BODY MR IMAGING AT CHILDREN'S NATIONAL

A Brief Guide to MRI Imaging

by Hansel J Otero M.D.

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Chapter 1: *Body MRI Basics*

Basic MRI Terminology

Coil: Loop(s) of wire to create or defect magnetic fields within the MRI. Proper coil type and size are imperative for achieving the appropriate field of view and high-resolution images.

DWI: Diffusion Weighted Imaging. Measures Brownian motion of water molecules within a voxel of tissue. Sequences are based on echo planar imaging with inherent T2 characteristics, thus, there is a potential for T2 shine-through. Corresponding low signal on ADC map images confirm restricted diffusion. B-values determine the degree of diffusion weighting. Examples include cellular swelling (i.e. acute stroke), dense cellularity (i.e. certain malignancies), and abscesses.

ETL: Echo Train Length. Number of 180-degree radiofrequency pulses and echo sampling for fast/turbo spin echo imaging.

Fast Spin Echo: Multiple rapid 180-degree rephrasing pulses are used for each initial 90-degree pulse. Favors T2 weighting.

FOV: Field of view is the imaged area (2 or 3 dimensions) which is subdivided into rows and columns (matrix). This determines the voxel size. The smaller the FOV (keeping the matrix constant), the smaller the voxel which results in increased resolution. The tradeoff is decreased signal-to-noise ratio. Increasing the FOV also decreases aliasing.

GRE: Gradient Echo. Echo signal is created with free induction decay following reversal/alteration of magnetic gradients. Field inhomogeneity results in increased susceptibility artifacts which is sometimes taken advantage of (SW/SWAN sequences).

K-space: Conceptual matrix containing raw MRI data which is converted via the Fourier transform to an image. Central k-space = contrast. Peripheral k-space = spatial resolution. Radial k-space sampling (Propeller sequences), for instance, samples k-space quickly but redundantly to decrease motion artifact.

Matrix: Rows and columns (representing phase and frequency) of the FOV which determine voxel size and, thus, resolution. For example, dividing the FOV into more rows and columns increases the matrix size and results in smaller voxels, increased resolution, but also increased noise. Tip: increase the matrix in the frequency direction to increase resolution without adding time.

NEX: Number of Excitations. Number of times k-space is sampled (i.e. NEX of 2 scans the FOV twice). Increasing the NEX, increases the signal-to-noise ratio but results in increased scan time.

PD: Proton Density. Long TR, short TE diminishes T1 and T2 differences emphasizing the number of protons in a tissue volume.

Scan Time: (TR * phase encoding steps * NEX) / ETL. Shortening scan time not only increases throughput but also potential decreases motion artifact and anesthesia time if applicable.

Sequences: Predetermined arrangement of radiofrequency or gradient pulses within the magnetic field in time.

Spin Echo: In a magnetic field, a 90-degree flip radiofrequency pulse. As the protons decay (inherent tissue T1/T2 characteristics), another 180-degree inversion pulse is applied. The protons then refocus resulting in an echo that is sampled at a given TE.

T1: Longitudinal relaxation time which is tissue-specific. Short TR, short TE spin echo imaging results in T1 weighted sequences. Contrast produces T1 shortening (increased/bright signal) on T1 sequences.

T2: Transverse (spin-spin) relaxation time which is also tissue-specific. Long TR, long TE spin echo imaging results in T2 weighted sequences.

T2*: T2 interactions with local field inhomogeneity. T2* is always less than T2.

TE: Echo Time. In spin-echo imaging, time between 90-degree radiofrequency pulse and signal sampling. Affects T1/T2 weighting.

TR: Time of Repetition. Time between radiofrequency pulses. Effects T1/T2 weighting and is important in determining overall scan time.

T1 T2 and PD Weighting/Contrast

Spin Echo Sequence -- Choice of TR and TE for Contrast Weighting --		
TR	TE	
	Short (Less than 40 milliseconds)	Long (More than 75 milliseconds)
Short (less than 750 Milliseconds)	T_1 - Weighted	NO! Contrast Means Nothing!
Long (More than 1500 milliseconds)	PD - Weighted	T_2 - Weighted

Gradient Echo Sequence -- Choice of TR, TE and Flip Angle ⍰ for Contrast Weighting --		
Flip Angle	TE	
	Short (Less than 15 milliseconds)	Long (More than 30 milliseconds)
Short (less than 40 degrees)	PD - Weighted	T_2 - Weighted
Long (More than 50 degrees)	T_1 - Weighted	NO! Contrast Means Nothing!
Notes: TR is always short (less than 750 ms) compared with SE sequences. TRs require larger flip angles to show T1 weighting; at short TRs, even 45° flip angles may have T1 weighting		

Motion Correction

1. Breath Holding: Eliminates motion in willing and able patients (older, healthy kids). Necessitates fast sequences.

2. Respiratory Triggering: Compiles the image based on data sampled only during a portion of the respiratory cycle. Because some data is discarded, the scan time is increased. Most important for low thoracic and upper abdominal imaging.

3. Cardiac Gating: Similar to respiratory gating in that only data sampled during certain portions of the cardiac cycle are used to decreased motion variation.

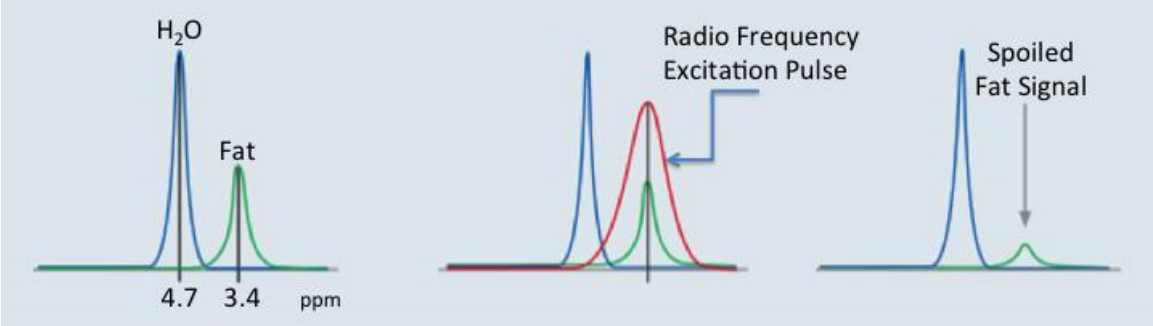
4. Radial sampling of K-space (PROPELLER-GE/ BLADE-Siemens): K-space is sampled in a radial fashion, building central redundancy. This ultimately decreases the ghosting/aliasing artifact typically associated with motion.

5. Reducing Scan Time: MRI studies can be anxious for patients who often become restless during long scans. Keeping a scan short can have a great impact on motion artifact, particularly if vital sequences such as post contrast imaging are saved for the end.

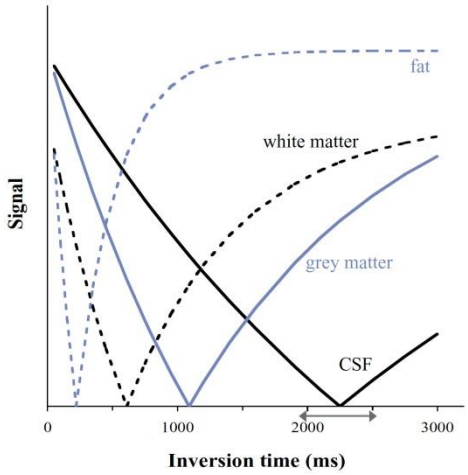
6. Sedation: If motion cannot be overcome by other means, sedation may be required.

Fat Suppression

1. Fat Saturation: Frequency selective radiofrequency pulse is applied to saturate fat-bound protons. Then spoiler gradients are applied that de-phases and eliminates the fat signal, thus, leaving water-bound protons. This method is particularly sensitive to field inhomogeneity.



2. Inversion recovery:
    a. **Short tau inversion recovery (STIR).** A 180-degree inversion pulse is applied. The TI Inversion Pulse time is set (to about 200 milliseconds on 1.5T magnets and about 250 milliseconds on 3.0T magnets) so that fat-bound proton excitation pulse is zero, eliminating them from the signal. This technique is insensitive to field inhomogeneity.
    b. **Fluid Attenuated Inversion Recovery (FLAIR).** Sets the inversion time to CSF (TI is between 2000 milliseconds at 1.5T and 2500 milliseconds at 3.0T) nulling instead of fat nulling.



3. Dixon Technique: Utilizes chemical shift – differences between fat and water-bound proton resonance frequencies. Immediately following excitation, water and fat protons are aligned in the same phase. Based on differences in precession via chemical shift, water and fat protons can be imaged in-phase (additive signal) or out-phase (subtractive signal). Tissues with microscopic fat (such as adrenal adenomas) will experience a signal drop on out-phase imaging. India ink artifact is the result of signal void in voxels where opposed water and fat protons cancel each over out.
    1.5Tesla in-phase is 0, 4.4, 8.8…., out-of-phase is 2.2, 6.6, 11.0 …

If you think that every 180-degrees happens every 2.2 milliseconds
Even whole counting numbers (0,2,4,6,8,10…) multiplied by 2.2 milliseconds gives you the correct in-phase
Odd whole counting numbers (1,3,5,7,9…) multiplied by 2.2 milliseconds gives you the correct out-of-phase

3.0 Tesla in-phase is 0, 2.2, 4.4…, out-of-phase is 1.1, 3.3, 5.5…
at 3T things are spinning twice as fast so 180-degrees happens every 1.1 milliseconds
Even whole counting numbers (0,2,4,6,8,10…) multiplied by 1.1 milliseconds gives you the correct in-phase
Odd whole counting numbers (1,3,5,7,9…) multiplied by 1.1 milliseconds gives you the correct out-of-phase

4. IDEAL (Iterative decomposition of water and fat with echo asymmetry and least-squares estimation) and VIBE (Volumetric Interpolated Breath Hold Examination) utilize these principles allowing four images to be deconstructed from a single sequence: 1) Water Image (fat suppressed), 2) Fat Image (water suppressed), 3) In-Phase Image, and 4) Out-Phase image. These sequences are insensitive to field inhomogeneity. TR is increased (hence time) to allow for the necessary data acquisition.

Key Reference:

Fat Suppression Techniques –A Short Overview
Wilhelm Horger; Berthold Kiefer Siemens Healthcare
http://static.healthcare.siemens.com/siemens_hwem-hwem_ssxa_websites-context-root/wcm/idc/siemens_hwem-hwem_ssxa_websites-context-root/wcm/idc/groups/public/@global/@imaging/@mri/documents/download/mdaw/mtmz/~edisp/fat_suppression_techniques-00033824.pdf
http://mri-q.com/in-phaseout-of-phase.html
http://www.scmr.org/assets/files/members/documents/GE_physics_8_for_SCMR.pdf
https://ucrfisicamedica.files.wordpress.com/2010/10/mri.pdf

IV Contrast

Intravenous Contrast:

Gadolinium based intravenous contrast agents are crucial for many diagnostic indications. The two main risks to be aware of are 1) Adverse Reactions and 2) Nephrogenic Systemic Fibrosis (NSF).

1) Adverse Reactions: Allergic or allergic-like reactions are rare with gadolinium-based contrast agents and occur much less than with iodinated contrast. Prior allergic reaction to gadolinium contrast agents are the clearest contraindication. Administration, however, may still be considered depending on the clinical situation with appropriate premedication. Other allergic reactions such as to iodinated contrast or shellfish are not contraindications although any allergy increases patient's odds of having another unrelated allergy. If there remains a high level of clinical concern by a patient or provider, consider premedication.
2) NSF: Following appropriate education, NSF has become very rare. Risk factors should be evaluated on all patients prior to administering gadolinium contrast. Both 1) Chronic Kidney Disease (with or without dialysis) with a GFR of >30 and 2) Acute Kidney Injury are contraindications. Be wary of acute

kidney injury as the calculated GFR based on serum creatinine can be unreliable. If in question, consider another study or nephrology consultation as clinically appropriate.

Contrast Agents:

Group I: Older class of gadolinium contrast. Highest association with NSF.
Gadopentetate dimeglumine (Magnevist)

Group II: Few, if any, NSF cases.
Gadobenate dimeglumine (MultiHance)
Gadobutrol (Gadovist)*
Gadoterate meglumine (Dotarem)*
Gadoteridol (ProHance)

Group III: Recent specialty agents.
Gadofosveset trisodium (Ablavar) – Blood pool agent, good for vascular/MRA.
Gadoxetate disodium (Eovist) – Hepatobiliary agent.

Dotarem is our contrast agent of choice for most applications. There is a theoretical benefit due to macrocyclic binding of gadolinium which theoretically diminishes disassociation. The exception is in young children (<2 years old) where we use Gadovist due to FDA approval.

Consider Ablavar when evaluating vascular malformation. The contrast agent stays in the blood pool allowing improved visualization with MRA techniques.

Eovist is often used for hepatobiliary imaging. Initial first pass imaging is similar to other agents, however, delayed 20-minute imaging can be acquired to take advantage of the hepatobiliary excretion.

Key References:
ACR Contrast Manual
http://www.acr.org/Quality-Safety/Resources/Contrast-Manual

Pediatric GFR Calculator
National Kidney Foundation – Pediatric GFR Calculator
https://www.kidney.org/professionals/Kdoqi/gfr_calculatorPed

Advanced Imaging Sequences

General Considerations: There are many MR sequences all with different levels of complexity from confusing to impossible to understand. To complicate this complicated topic, sequences are often manufacturer specific. What GE calls SSFSE, Siemens calls HASTE. What Siemens calls RESTORE, Philips calls DRIVE. Some sequences are similar but are proprietarily different. As such, it is difficult to find a single source to explain what all these mean and their applications. Below are a few of such advanced imaging sequences which we use often at CNMC.

Post-contrast Sequences:

1. Spin Echo T1: Gadolinium causes T1 shortening. Pre-contrast T1 imaging is important to exclude other causes of inherent T1 shortening (fat, blood products, mineralization, etc.).
2. LAVA: Liver Acquisition with Volume Acquisition. Fast spoiled gradient echo technique which allows for quick T1 imaging with homogenous fat suppression. Speed allows for rapid multiphase imaging. LAVA-Flex is a modified 3D sequence that generates water/fat separation type fat suppression like IDEAL/VIBE sequences.

Other Core Body Sequences:

1. CUBE: Fast/Turbo spin echo 3D sequence which can generate sub-millimeter isotropic (square) voxels. Isotropic imaging improves reformat constructions. As a spin echo sequence, can be T1, T2, PD, or FLAIR weighted.
2. FIESTA: Fast Imaging Employing Steady-state Acquisition. Steady state gradient echo sequence using very fast TR and TE resulting in heavy T2 (i.e. water) weighting. Tissue contrast is degraded, however. The result can be used to create multiphase images (e.g.: MR enterography cine sequence) or cardiac gated single-phase images (i.e.; bright blood non-contrast angiography).

Angiographic Sequences:

1. Non-contrast Angiography (TOF): Time of Flight MR Angiography. Gradient echo sequence in which the imaged slice (in 2D methods) or voxel (3D methods) is saturated resulting in suppressed background signal. Non-saturated blood flows into the slice/voxel, allowing for so-called flow related enhancement. A pre-saturation pulse on one side of a slice can suppress directional flow as well (i.e. negating downward flow from a neck MRA would suppress venous signal).
2. Non-contrast Angiography (FIESTA): Heavy fluid contrast and high-resolution results in good visualization of vessels. Think cranial nerves in neuro FIESTA imaging.
3. Time-resolved MRA (TRICKS/TWIST): Typically presented as a series of MIP images displaying passage of the contrast bolus (might contain 20+ images at a rate of 2-5 frames per second). It begins by acquiring a non-contrast, full-resolution image of the anatomy of interest. During passage of the contrast, the center of k-space is sampled much more frequently than the periphery. The data from the different partial k-space samplings are combined to create a series of time-resolved images with satisfactory spatial resolution. The original non-contrast image is used as a mask for subtraction to improve vascular conspicuity.
4. Multiphase (dynamic) T1 FS Images (MPH LAVA/VIBE): 3Dl spoiled gradient echo pulse sequence using segmented special water/fat separation technique to provide enhanced image contrast and uniform fat suppression. It allows for multiple time points imaging as contrast progresses, during short breath holds (must common for liver imaging- arterial, late arterial, portal venous-venous/equilibrium phases- but also used in vascular malformations and other tumors)
5. InHance: GE specific which include InHance 2D, InHance 3D, and InHance IR methods. Variations on TOF imaging and, in the case of InHance IR, uses inversion recovery to suppress background tissue and venous flow resulting in excellent non-contrast MR angiography.

Double Inversion Recovery: Black blood sequence primarily used in cardiac imaging. First 180-degree pulse is applied to all slices, inverting magnetization of all tissues. The second 180-degree pulse immediately follows but only at the imaged slice, re-inverting tissue in that slice only. This, moving blood remains inverted and is not sampled.

Chapter 2: *MRI Protocoling*

Goals:

1. To validate the clinical indication for the study including but not limited to: need for contrast, multiple studies, area of coverage
2. To guide the technologist in planning the exam, including coil selection (expected coverage), need for respiratory bellow/EKG leads, type of contrast, power injector
3. To plan for the best diagnostic images to answer the clinical question without exposing the patient to unnecessary and potentially harmful sedation, contrast, stress, noise, heat

Process:

1. All non-emergent protocols (i.e.; excluding emergencies and same day add-ons) should be in RIS 24 hours before the study
2. Notes should include: 1) laterality/coverage, 2) contrast selection, 3) Power injector or not
3. Orders for contrast should be signed at the time of protocoling. If orders are not available a phone order is ok
4. The radiologist is in charge of cancelling/explaining delays due to: 1) unclear orders/insufficient clinical information that should have been obtained at the time of protocoling 2) Safety information not communicated to the lead tech
5. Customize protocols are allow and often necessary but discouraged

Advantages of Standard Protocols:

1. Easier for the tech to concentrate on patient communication and sequence prescription details
2. Practice leads to perfection: using the same sequences, in the same order, allow for better performance of technologist
3. Allow to complete quality studies that finish within the allotted hour
4. Faster QA'ing when the sequences follow a routine (expected) order
5. Anticipate questions from clinicians and subspecialty interpretation beyond diagnosis (staging of malignancies, respectability, vascularity, slow flow vs fast flow etc.)

<u>All standard protocols available in RIS (Centricity and soon RadNet) are listed below</u>

Chapter 3: *Body Protocols*

Body Protocol Sections

Chest

Generic Chest

1. Axial LAVA- Breath Hold
2. Axial T2 FS PROPELLER
3. Coronal SSFSE
4. Coronal Double IR
5. Axial DWI RTr
6. Coronal FIESTA (MRA w/o GD+)(TR<4.0)

Optional Contrast

7. Axial LAVA GD+
8. Coronal or Sagittal T1 FS GD+

Liszewski MC, Hersman FW, Altes TA, Ohno Y, Ciet P, Warfield SK, Lee EY. Magnetic resonance imaging of pediatric lung parenchyma, airways, vasculature, ventilation, and perfusion: state of the art. Radiol Clin North Am. 2013 Jul;51(4):555

Mediastinum

1. Axial FSPGR IP/OOP
2. Axial T2 FS PROPELLER
3. Axial FIESTA (Above the heart only)
4. Coronal DOUBLE IR T1
5. Coronal SSFSE FS
6. Axial DWI (RTr)

Optional Contrast

7. Axial LAVA GD+
8. Coronal T1 FS GD+

Ackman JB. A practical guide to nonvascular thoracic magnetic resonance imaging. J Thorac Imaging. 2014 Jan;29(1):17

Thymus

1. Axial FSPGR IP/OOP
2. Axial T2 FS PROPELLER
3. Coronal DBL IR T2 FS, LONG TE
4. Coronal DOUBLE IR

Optional Contrast

5. Axial LAVA PRE-GD
6. Axial MPH LAVA GD+ (30 s, 60s, 3 m)
7. Coronal T1 FS POST GD

Ackman JB, Wu CC. MRI of the thymus. AJR Am J Roentgenol. 2011 Jul;197(1):W15-20

Rib Lesion

1. Axial LAVA
2. Axial T2 FS PROPELLER
3. Coronal SSFSE
4. Coronal T1

5. Sagittal SSFSE

contrast

6. Axial LAVA
7. Coronal T1 FS GD+

OPTIONAL

8. Coronal (or Sagittal) T2 FS RTr

Vascular Ring (Stridor)

1. Coronal DOUBLE IR
2. Axial 2D FIESTA
3. Sagittal FSPGR CINE (AIRWAY)
4. Coronal FSPGR CINE (AIRWAY)

IF RING IS CONFIRMED: CONTRAST

5. Coronal TRICKS (TR: 2.5 sec, 30 phases)
6. Axial 3D INHANCE
7. Axial LAVA (or FSPGR if LAVA does not work)

OPTIONAL

8. Axial T2 FS PROPELLER
9. Axial LAVA-PRE
10. Coronal FIESTA

Smith BM, Lu JC, Dorfman AL, Mahani MG, Agarwal PP. Rings and slings revisited. Magnetic Resonance Imaging Clin N Am. 2015 Feb; 23(1): 127

Chest Vascular Malformation

1. Axial LAVA
2. Axial T2 FS PROPELLER
3. Coronal FSEIR RTr
4. Coronal T1

Dynamic Contrast

5. Coronal TRICKS (Temp Res: 2.5 s; 20 phases)
6. Axial LAVA GD+
7. Coronal LAVA GD+

OPTIONAL

8. Delay Axial LAVA GD+

Flors L, Leiva-Salinas C, Maged IM, Norton PT, Matsumoto AH, Angle JF, Hugo Bonatti M, Park AW, Ahmad EA, Bozlar U, Housseini AM, Huerta TE, Hagspiel KD. MR imaging of soft-tissue vascular malformations: diagnosis, classification, and therapy follow-up. Radiographics. 2011 Sep-Oct; 31(5):1321

Pectus Excavatum

1. Axial LAVA BH
2. Axial SSFSE
3. Coronal T2 PROPELLER RTr

ABDOMEN

MR Enterography (Crohn's/IBD)

1. Coronal SSFSE T2 NO FS ABD/PEL
2. Coronal LAVA FLEX BH ABD/PEL
3. Axial SSFSE T2 with FS
4. Sagittal SS FSE T2 WITH FS
5. Axial DWI (bowel)

Dynamic Contrast

6. Axial LAVA GD+
7. Coronal LAVA GD+
8. Axial T1 FS PELVIS GD+
9. Coronal MPH FIESTA

Mollard BJ, Smith EA, Dillman JR. Pediatric MR enterography: technique and approach to interpretation-how we do it. Radiology. 2015 Jan;274(1):29-43. doi: 10.1148/radiol.14122449

Appendicitis (Fast MRI)

1. Coronal SSFSE ABD/PELVIS
2. Coronal SSFSE FS ABD/PELVIS
3. Axial SSFSE ABD/PELVIS
4. Axial T2 FS RTr PELVIS
5. DWI RTr Lower abdomen/pelvis only

Dillman JR, Gadepalli S, Sroufe NS, Davenport MS, Smith E, Chong ST, Mazza MB, Strouse PJ. Equivocal Pediatric Appendicitis: Unenhanced MR Imaging Protocol for Non-sedated Children-A Clinical Effectiveness Study. Radiology. 2015 Oct 9:150941.

Abdomen Tumor

Breath Hold

1. Coronal T1 PROPELLER
2. Axial T2 FS RTr PROPELLER
3. Axial LAVA
4. Coronal T2 FS RTr
5. Axial DWI
6. Coronal TRICKS
7. Axial LAVA GD+
8. Coronal LAVA GD+
   OPTIONAL
9. Sagittal T1 FS GD+

Free Breathing (heavy breathers)

1. Coronal T1 PROPELLER
2. Axial T2 FS RTr PROPELLER
3. Axial LAVA
4. Coronal T2 FS RTr
5. Axial DWI
6. Coronal TRICKS
7. Axial T1 FS GD+
8. Coronal T1 FS GD+
   OPTIONAL
9. Sagittal T1 FS GD+

Kidney Mass

1. Sagittal SSFSE w/o FS
2. Axial T2 FS RTr PROPELLER
3. Coronal Oblique T2 FS 3D CUBE
4. Coronal Oblique T1 PROPELLER
5. Axial DWI (RTr)

DYNAMIC CONTRAST

6. Coronal Oblique Multiphase LAVA GD+
7. Axial T1 FS GD+ RTr
8. Axial InHance GD+ (MRA)

OPTIONAL

9. 15-minute delay Axial T1 FS (if diverticulum suspected)
10. Coronal Oblique FSEIR GD+ (for suspected pyelonephritis)

Renal Artery MRA

1. Coronal oblique T2 FS PROPELLER
2. Ax InHance

POWER INJECTOR: Rate: 1-1.5 cc/sec, minimum volume: 4 cc, TR <3s, scan duration: 90 seconds

3. GD+ Coronal (True Coronal) TRICKS
4. GD+ Coronal (True Coronal) InHance
5. GD+ Coronal 3D CUBE T1 FS

Klee D, Lanzman RS, Blondin D, Schmitt P, Oh J, Salgin B, Mayatepek E, Antoch G, Schaper J. Non-enhanced ECG-gated respiratory-triggered 3-D steady-state free-precession MR angiography with slab-selective inversion: initial experience in visualization of renal arteries in free-breathing children without renal artery abnormality. Pediatr Radiol. 2012 Jul;42(7):785-90. doi: 10.1007/s00247-011-2343-5

MR Urogram

Give LASIX and CLAMP FOLEY

1. SAG T2 SSFSE
2. Axial T2 FS RTr PROPELLER
3. Coronal Obli T2 FS RTr
4. Coronal Obli 3D T2 FS RTr

UNCLAMP FOLEY

DYNAMIC CONTRAST

5. COR LAVA FLEX +GAD (including mask to act as pre)

OPTIONAL

6. Ax T1 FS (Delay)

Delgado J, Bedoya MA, Adeb M, Carson RH, Johnson AM, Khrichenko D, Canning DA, Darge K. Optimizing functional MR urography: prime time for a 30-minutes-or-less fMRU. Pediatr Radiol. 2015 Aug;45(9):1333-43

Liver Transplant

1. Axial T2 RTr PROPELLER (Skip 0)
2. Axial LAVA
3. Coronal Double IR
4. Coronal T2 FS RTr
5. Axial DWI
6. 3D MRCP RTr

CONTRAST

7. Axial MPH LAVA
8. Coronal 3D InHance inflow
9. Axial T1 FS

Optional

10. Coronal FIESTA MPH (if InHance fails)
11. 2D Thick or Thin Slab MRCP (if 3D fails)

Conservative adaptation from Georgetown liver transplant protocol:

T2 HASTE (SSFSE), T1 DIXON 4 ECHO, T2 HASTE IR (SSFSE IR or FS), TRUE FISP (FIESTA), PRE-GAD T1 VIBE (LAVA) FS, DYNAMIC T1 VIBE (LAVA) FAT SAT X 3, DIFFUSION/ADC (DWI), DELAYED T1 VIBE FAT SAT (LAVA)

Ferriscan

1. Axial T1 Propeller
2. Axial T2 FS RTr
3. Axial T2* MAP (BH IF POSSIBLE)
4. Axial DWI
5. *Axial Liver 6 TE (11 Slices 5/5 or 6/6 -FOV must cover entire torso and saline bag)
6. *Duplicate previous series (only TE changes-9TE)
7. *Duplicate previous series(12TE) Manual pre-scan
8. *Duplicate previous series(15TE) Manual pre-scan
9. *Duplicate previous series(18TE) Manual pre-scan

*FERRISCAN sequences needed (all others are optional if combining with other liver study)

Liver Tumor (Hepatobiliary – Eovist)

1. Axial T1 2D DUAL ECHO (IP/OOP)
2. Axial LAVA Pre-contrast

*** POWER INJECTION ***0.1 ml/kg

3. Axial LAVA (At 15, 35 and 70 secs after injection)
4. Coronal T2 FS RTr
5. Coronal 3D MRCP RTr
6. Axial DWI RTr
7. Axial InHance
8. Axial PROPELLER T2 FS RTr
9. Axial LAVA (20 MIN. DELAY)
10. Coronal LAVA (20 MIN. DELAY)

Ringe KI, Husarik DB, Sirlin CB, Merkle EM. Gadoxetate disodium-enhanced MRI of the liver: part 1, protocol optimization and lesion appearance in the non-cirrhotic liver. AJR Am J Roentgenol. 2010 Jul;195(1):13-28. doi: 10.2214/AJR.10.4392.

MRCP

1. Coronal SSFSE FS with BH (7 mm skip 0)
2. Axial T2 SSFSE (3 mm) no FS no BH
3. Coronal 3D MRCP RTr
4. Axial T2 FS RTr Propeller

OPTIONAL

5. Coronal FSEIR RTr
6. 2D Thick or thin Slab MRCP (if 3D MRCP fails)

Egbert ND, Bloom DA, Dillman JR. Magnetic resonance imaging of the pediatric pancreatobiliary system. Magnetic Resonance Imaging Clin N Am. 2013 Nov;21(4):681-96. doi: 10.1016/j.mric.2013.04.009

MRCP with Contrast (EOVIST)

(Evaluation of bile duct injury due to trauma, anastomotic leak or biloma)

1. Axial LAVA pre
   ***Power Inject ***
2. Axial LAVA at 15, 35, 70 secs
3. Coronal SSFSE FS with BH (7 mm skip 0)
4. Axial T2 FS RTr Propeller
5. Coronal 3D MRCP RTr
6. Coronal and Axial LAVA 10-20-30 Minutes
7. Additional delays up to 45-minute delay

Egbert ND, Bloom DA, Dillman JR. Magnetic resonance imaging of the pediatric pancreatobiliary system. Magnetic Resonance Imaging Clin N Am. 2013 Nov;21(4):681-96. doi: 10.1016/j.mric.2013.04.009

Hepatoblastoma (Consider switching to Eovist protocol)

1. Axial Lava-Flex
2. Axial T2 FS RTr PROPELLER
3. Axial DWI
4. Coronal FIESTA MPH
5. Coronal Double IR

Contrast

6. Coronal MRA Tricks (Arterial to PV Phase)
7. Axial InHance
8. Axial LAVA

Pancreas

1. Axial T1 2D Dual-Echo
2. Axial T2 FS RTr
3. Axial DWI RTr
4. Axial T1 PROPELLER
5. Coronal 3D MRCP RTr

Dynamic contrast

6. Axial LAVA-FLEX MPH (3 phases + mask)
7. Coronal LAVA-FLEX
8. Axial Inhance

OPTIONAL

9. Axial T1 FS

Mesenteric Tumor

1. Coronal T1 Abdomen/pelvis
2. Coronal SSFSE FS Abdomen/Pelvis
3. Coronal MPH FIESTA
4. Ax T2 FS PROPELLER
5. Ax DWI
6. Ax LAVA

CONTRAST

7. Ax MPH LAVA (15 sec, 45 secs, 60 secs, 90 sec)
8. Coronal T1 FS

OPTIONAL

9. Sag T2 FS RTr

Adrenal Tumor

1. Coronal T1 PROPELLER
2. Axial LAVA (4 recons)
3. Axial T2 FS PROPELLER RTr (abdomen only)
4. Coronal T2 FS RTr
5. Axial DWI
6. Axial LAVA +GD
7. Coronal T1 FS +GD

Nour-Eldin NE, Abdelmonem O, Tawfik AM, Naguib NN, Klingebiel T, Rolle U, Schwabe D, Harth M, Eltoukhy MM, Vogl TJ. Pediatric primary and metastatic neuroblastoma: MRI findings: pictorial review. Magnetic Resonance Imaging. 2012 Sep;30(7):893-906

MALS (Median Arcuate Ligament Syndrome)

1. Axial LAVA BH (Upper abdomen)
2. Axial 3D INHANCE
3. Sagittal Oblique FSPGR CINE Inspiration (Angled Along Celiac Artery Origin)
4. Sagittal Oblique FSPGR CINE Expiration (2 SETS)

5. Sagittal MULTIPHASE FIESTA (celiac artery)
6. Coronal SSFSE T2 FS

Gaucher (including infiltrative disease)

1. Axial T1 PROPELLER
2. Axial T2 FS RTr
3. Axial SSFSE
4. Coronal LAVA-FLEX
5. Coronal SSFSE with FS
6. Axial DWI

MRV Abdomen

1. Axial T2 FS PROPELLER RTr
2. Axial LAVA BH

POWER INJECTION Rate: 1.0 cc/sec

3. Coronal TRICKS (Temp res ~3 sec, run for 2 minutes)
4. Axial LAVA
5. Coronal 3D FSPGR
6. Axial FIESTA

Pelvis

Female Pelvis

1. Axial LAVA with BH
2. Axial T2 FS
3. Sagittal T2
4. Sagittal T1
5. Coronal T2 SSFSE with FS
6. Axial DWI (500, 1000)

If Contrast:

7. Axial LAVA-FLEX GD+ with BH
8. Coronal FSPGR 3D

OPTIONAL:

9. Long Axis Uterus T2 (Uterine anomalies)
10. Short Axis Uterus T2 (Myometrium)

Acquisition Techniques for MR of the Uterus and Adnexa Nghiem-SCBT-MR-2011

Perirectal Disease

1. Axial oblique T2
2. Axial oblique T2 FS
3. Coronal oblique T1 IDEAL
4. Coronal oblique T2 FS

5. Axial oblique T1 FS GD+
6. Coronal oblique T1 FS GD+

OPTIONAL

7. SAG T1 FS
8. Sag T2 FS

Morris J, Spencer JA, Ambrose NS. MR imaging classification of perianal fistulas and its implications for patient management. Radiographics. 2000 May-Jun;20(3):623-35

O'Malley RB, Al-Hawary MM, Kaza RK, Wasnik AP, Liu PS, Hussain HK. Rectal imaging: part 2, Perianal fistula evaluation on pelvic MRI--what the radiologist needs to know. AJR Am J Roentgenol. 2012 Jul;199(1): W43-53

MRV Pelvis (suspected May-Thurner Syndrome)

7. Axial T2 FS PROPELLER RTr
8. Axial LAVA (from bifurcation to femoral heads)

POWER INJECTION Rate: 1.0 cc/sec

9. Coronal TRICKS (Temp res ~4 sec, run for 2minutes)
10. Axial LAVA
11. Coronal 3D FSPGR
12. Ax Inhance

OPTIONAL

13. Ax MPH FIESTA

Chest/Abdomen/Pelvis

Venous Access

1. Coronal MULTIPHASE FIESTA
2. Axial 2D FIESTA MRV PELVIS
3. Axial 2D FIESTA MRV ABDOMEN
4. Axial 2D FIESTA MRV CHEST/MID NECK

Opsoclonus/Myoclonus (Suspected Neuroblastoma)

1. Coronal DOUBLE IR Chest and Abdomen
2. Axial DWI RTr Chest
3. Axial T2 FS PROPELLER RTr Chest
4. Coronal T1 PROPELLER Abdomen/Pelvis
5. Axial T2 FS PROPELLER Abdomen/Pelvis
6. Axial DWI RTr Abdomen/Pelvis

***OPTIONAL GD (If tumor seen) ***

7. AX T1 FS post
8. Coronal LAVA post

Whole Body (Genetic Oncology/ FUO)

1. Coronal T1
2. Coronal FSEIR
3. Axial DWI
4. Axial FSEIR

OPTIONAL

5. SAG STIR of Spine

*** REPEAT Protocol for Lower area as needed (without RTr or PROPELLER) ***

Davis JT, Kwatra N, Schooler GR. Pediatric whole-body MRI: A review of current imaging techniques and clinical applications. J Magnetic Resonance Imaging. 2016 Oct;44(4):783-93. doi: 10.1002/jmri.25259

Whole Body (NF-1)

1. Coronal FSEIR (BH) (5 mm/0)
2. Axial FSEIR (5 mm/0)

Under NIH protocol for tumor volumetrics (Phase 2 Selumetinib Study)

Lymphatic Mapping (Lymphangiectasia- Chest, abdomen, pelvis and upper thighs)

1. Coronal 3D SPACE (heavily T2 weighted) (MRCP equivalent)
2. Coronal 3D STIR
3. Coronal T1 PROPELLER
4. Axial High Res T2 FS RTr

SPECIALS (Neurofibromatosis)

NF 1 (Low risk)

1. Coronal FSEIR (BH) (5 mm/0)
2. Axial FSEIR (5 mm/0)

Ahlawat S. Current whole-body MRI applications in the neurofibromatosis: NF1, NF2, and schwannomatosis. Neurology. 2016 Aug 16;87(7 Suppl 1):S31-9.

NF 1 (High risk)

1. COR T1 IDEAL (Water + IP)
2. COR FSEIR (might require RTr or cardiac gating based on anatomy)
3. AX FSEIR or T2 IDEAL
4. AX T1 FS + GAD
5. COR T1 FS + GAD

Yu YH, Wu JT, Ye J, Chen MX. Radiological findings of malignant peripheral nerve sheath tumor: reports of six cases and review of literature. World J Surgical Oncology. 2016 May 10;14:142

Chapter 4*: Guide to MRI QA*

The overarching objective is to get the best diagnostic study possible to answer the clinical question in a safely manner but NOT to make diagnoses "on the fly" nor to provide definitive diagnosis of incidental findings. As oppose to adults were it rarely happens, at CNCM (and most children's hospitals) almost all MRI's are QA'ed for:

4. Coverage
5. Motion
6. Artifacts
7. Additional special sequences/planes

QA'ing studies should be done PROMPTLY. To avoid unnecessary delays, the MRI technologists at CNMC:

1. Do not QA standard knee studies ("knee injury protocol")
2. Call the radiologist only AFTER administering contrast in all MRE cases
3. Move to administer contrast, if there is no response from the radiologist 5 minutes after initial page

Coverage

Coverage is inversely related to imaging time (axial) AND in plane resolution. Hence, limiting coverage to the area of clinical concern is key for safer (decreased sedation time), more comfortable studies and is also crucial in assuring access ON TIME to MRI for all CNMC patients

1. Limiting coverage to the organ of interest (kidneys) or appropriate anatomic region (e.g. only abdomen for liver, pancreas, adrenals and only pelvis for ovaries, uterus, testes) is important to maintain diagnostic *spatial resolution*.

The in-plane spatial resolution is determined by FOV and matrix. For example, increasing the FOV from 30 cm to 40 cm with a similar 256x256 matrix, would increase the pixel size from 1.1 mm (smallest size of object detected) to 1.6 mm (See figures 1 and 2).

Alternatively, if one were to increase the matrix size to 320x320 to be able to image the 40 cm without losing resolution, the imaging time would increase by 25%.

In summary, increasing the area of coverage either decreases the resolution of the images or increases the imaging time

Unaware clinicians mistakenly order MRIs the same way one would order a CT (i.e. requesting abdomen and pelvis as a single entity), to the best of our ability, this should be avoided. Reasonable clinical scenarios that require imaging the abdomen and pelvis include MR enterography, MR Urogram, bowel neoplasms, mesenteric malignancies, paraneoplastic syndromes

2. If a ***large field of view*** is necessary, coronal (or sagittal) plane is preferred (for determining disease extension in non-localized exams such as the limping toddler or large vascular malformations) with limited axial imaging to provide anatomic detail. Axial can be limited by deciding on a smaller area of interest from the coronal plane OR imaging with thicker slices

3. Going from a large FOV "exploratory" sequence to a small FOV "high resolution" sequence might require changing the coil. Planning accordingly is required because a small FOV with a larger coil or improper positioning might lead to aliasing ("wrap around") artifact

Motion

Motion is the single most common artifact and a key determinant of quality of MR images. In dealing with motion, one should quickly decide if this is voluntary, involuntary predictable (cardiac, breathing) or involuntary unpredictable motion (cough or tremor).

1. The first and most important tool to avoid motion is to create a comfortable friendly environment and engage the patient thoroughly explaining the need to minimize motion in order to get a higher quality faster study. Smaller or inexperience patient might require a break in between sequences. Avoiding a full bladder and explaining when and how to hold their breath are also key. Appropriate pain management might also be needed. This aspect of our practice is completely reliant on the technologists. The only questions for the radiologist are:
    a. Are these images of diagnostic quality?
    b. Should the patient receive sedation or anxiolysis instead?

2. Cardiac gating/respiratory triggering:
   In the GE systems, we can use cardiac or respiratory gating but **not both** at the same time. Respiratory triggering is available for T2-w, DWI, and MRCP sequences but not for T1. Respiratory triggering assumes a regular breathing patter detected by the bellows and while eliminates respiratory motion by averaging signal over 2-4 breathing cycles, it results in a longer acquisition (using a 40% window increases time by 2.5X) and it is more susceptible to non-respiratory motion. In non-sedated patients with motion in their images, a better approach is to image faster (half fourier- SSFSE) or to use radial acquisition (PROPELLER-below)
3. Breath hold:
   Useful in older patients able to follow commands. Available for T1, T1FS (LAVA) and post contrast images. Proper coaching is necessary BEFORE initiating the exam
4. Image faster:
   SSFSE and DWI images are fast acquisition techniques that minimize motion. In particular SSFSE minimizes in-image motion while motion can be detected between an image and the next.
5. Increase averages (NEX):
   Increasing the number of NEXs increases signal AND reduces certain type of motion by averaging it over several cycles. It does however increases time
6. Radial acquisition
   PROPELLER: (Periodically Rotated Overlapping Parallel Lines with Enhanced Reconstruction) is a motion reduction method that samples k-space (which contains the highest signal amplitude and contributes most to image contrast) in a rotating fashion using radially directed strips. By oversampling the center of k-space, it improves the signal-to-noise and contrast-to-noise. Oversampling, also provides redundancy of information and if the patient moves in-between lines, the data can be corrected (or discarded). PROPELLER only corrects ***in-plane motion***. The degree of motion correction can be substantial, and PROPELLER should be routinely used on any patient likely to not hold still during the scan.

The downside is an increased scan time (which could be partially written off by increasing the acceleration factor).

When dealing with a moving patient, also consider which sequences are the MOST IMPORTANT for diagnosis and prioritize those. Remember that insisting in repeating the same sequences will likely result in similarly inadequate images while prolonging the examination and making the patient even more prompt to motion due to fatigue. An additional strategy for dealing with motion is promptly acquiring post contrast images in those studies that absolutely require them (e.g.; MR angiography, MRE, tumor evaluation) and only after, trying to repeat some of the suboptimal quality T2-w, DWI, PD, or steady state (FIESTA) images.

Artifacts

MR artifact are too many and too complex to review here. Some common problems that require basic timely understanding are:

1. Failure of fat saturation: Chemical (traditional) fat saturation fails because of field inhomogeneity's (large FOV or too close to the coil edge), non-geometric anatomy of interest (transition from neck to chest or from pelvis to thighs), or inappropriate shimming among others. When chemical fat saturation fails or is expected to fail, inversion recovery (STIR/FSEIR) or water/fat (IDEAL/LAVA) sequences should be use
2. Aliasing ("wrap around"): Aliasing occurs when additional anatomy is outside the area of interest and signal from this "unwanted" anatomy forms an image in the opposite end of the FOV. Solutions are to increase the FOV, change the coil to a smaller surface coil, or reposition the patient to avoid the interfering anatomy (e.g. arms up in imaging the abdomen)
3. Signal loss at the edges of the coil: If the anatomy of interest is too close to the coil edge and there is significant signal loss or obvious artifact, repositioning is the only viable strategy. Signal should be checked and verified from the localizers. Attempts to overcome suboptimal positioning by increasing the excitations will cost more time with only marginal image quality gains.
4. Motion: discussed above
5. Low SNR: specially when dealing with small anatomies, consider 1) using a smaller surface coil, 2) INCREASING the slice thickness (and adding a second orthogonal plane), or 3) increasing the number of excitations (NEXs).
    a. Increasing the number of NEX is the least efficient tactic. Each additional NEX will double the imaging time while gaining ~30% in signal
    b. Doubling the slice thickness will exponentially increase the signal (x^2) without time cost

Additional sequences

Providing real time feedback on MR mage quality does not mean to improvise new sequences or request additional images to gain time or increase diagnostic confidence. It is however, the time to identify key sequences that might help establishing the diagnosis or narrowing the differential. Common examples include:

1. DWI: add to non-contrast studies to help differentiate between fluid collections and abscess or differentiate cysts from T2-bright solid neoplasms. It also helps identifying organs with physiologic restriction such as the spleen, ovaries and testes. Although coronal, sagittal and oblique DWI sequences are available, any plane other than axial is more prompt to ghosting and geometric distortion.
2. Dynamic contrast: helpful as an "unexpected" addition to regular post-contrast sequences when:
    a. Pre-contrast images suggest a vascular malformation or hemangioma.
    b. Characterizing solid tumors in the liver, pancreas, spleen
3. Delayed contrast:
    a. Connection to the collecting system (caliceal diverticula)
    b. Leaks (bile leak=Eovist; urinary leak/urinoma= dotaem/gadavist; chylous ascites/chylothorax= lymphatic injection/MR lymphangiogram)
4. Angiographic sequences: TOF/FIESTA/Inhance: if evaluating blood supply or patency of vessels
5. Additional planes: when there is distortion of normal anatomy (e.g.; large tumors, large amount of fluid, severe scoliosis) adding a third plane (usually sagittal) should be considered. However, in the majority of cases are not necessary for diagnosis.

Figure 1:

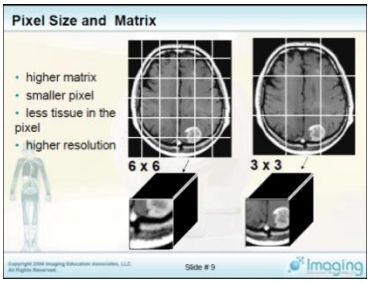
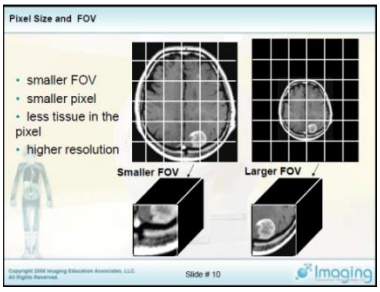


Figure2:



Note: A higher matrix eliminates the pixelated appearance of the image (higher resolution) but ***Less tissue in the pixel translates into less signal!*** (Darker images with less contrast)

Chapter 5: *MRI Contrast*

"The administration of intravascular contrast media to neonates and children is more complicated than in adults because of multiple factors including the use of small volumes of contrast medium, the use of small gauge angiocatheters, and unusual vascular access sites".

ACR Manual on Contrast Media Version 10.1 2015

1. Contrast Selection and dosage:

Agent	Chemical Properties	Dose	Clinical Use	FDA Approval
Dotarem (gadoterate)	**Gd-based, macrocyclic*, ionic**	**0.2 ml/kg**	**General**	**Not FDA approved <2 years-old**
Magnevist (gadopentetate)	**Gd-based, linear, ionic**	**0.2 ml/kg**	**General**	**Not FDA approved <2 years-old**
Eovist (gadoxetate)	**Gd-based, linear, ionic**	**0.1 ml/kg**	**Liver lesions/focal liver abnormalities (50% hepatobiliary excretion)**	**FDA approved as young as term neonates**
Ablavar (gadofosveset)	**Gd-based, linear, ionic**	**0.12 ml/kg**	**MRA, MRV, Vascular malfs(binds to albumin; ~1 hr of blood pooling after injection)**	**Not FDA approved in children**
Gadavist (gadobutrol)	**Gd-based, macrocyclic*, non-ionic**	**0.1 ml/kg**	**General**	**FDA approved as young as term neonates**

2. Using a Power Injector
    a. Indications (when dynamic contrast is desired):
        i. MR angiography
        ii. MR venography
        iii. MR Urogram
        iv. Evaluation of vascular malformations
        v. Evaluation of abdominal tumors (adrenal, hepatic, pancreatic and renal- i.e. early versus delayed enhancement and washout)
    b. Supporting Evidence:
        i. Power injector provides "superior image quality and vascular attenuation" (compared to manual injection)[1]
        ii. The rate of contrast extravasation for MRI is about half than that of CT[2]

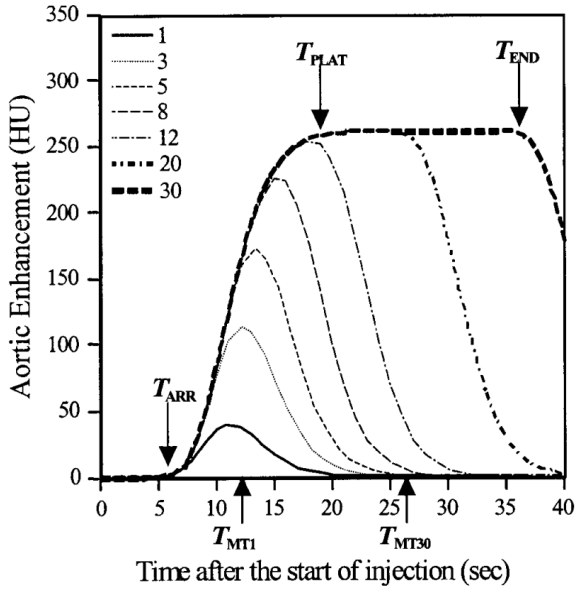
iii. Extravasation rates in children appear to be similar to those in adults (0.3%)[3]
iv. Power injector can be used safely with 24-gauge angiocatheters in a peripheral location using a maximum flow rate of 1.5 mL/sec and a maximum pressure of 150 psi[3]
v. After extravasation, compartment syndrome risk is only theoretical due to very low volumes use and symptoms are very rare because gadolinium is less toxic to the skin than iodinated contrast[8]

3. Diluting contrast
    a. When dynamic contrast is needed and the total contrast volume is under 5 mL, ALL contrast agents should be diluted to up to 1 part Gd-CM in 6 parts saline to achieve a minimal volume of 3 mL

Weight	**Contrast Dose (Dotarem/Gadavist)**	**Dilute to total volume of**	**Contrast Dose (Eovist/Ablavar)**	**Dilute to total volume of**	**Saline Chaser**	**Injection rate**	**Power Injector PSI**
2.5-4.9 kg	0.5 – 1 cc	2 cc	0.3 - 0.5 cc	1.5 cc	5 cc	0.5 cc/sec	150 PSI
5-10 kg	1 – 2 cc	3 cc	0.5 – 1 cc	2.5 cc	5 cc	0.7 cc/sec	150 PSI
11- 15 kg	2.2 – 3 cc	4 cc	1.1 – 1.5 cc	4 cc	10 cc	1 cc/sec	200 PSI
16-20 kg	3.2 – 4 cc	5 cc	1.6 – 2 cc	5	10 cc	1.5 cc/sec	300 PSI
21 - 25 kg	4.2 - 5 cc	5 cc	2.1 – 2.5 cc	5	15 cc	1.5 cc/sec	300 PSI

Use these parameters for all cases requiring dynamic contrast by either multiphase LAVA (e.g.; Renal Lesion, Liver Lesion) or TRICKS (e.g.; Vascular Malformation)

    b. Why?
        i. Weight-base contrast dosage results in very low contrast volume (<1 ml for newborns and young infants).
        ii. Low contrast volumes do NOT provide an enhancement peak long or high enough to image in the arterial, portal venous or systemic venous phases (allow only for equilibrium/delayed enhancement evaluation)-See graphs below[4]
    c. Pharmacodynamics of contrast in pediatrics is not different from adults and is mostly dependent on body size (not age or gender)[5]
    d. Diluted gadolinium improves image quality (by eliminating “first pass” artifacts in both T2 and T1w- images) when using eovist[6] and during MR lymphangiogram[7]; it is common practice in cardiac MRI and standard of practice for arthrograms



Short (1 sec- solid line in the graph) injection duration results in very narrow, asymmetric enhancement curves with suboptimal Peak Aortic Enhancement. Dilution of contrast with longer duration of injection not only provides a broader, more symmetric and higher peak enhancement but also provides a wider timing window for proper arterial imaging.

4. Injection rate:
    a. Varies with the indication from very low injection rates (0.1 cc/sec for MR Urogram to up to 2 ml/sec in MR angiography); Because of low total injected volumes and gadolinium pharmacodynamics (i.e; distribution in plasma), high injection rates are unnecessary in children. Recommended rate is 0.5-2 cc/sec (equivalent to fastest typical rate during hand injections. See table below)
    b. The total injection time needs to be at least 3 seconds

5. Safety Practices:
    a. All IV catheters should be tested with saline before contrast injection
    b. Power injector tubing should always be tested and primed before contrast injection
    c. If IV access is secure, nurses should go back to monitoring the patient outside the room before injection
    d. If IV access is tenuous, hand injection might be considered but not mandatory (at the discretion of the nurse)
    e. If hand inject, which is discourage, the staff injecting (either nurse or tech) should stay in the room until the "first pass" contrast sequence is completed

6. Other Safety Data:
    a. Gadolinium contrast agents are commonly used "off label" in children without any evidence of significant differences in risk with the adult population. In each case a risk benefits analysis will determine the appropriateness and relative safety of contrast use
    b. In view of current preliminary evidence showing permanent GD deposition in the basal ganglia of unknown clinical significance, use of contrast for "completeness" or

"routine", is discouraged. Each Gadolinium dose administration must be clearly indicated.

c. In a large series (437 patients -range 0.13–41.2 years-) that received blood pool contrast (ABLAVAR) only two (2) adverse events both being hypersensitivity reactions. Ablavar was hence deemed safe for children when appropriate (Paper #: PA-026 SPR 2014)

References

1. Saake M, Lell MM, Rompel O, et al. Contrast medium application in pediatric high-pitch cardiovascular CT angiography: Manual or power injection? *J Cardiovasc Comput Tomogr*. 2014;8(4):315-322. doi:10.1016/j.jcct.2014.05.002.

2. Shaqdan K, Aran S, Thrall J, Abujudeh H. Incidence of contrast medium extravasation for CT and MRI in a large academic medical centre: a report on 502,391 injections. *Clin Radiol*. 2014;69(12):1264-1272. doi:10.1016/j.crad.2014.08.004.

3. Amaral JG, Traubici J, BenDavid G, Reintamm G, Daneman A. Safety of power injector use in children as measured by incidence of extravasation. *AJR Am J Roentgenol*. 2006;187(2):580-583. doi:10.2214/AJR.05.0667.

4. Bae KT. Peak contrast enhancement in CT and MR angiography: when does it occur and why? Pharmacokinetic study in a porcine model. *Radiology*. 2003;227(3):809-816. doi:10.1148/radiol.2273020102.

5. Wible JH, Tata PN V, Napoli AM, Lowe LH, Kearns GL. Pharmacokinetics of gadoversetamide injection, a gadolinium-based contrast agent, in pediatric patients. *Magn Reson Imaging*. 2009;27(4):512-518. doi:10.1016/j.mri.2008.08.002.

6. Motosugi U, Ichikawa T, Sou H, et al. Dilution method of gadolinium ethoxybenzyl diethylenetriaminepentaacetic acid (Gd-EOB-DTPA)-enhanced magnetic resonance imaging (MRI). *J Magn Reson Imaging*. 2009;30(4):849-854. doi:10.1002/jmri.21913.

7. Krishnamurthy R, Hernandez A, Kavuk S, Annam A, Pimpalwar S. Imaging the Central Conducting Lymphatics: Initial Experience with Dynamic MR Lymphangiography. *Radiology*. 2015;274(3):871-878. doi:10.1148/radiol.14131399.

8. MRI Contrast Agents and Adverse Reactions. available at: http://www.mrisafety.com/SafetyInfov.asp?SafetyInfoID=245