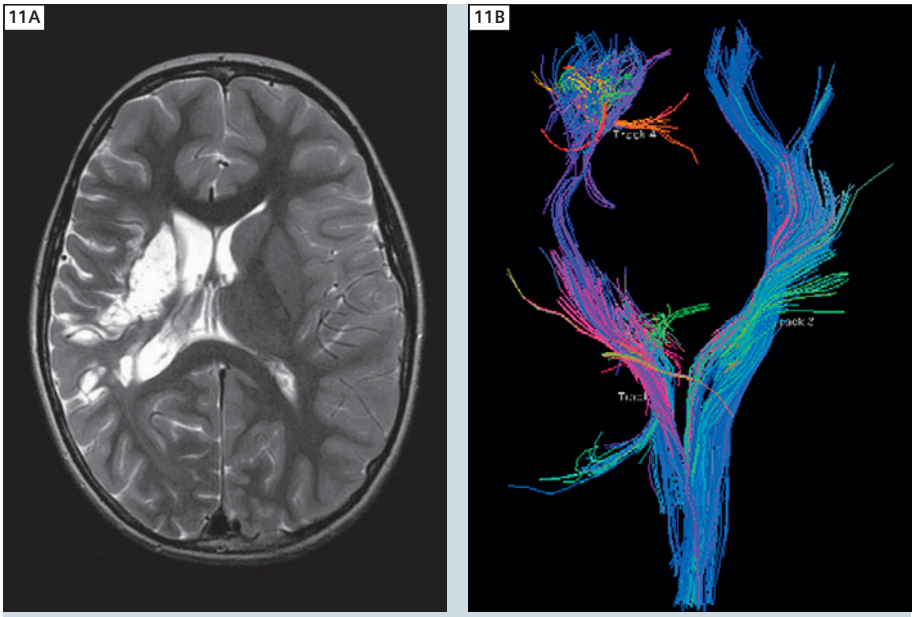
The improved SNR at 3T means that higher B values (>1000 s/mm^2), thinner slices and imaging in a greater number of directions are possible, thereby improving DWI. Magnetic susceptibility artefact is more pronounced with EPI, and may be a problem with DWI at higher field strengths [32], especially with dental braces that are common in older children. This can be con trolled – to an extent – with volume shimming, parallel imaging techniques, and bandwidth adjustment.
In the neonatal period, *syngo* DWI is very important for the assessment of hypoxic ischaemic encephalopathy, as it may present with subtle findings on the routine sequences (Fig. 9). It is also useful in the context of pediatric stroke, including vasculitis and sickle cell disease; also with traumatic brain injury and demyelinating disorders.
The benefit of DTI, when compared to conventional DWI, is the capability to determine white matter fibre orientation within collimated bundles – this directional information is displayed using 2D directionally encoded color anisotropy images or by 3D fibre tractography (Fig. 11). Also, qualitative measures derived fromDTI, i.e., mean diffusivity and fractional anisotropy (FA) are rotationally invariant, and thus, in theory, not affected by changed head position or fibre orientation.
DTI is becoming increasingly important in the preoperative assessment of patients with brain tumors. Relationship of the mass with important white matter tracts can be demonstrated, and thus assist the surgeon in preserving function, while maximising lesion resection. With further advances, tractography can potentially enable more comprehensive assessment of other neural tract or pathway specific conditions, such as post delivery brachial plexus injuries; and aberrant connectivity in structural brain malformations.



10 Coronal T2 STIR whole body MRI for metastatic neuroblastoma.

4.7. 3D imaging and 3D dynamic MRA

The greater SNR enables faster acquisition of 3D data sets which are now routinely performed in our practice at 3T,



11 Sequela of right middle cerebral artery embolic occlusion secondary to traumatic internal carotid artery dissection. **(A)** Axial T2 image demonstrates cystic encephalomalacia and volume loss **(B)** disruption of the major white matter tracts (color coded) as depicted by tractography.

especially for post contrast imaging. Dynamic 3D imaging has also become practical with applications such as TWIST which enables sub-second time sequential 3D imaging.We have used this technique to evaluate the flow through complex vascular malformations, for planning treatment.

4.8. Challenging high field regions: cardiac and spinal imaging

There are definite advantages in having greater SNR for cardiac and spinal imaging, however, both regions have several high field issues, which come together to make these areas particularly challenging.

4.8.1. Cardiac imaging at 3T

The major indications for pediatric cardiac MR imaging are for assessment of ventricular function, the major vessels and post-operative anatomy in the context of congenital heart disease. However, all types of pathology including coronary artery abnormalities, cardiomyopathy, infiltrative disorders and cardiac tumors are imaged.

3T cardiac MRI has potential for improved coronary artery evaluation, and delayed enhancement imaging in conditions such as cardiomyopathy and assessment for arrythmogenic right ventricular dysplasia – these may be SNR-limited at lower field strengths.

Steady state free procession (TrueFISP) imaging, is very important in cardiac MRI at 1.5T. For the best TrueFISP imaging the TR is kept as short as possible (<4 ms), the flip angle as high and uniform as possible (all of which increase the SAR), and the magnetic field must be homogeneous (which is challenging at 3T). At 1.5T, the TrueFISP sequence is already at the SAR limit and to reduce the SAR at 3T, the flip angle must be reduced. This makes the blood pool darker and reduces the contrast between the blood pool SNR.

B_1 inhomogeniety artefact, susceptibility artefact and off resonance effects tend not to be a significant problem with cardiac imaging at 1.5T, however, occur unpredictably and can be severe at 3T [33]. Field inhomogeniety can be controlled by tight shimming and frequency correction.

Application of parallel imaging techniques may increase the clinical utility of 3T cardiac MRI. Higher acceleration factors enable smaller acquisition windows, and support segmented acquisition schemes, an advantage for the higher heart rates of pediatric patients. Also, the energy deposition can be reduced due to fewer phase-encoding steps [33]. Improved MRA at 3T is very useful in the assessment of the major arteries and veins which are very important in children with congenital heart disease. This is particularly true of the pulmonary arteries, which commonly require assessment in the neonatal period.

4.8.2. Spine imaging

T1 imaging of the spinal cord is difficult at 3T. T1 prolongation results in reduced contrast between the grey and white-matter. This is accentuated in pediatric imaging due to the increased water content of neural tissue, especially before myelination is complete. In addition, CSF signal intensity at 3T is greater than at 1.5T which means there is reduced contrast between the spinal cord/conus and the surrounding CSF.

Gradient sequences such as T1 FLAIR may lessen the problems associated with T1 lengthening, with the potential of optimum contrast at 3T, at normal as well as abnormal tissue interfaces [26]. Studies comparing post-contrast T1 spin echo and gradient images have yielded equivocal results with regard to lesion conspicuity and detection – this may be overcome by acquiring one of each, in different planes [26]. In addition, CSF flow artefacts increase with higher field strength, due to the increased signal and spatial misregistration. The highly pulsatile CSF flow in children can cause a severe artefact which can obscure important pathology, such as leptomeningeal tumour spread. Gradient moment nulling may prove to be useful for CSF flow compensation [11]. Cardiac gating may also be used to overcome these effects [9].

5. Conclusion

3T MRI is being increasingly performed for clinical purposes. The signal increases four-fold when compared to imaging at 1.5T, and can translate to an observed SNR gain of 1.7–1.8. The increased SNR

is a significant advantage in pediatrics – improved spatial and temporal resolution assist in overcoming the major anatomic, physiologic and behavioural challenges of imaging children. Rapid changes with development and maturation can also be better assessed.

The challenges inherent to imaging at high field strength remain pertinent – important among these are the altered T1 contrast, artefacts and safety issues, especially SAR. These necessitate modification of the imaging protocols used at 1.5T. Ongoing physicist input, and technical support is essential. Hardware advances especially improved gradients, dedicated coils and sequences are very useful in this regard. The above mentioned challenges also create opportunities at 3T, with improvement in MRA, *syngo* ASL, *syngo* SWI, fMRI and MRS – all of which have distinctive applications in pediatrics. The SNR gain can be used as a trade-off, when compensating for the altered relaxation times and 3T specific artefacts.

3T MRI has the potential to image all the systems in pediatrics. Optimising the parameters with due consideration to specific pediatric features, such as the increased water content of non myelinated brain, is essential. Some 3T artefacts inherent to specific anatomic regions, like the dielectric effects encountered in adult abdominal imaging, are less problematic in pediatrics due the smaller size. On the other hand, the neonatal brain and pediatric spine are difficult to image at 3T. Several factors also limit cardiac imaging at present. Further improvements in coil technology and newer sequences may help overcome the challenges that remain.

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