



CAR Standard for Magnetic Resonance Imaging

The standards of the Canadian Association of Radiologists (CAR) are recommendations and are intended as guidelines to assist radiologists and MRI imaging specialists in performing optimal MRI examinations. The suggested guidelines cannot be all-inclusive due to the continuously evolving variety of equipment, techniques and indications. They should be modified by qualified MRI radiologists and imaging specialists, and, where necessary, in consultation with medical physicists, to perform the appropriate study to answer the clinical question. These guidelines are educational and not intended to establish a legal standard. The Medical Director of the MRI department or facility and the supervising MRI radiologist or specialist is responsible for the choice of examination technique. The physician and MRI physicist may modify an existing standard as determined by the individual patient and available resources. Adherence to CAR standards will not assure a successful outcome in every situation. The standards should not be deemed inclusive of all proper methods of care or exclusive of other methods of care reasonably directed to obtaining the same results. The standards are not intended to establish a legal standard of care or conduct, and deviation from a standard does not, in and of itself, indicate or imply that such medical practice is below an acceptable level of care. The ultimate judgment regarding the propriety of any specific procedure or course of conduct must be made by the experts in the field in light of all circumstances presented by the individual situation. The MRI technologist must possess the knowledge, skills and judgment to optimize and or make changes to techniques according to resultant images.

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I. INTRODUCTION AND DEFINITION

Magnetic resonance imaging (MRI) is a cross sectional imaging technique that uses a large magnetic field, rapidly fluctuating orthogonal magnetic field gradients, and electromagnetic radiation in the form of radiowaves (i.e. radiofrequency (RF) energy). The interaction between the RF energy at characteristic frequencies and specific nuclear species (atoms) in the tissues, while in the presence of a local magnetic field is the basis behind MRI function. In essence nuclei (predominantly the hydrogen ^1H nucleus, also referred to as a proton due to its nuclear structure being comprised of 1 proton and no neutrons) will absorb RF energy at a specific frequency after the body has been placed in a strong magnetic field. The larger the magnetic field (B_0), the greater the signal to noise ratio (SNR) and will require greater frequency of RF irradiation. Clinical MRI scanners are most often 1.5 Tesla (1.5T). However, there has been a recent surge in the popularity of 3T clinical systems due to their superior SNR, reduced requirement for contrast agent dose, and improved spatial and spectral resolution. Overall, MRI provides excellent differentiation of normal tissues and exceptional sensitivity to disease. This sensitivity is based on the high degree of inherent contrast due to variations in tissue magnetic relaxation properties (i.e. T_1 and T_2) and variations in proton density, the large spectrum of MRI pulse sequences that allow various kinds of contrast, and the wide control of tissue acquisition parameters.

There is a plethora of MRI pulse sequences available that can be used to obtain, not only spectacular anatomic details, but also information relating fine structure, metabolism, and function. For example, magnetic resonance angiography (MRA) uses selected MRI pulse sequences in order to visualize the blood vessels. There are three major families of MRA techniques: time of flight (TOF) or inflow angiography, phase contrast (PC) angiography (related to the phase shift of the flowing proton spins) and dynamic gadolinium-enhanced (DGE) MRA. Quantification of flow is also possible using phase contrast acquisitions.

A contrast based perfusion study uses bolus injection of gadolinium and rapid acquisition of multiple organ volumes. Perfusion studies are usually done to determine regional blood flow and blood volume in patients presenting with tumor and acute stroke.

Diffusion weighted pulse sequences which enable study of proton motion with the use of powerful gradients. The most common clinical indication is for detection of acute ischemic stroke. This is also helpful in assessment of abscess and tumors, and there is a growing list of potential applications in many body systems.

In addition to anatomical based acquisitions, newer MRI methods have evolved and are now reaching clinical utility. Examples include diffusion tensor imaging (DTI), functional MRI (fMRI) and magnetic resonance spectroscopy (MRS).

In pediatrics, MRI is well established as the imaging modality of choice for most conditions affecting the brain and spinal cord of infants and children. MRI is valuable in the evaluation of complex congenital heart disease, as well as vascular malformations and neoplasms involving the head and neck, chest, abdomen, pelvis and extremities. MRI can elucidate complex congenital malformations of the urogenital tract. MR urography is an emerging application that may one day replace techniques based on x-rays and radioisotopes at some institutions. MRI is considered superior to CT in many applications, because it avoids ionizing radiation, and also because it offers superior soft tissue discrimination. The information provided by MRI may, in other cases, be complementary to that provided by CT, US and/or nuclear medicine tests.

For health professionals consulting this document, please note that a list of vendor technical descriptions, comparisons and specifications can be accessed on the Siemens Global Website. A Link to the MRI Acronyms document produced by Siemens Medical can also be found in Appendix C.

II. QUALIFICATIONS OF PERSONNEL

A. THE RADIOLOGIST AND APPROPRIATELY QUALIFIED MEDICAL PERSONNEL

Physicians involved in the performance, supervision and interpretation of magnetic resonance imaging should be Diagnostic Radiologists and must have documented experience or Fellowship or Certification in Diagnostic Radiology with the Royal College of Physicians and Surgeons of Canada and/or the Collège des médecins du Québec or equivalent. Also acceptable are appropriate imaging fellowship-trained physicians, as well as foreign Specialist qualifications if the physician so qualified holds an appointment in Radiology with a Canadian University or appropriate licensing authority.

As new imaging modalities and interventional techniques are developed, additional clinical training, under supervision and with proper documentation, should be obtained before radiologists interpret or perform such examinations or procedures independently. Such additional training must meet with pertinent provincial/regional regulations. Continuing professional development must meet with the requirements of the Maintenance of Certification Program of the Royal College of Physicians and Surgeons of Canada.

B. MEDICAL PHYSICISTS

An MRI physicist should perform initial acceptance testing of the MRI system immediately following installation, and prior to any clinical scanning. The medical physicist is preferably someone on-site, but they can also be contracted to perform the testing. The credentials of the medical physicist should include a PhD in MRI physics (or other related MRI technology). Furthermore they should also be accredited by either the Canadian College of Physicists in Medicine (CCPM) or one of the affiliated professional engineering societies in Canada (i.e. P.Eng) and shall have specific training and experience in MRI. Training and experience shall include detailed knowledge of the physics of MRI, system components and performance, safety procedures, acceptance testing, and quality control testing. Acceptance testing may be done by a team of medical physicists as long as at least one of the group members has the aforementioned credentials and can vouch for the testing quality of the team.

C. MR TECHNOLOGISTS

The medical radiation technologist must be certified by the Canadian Association of Medical Radiation Technologists (CAMRT) in the discipline of magnetic resonance (RTMR) or be registered with the provincial regulatory body and authorized to work in the discipline of magnetic resonance.

The technologist is primarily responsible for performing the MRI scans and maintaining the overall safety of patients, staff and equipment within the MR environment. This includes careful screening and preparation of patients, ensuring patient comfort, adjustment of protocols (if required) to produce high quality, diagnostic scans, technical and quality evaluation of images and relevant quality assurance. MR technologists are also responsible for the MRI room safety and ensuring that no maintenance staff enters the room without direct supervision. All personnel have to be screened and educated about MRI by the MR technologist. MR technologists, if adequately trained, could also perform intravenous gadolinium injections requested by the responsible physician. Continued education of technologists is encouraged by the CAMRT and should meet pertinent provincial regulations.

D. FIELD ENGINEERS (FE)

The MRI field engineer (aka, service engineer) shall be responsible for system installation, calibration, and preventive maintenance (PM) at regularly scheduled intervals. The schedule is to be dictated by the specific vendor and clearly described prior to MRI purchase. The service engineer's qualification will be ensured by the corporation responsible for service and the manufacturer of the MR equipment used at the site. It is highly recommended the site use a FE who is employed by the manufacturer of the MRI system. The FE should be in routine communication with the site MRI charge technologist and physicist. Preventive maintenance shall be scheduled, performed and documented by a qualified service engineer on a regular basis. Service performed to correct system deficiencies shall also be documented and service records maintained by the MR site.

III. CHOICE OF AN MR SYSTEM

Many systems are available on the market with different magnetic field and gradient strengths. The most prevalent magnetic fields currently in the Canadian install base are 1.5 Tesla and 3 Tesla, although there are a few 1.0 Tesla systems (mainly specialized such as peripheral MRI systems). In addition, closed (i.e. tube) and open configurations are offered. The magnetic field gradients will directly influence image resolution and partly the acquisition speed. Also, when purchasing a system there are a plethora of RF coils and pulse sequences available for purchase. Purchase of a system is obviously subject to financial and site considerations. However, knowledge of the referral base and clinical needs is also necessary and will help dictate the appropriate choice. Before purchasing a system, it is highly recommended that a team be set up which will include a radiologist with previous MR experience, a medical physicist with previous MR experience, MRI technologist and administrators. In addition to the MRI system the team who will be responsible for the MRI purchase must also consider all ancillary equipment that will also be required in the MRI facility. For example power injector, and MRI compatible physiological monitoring and anesthesia systems. Prior to MRI purchase it is essential for the purchasing team to meet and discuss all needs and wants prior to various site visits. This will make site visits highly efficient and thorough.

IV. EQUIPMENT SPECIFICATIONS

The MR equipment specifications and performance shall meet all provincial and federal guidelines, including Health Canada guidelines. Health Canada approval is required prior to the scanning of the first patient. It is recommended a system be purchased that is either already approved or in the process of being 510k approved. The guidelines include, but are not limited to, specifications of maximum static magnetic field strength maximum rate of change of magnetic field gradients (dB/dt), maximum radiofrequency (RF) power deposition (specific absorption rate; SAR), and maximum auditory noise levels.

It is recommended that purchase and upgrade specifications be written by the medical physicist in consultation with the supervising MR physician and the MR technologist.

V. QUALITY CONTROL PROGRAM

The objective of an MR quality control (QC) program is to provide a series of tests and measurements which may be performed on a regular basis to determine if the MR system is performing in a reproducible and predictable manner. Protocols for routine system performance testing are still evolving. Quality control test should be conducted under the supervision of the medical physicist (if present on site), with review at least every six months by the supervising radiologist. A preventive maintenance program is recommended as a mean to minimize unscheduled down time.

Following acceptance testing each MRI site will be required to maintain their level of scan quality through the performance and assessment of weekly quality assurance / quality control (QA/QC) testing where appropriate. Acquisition of the test data can be done by a MRI technologist (all MRI technologists should be trained to run and assess basic QA/QC scans) who has been trained by the MRI physicist in the QA/QC acquisition procedure. Testing is best done on a routine schedule, first thing in the morning, prior to clinical scanning. It is highly recommended the site follow the American College of Radiology (ACR) guidelines for this procedure. This requires an ACR phantom and MRI physicist. In absence of ACR accreditation other weekly QA/QC procedures can be followed as recommended by the specific MRI vendor. As with acceptance testing an MRI physicist, certified either through the Canadian College of Physicists in Medicine, or one of the Canadian Professional Engineering societies, and having specific training and experience in MRI is required to analyze and maintain a record of the QA/QC data.

A quality control program with written procedures and logs shall be maintained at the MR site. The ongoing quality control program assesses relative changes in system performance as determined by a technologist and medical physicist (if present on site). It is highly recommended a qualified MRI physicist (see above for qualifications) be consulted at least once per year to assess QA/QC results and provide recommendations (if any).

A. QUALITY CONTROL TESTS

The following quality control tests shall be performed and documented:

- a. measurement of central frequency
- b. measurement of system signal-to-noise ratio on a standard head or body coil
- c. table positioning
- d. geometric accuracy
- e. high and low contrast resolution
- f. artifact analysis

B. PERFORMANCE EVALUATION TESTS

The following quality control tests shall be reviewed by the medical physicist annually, and after any major upgrade or major change in equipment:

- a. review of daily quality control testing records
- b. measurement of image uniformity
- c. measurement of spatial linearity
- d. measurement of high contrast spatial resolution
- e. measurement of slice thickness, locations and separations
- f. assessment of image quality and image artifacts
- g. eddy current compensation
- h. system shim

All quality control testing shall be carried out in accordance with specific procedures and methods.

Preventive maintenance shall be scheduled, performed and documented by a qualified service engineer on a regular basis. Service performed to correct system deficiencies shall also be documented and service records maintained by the MR site.

VI. ACCEPTANCE TESTING

Acceptance testing is intended to measure quantifiable system parameters which may then be compared to the manufacturer's specifications. A complete evaluation of the system performance shall be conducted by a medical physicist after completion of installation and prior to regular patient imaging'.

The acceptance testing should include a detailed description and inspection of the entire MRI site. This should include assessment of the MRI equipment room, control room, magnet room, patient prep area, and patient waiting area. This general assessment should be done for construction irregularities and incomplete features, locations and functionality of lighting and safety switches, patient/staff flow, safety features (MRI compatible fire extinguishers, emergency off switches, patient monitoring, security, etc.), Faraday shield grounding and integrity, installation neatness and completion. The fringe field of the MRI also needs to be detailed by the physicist (even though a similar document may have been provided by the vendor). Field lines should be measured using a tri-directional Hall effect magnetometer, and reported on a site drawing.

System performance tests should be repeated as a routine part of the acceptance test. All vendors will do these during their install process. They need to be repeated with the independent physicist present. There are overall vendor specific system tests and also tests for shim, eddy currents, stability, quadrature ghosting, system performance, SNR, white pixel, coherent noise, geometric distortion, slice cross talk, slice position/thickness accuracy, low contrast object detectability and high contrast spatial resolution tests, ghosting tests, and RF linearity. A general evaluation of specialized pulse sequences (i.e. sequences that are not routinely on all MRI scanners) is required. Testing of all pulse sequences is not

possible, nor practical, and as such would be part of clinical acceptance testing which is done after the scanner has been “handed over” by the vendor and physicists to the clinical MRI facility. Sequences that should be assessed include MR spectroscopy (1H MRS, be it PRESS or STEAM), multi-nuclear spectroscopy (MNS, e.g. ^{31}P , ^{23}Na , etc.). Spectroscopy, as a very sensitive technique, provides a telltale signature of system health. In addition to specialized sequences parallel imaging and acceleration (in both phase encode directions) should be verified and tested for speed, SNR and artifacts. Lastly patient monitoring associated with the scanner (i.e. pulsed oximeter and respiratory bellows) should be verified for functionality and sensitivity. If the physicist has access to it a portable waveform generator can be used to test ECG functionality.

All RF coils need to be tested for functionality and have SNR measurement performed as a baseline. Individual elements of multichannel RF coils also need testing to verify each element. These scans provide a valuable baseline measurement for future comparisons of system health.

Hard copies of the acceptance report should include tests and measured values, data evaluation graphs, and photographs showing deficiencies described in the text. Hard copies of the report should be provided to the MRI facility (one for the MRI control room and one for the managing director of the diagnostic imaging department), and one to the MRI vendor. The physicist should also provide a digital copy of the report on a CD, with all baseline data acquired in the tests and any vendor specific reports from the MRI system. The written report should include a list of recommendations and suggested changes. It is the responsibility of the vendor to ensure all hardware/software and technical deficiencies defined in the deficiency list are addressed immediately and prior to clinical usage. It is the responsibility of the hospital to address all other aspects of the recommendations. The report should be evaluated and discussed by representative(s) of the vendor (e.g. the field engineer), the managing director of MRI in the diagnostic imaging department, the MRI charge technologist, and the lead physician of the MRI unit.

VII. QUALITY IMPROVEMENT PROGRAMⁱ

A documented, systematic quality improvement program should be established under the direction of the supervising physician radiologist in order to monitor and evaluate such problems as claustrophobia, sedation, administration of contrast agents, equipment malfunctions and accidents (such as metallic objects entering the scan room) endangering patients or workers. Monitoring should include the evaluation of the accuracy of radiologic interpretations as well as the appropriateness of examinations. Incidence of complications and adverse events should be recorded and periodically reviewed in order to identify opportunities to improve patient care.

Data should be collected in a manner that complies with statutory and regulatory peer review procedures in order to protect the confidentiality of the peer review data.

VIII. MRI SAFETY

Safety guidelines, practices, and policies shall be written, enforced, documented, and reviewed at least annually by the supervising radiologist and the MR charge technologist. All technologists and other supporting staffs working in the MRI department are expected to review safety policies annually. It must be understood that these safety practices are important not only for the patients but also for others who will be accompanying the patient or enter in the magnetic fields of MRI scanners. All MRI safety incidents or ‘near incidents’ must be reported to the lead physician of the MRI unit in a timely fashion and should be analyzed and used in future quality improvement process.

These guidelines take into consideration potential interactions of the strong static magnetic field with ferromagnetic objects in the environment of the scanner that might result in projectiles leading to injuries or damages. MRI compatibility or safety information about any external device should never be assumed if it is not clearly documented in writing and all necessary information must be obtained before bringing it into the scanner room.

The risks to the patient could be related to strong static magnetic field (especially patients with metallic implants or retained wires) or radiofrequency (RF) exposure or due to the gradient induced time varying magnetic field. Implant and

devices must be screened thoroughly as detailed below. It is important to note that practices should be in place to decrease the possibility of patient burns while scanning. This includes optimization of scanning protocol not to exceed the recommended Specific Absorption Rate (SAR) limit, proper padding, positioning and proper placement of patient monitoring devices. Extra care must be taken with sedated patients and those who are unable to maintain communication with the technologist.

CONTRAINDICATIONS

Contraindications include, but are not limited to, the presence of ferromagnetic cardiac pacemakers, certain heart valves, ferromagnetic intracranial aneurysm clips, implanted neuro-stimulators, certain otic implants and ferromagnetic foreign bodies in critical locations, e.g., the eye. Relative contraindications include claustrophobia and obesity.

The safety of MRI scanning during pregnancy has not been established. The decision to scan during pregnancy should be made on an individual basis after consideration of medical necessity and alternate imaging methods. This particularly applies to scanning during the first trimester.

MRI compatibility of implants and devices was previously listed as “MRI Safe” and “MRI Unsafe”. These two terms still apply, however there is now an exhaustive list of “MRI Conditional” items, where conditional levels go from 1 to 8 (the highest value being least likely to be MRI safe). MRI conditional levels have been established based on gradient spatial field, degree of ferromagnetic material, degree of RF associated heating. All these items are also related to the strength of the magnetic field. As there are more 3T clinical systems now available conditional levels are becoming more important for consideration. A table showing specific specs for the MRI system should be posted for all MRI technologists to visualize. Each system will differ in these and all employees on the MRI environment should be well aware of this.

Patients need thorough screening prior to scanning (see sample Safety Questionnaire in Appendix A). It is recommended that referring physicians be aware of screening protocols. Screening should be done at the referring physician’s office, upon registration in a clinical MRI facility, and again by the MRI technologist who will scan the patient. Screening should also be noted and reviewed at the booking office of the Diagnostic Imaging Department. Even with 4 levels of screening it is well known that patients will either forget to mention something, or not mention anything at all for fear of losing their scan slot. Patients must be educated as to the importance of the screening process.

Patient implant or devices must be carefully screened and followed to determine the exact type which may or may not be safe. It is the responsibility of the radiologist to confirm the exact type of device in consultation with the referring physician. It is suggested screening should be done using the assistance of “*Shellock FG. REFERENCE MANUAL FOR MAGNETIC RESONANCE SAFETY, IMPLANTS AND DEVICES: Most updated edition. Biomedical Research Publishing Company, Los Angeles, CA*”. If not present in this book devices/implants can also be searched online at www.mrisafety.com. As a last resort, MR technologists should contact the manufacturer of the device/implant to obtain information on MRI safety for that product. It is absolutely essential for MRI centers to have internet access to be able to research these devices and implants. Lack of internet access seriously jeopardizes patient safety.

CONTRAST AGENT USE AND SAFETY

There are many potential indications for the injection of contrast agents. In general, contrast agents are used for both intra- and extra-vascular compartments to achieve the following:

- a. Lesion detection,
- b. Lesion characterization including assessment of perfusion, and
- c. To assess luminal patency or to better visualize the endothelial or intramural abnormalities.

In general, it is desirable to acquire T1-weighted images (either spin echo (SE), turbo spin echo (TSE), or gradient echo (GE)) using the same technique both before and after the administration of gadolinium chelates.

Tissue specific contrast, combined contrast and delayed imaging are strategies that that could enhance the yield of contrast enhanced studies.

Gadolinium chelates should not be administered to patients with known or suspected hypersensitivity to the product or with severe hepatic or renal insufficiency. Nephrogenic systemic fibrosis (NSF) is a fibrosing disease, primarily involving the skin and subcutaneous tissues but also known to involve other internal organs. This is associated with gadolinium use in patients with severe renal insufficiency. For further safety recommendation, please refer to the Canadian Association of Radiologists (CAR) National Advisory on Gadolinium Administration and Nephrogenic Systemic Fibrosis, September 2008.

The same concerns regarding allergic reactions and nephrogenic systemic fibrosis (NSF) exist in children as they do in adults, and pediatric cases of NSF have been reported [1]. It should be noted that serum creatinine as a marker of renal function may be unreliable in infants. There are hypothetical concerns regarding the safety of gadolinium in neonates and infants less than one year of age, due to their immature renal function. Therefore, the risks and benefits of contrast enhancement must be weighed carefully in this population, and consideration should be given to nephrology consultation before making the decision to proceed with enhancement.

IX. USE OF SEDATION OR GENERAL ANESTHESIA

The technique of MRI puts significant demand on patients who are required to remain more or less immobile in a confined space for 20 - 60 minutes. The long tunnel configuration of the scanner could be frightening and claustrophobia is not uncommon. To address this issue, anxiolytics or conscious sedation is commonly used. Some facilities may use anesthesia. All facilities should have policies and procedures for administering sedation with proper monitoring, resuscitation facilities with designated trained staff, for appropriate patient monitoring post sedation and for the use of anesthesia. Non-Hospital facilities administering general sedation, or sedation requiring the monitoring of vital signs, should meet the standards of their provincial College for administering sedation.

In children, MRI frequently requires conscious sedation or general anesthesia due to the long imaging times and motion sensitivity inherent in the technique. Whenever possible, sedation should be avoided by using fast sequences (e.g. single shot fast spin echo), distraction (e.g. in-bore entertainment systems) and gentle coaching. A parent/caregiver should be allowed to accompany a non-sedated pediatric patient into the scanner suite. Specially trained pediatric nurses provide conscious sedation under the supervision of pediatric radiologists at many institutions. Pediatric anesthesiologists and intensive care specialists may also provide conscious sedation and are always required for general anesthetic. Conscious sedation is safer and more efficient when it is provided by a dedicated team [2]. Knowledge of pediatric cardiac life support and availability of the drugs and equipment needed for resuscitation of children of all ages/sizes are essential [3].

Prior to any sedation methods being used on a patient, screening must be done to identify possible health concerns (see sample Sedation Questionnaire in Appendix B). Patients should be interviewed to determine if they have any conditions that may lead to complications while undergoing treatment. A patient with a condition must be evaluated further to minimize the risk of patient injury due to the sedation method.

CLINICAL STANDARDS

The committee has attempted to enumerate the currently accepted techniques for MRI based on clinical experience, as summarized in peer-reviewed literature. Because the clinical application of MRI is still under development, it is not intended that the enumerated techniques (and indications in the reference document) be all-inclusive. It is very important that each site offering MRI have documented procedures for the indications and technical factors for each anatomic site. These procedures will need to be reviewed frequently. The final judgment regarding appropriateness of a given examination for a particular patient is the responsibility of the radiologist.

The indications for scanning could include any part of the human body, depending on the MRI software and hardware available and the efficacy and availability of competing imaging methods.

To accomplish its clinical purposes, MRI must be performed with adequate attention to technical abilities of the MRI scanner.

Spatial resolution, slice thickness, signal-to-noise (SNR), and acquisition time are all inter-related sequence parameters which have a major influence on the quality of the images, and thus the detectability of disease. In the performance of any MRI examination, major decisions have to be made regarding the appropriate coil, the imaging plane(s), the field of view (FOV), the slice thickness and slice gap, the imaging matrix, the number of excitations, band width selection, the pulse sequence parameters which maximize signal and contrast to noise and the requirement for ECG gating and respiratory compensation.

The purpose of these guidelines is not to prescribe the details of individual techniques, but rather to address the spectrum of recognized MRI applications and to outline the minimum requirements necessary to undertake these, and to which the radiologist, in conjunction with ancillary staff should aspire.

When necessary, gadolinium contrast agents and sedation shall be administered in accordance with institutional policy and provincial and federal law by a physician, who has trained in cardiopulmonary resuscitation (CPR) with respect to contrast induced adverse events. MR technologists, if adequately trained, could also perform intravenous gadolinium injections supervised by the responsible physician. An appropriately equipped emergency cart and designated trained staff must be immediately available to treat serious adverse reactions.

MRI compatible ventilators, and appropriate patient monitoring should be available at those sites undertaking general anesthesia and sedation studies.

Sedation is an issue of particular concern in pediatric imaging, where sedation is often required to achieve immobility during long imaging sessions. It is essential that members of the team providing sedation are trained in pediatric cardiac life support, and that drugs and equipment necessary for resuscitation of children of all ages/sizes are readily available. Gadolinium-based contrast agents should be used judiciously in neonates and infants less than one year of age, due to theoretical concerns based on their immature renal function.

RECOGNIZED CLINICAL APPLICATIONS OF MRI:

- A. ADULT AND PEDIATRIC BRAIN
- B. HEAD AND NECK
- C. ADULT AND PEDIATRIC SPINE
- D. ABDOMEN AND PELVIS (MALE AND FEMALE GENITOURINARY SYSTEM)
- E. MUSCULOSKELETAL SYSTEM
- F. CARDIOVASCULAR
- G. CHEST
- H. BREAST IMAGING
- I. FETAL IMAGING

A. ADULT AND PEDIATRIC BRAIN ⁱⁱ

Magnetic resonance imaging (MRI) of the brain is an excellent imaging modality for the evaluation and assessment of the anatomy and abnormal conditions of the brain, in adult and pediatric patients. MRI of the brain is the most sensitive technique available due to its direct multiplanar imaging capability and superior soft tissue resolution. This is particularly true in the posterior fossa [2, 3] where beam-hardening artifacts arising from the bone tend to degrade CT images.

MRI is a rapidly changing technology. The continuous improvements in technology will maintain this imaging modality at the forefront of the diagnosis of brain disorders.

Since the advent of magnetic resonance imaging, systems with a magnetic field of 1.5tesla (T) have been recognized as gold standard for different clinical applications. Ongoing advances in hardware and software have made these MRI systems increasingly compact, powerful and versatile leading to the development of higher magnetic field strength

systems (3.0T) for use in clinical practice and research purposes. Although 1.5T magnets are more readily available now, 3T imaging offers advantages such as higher signal, higher resolution, higher signal to noise ratio (SNR), higher sensitivity and potentially shorter imaging times.

In infants, the water content of the brain is much higher than in adults. The excess water present in the newborn is gradually lost from both the grey and white matter during the first two years of life. In order to optimally visualize pathology and differentiate grey and white matter on T2W images during this time period it is often useful to prolong the TE and TR values. TR times of 3000 msec or more and TE times of 120 msec or more are useful. It is also useful to obtain axial TIW sequences. This may be helpful to evaluate malformations of cortical development. The combination of T1- and T2 weighted imaging is also essential to evaluate the progress of myelination. In diffusion weighted imaging, it should be borne in mind that the greater water content of the infant brain, compared to the adult brain, translates into higher apparent diffusion coefficients in both grey matter and white matter.

INDICATIONS FOR MRI OF THE BRAIN

Primary indications include but are not limited to:

- a. Acute and chronic neurological deficits
- b. Aneurysm
- c. Arterial or venous/dural sinus abnormalities
- d. Ataxia
- e. Change in mental status
- f. Cortical dysplasia and migrational disorders
- g. Cranial nerve abnormalities
- h. Decreased level of consciousness in trauma patients not explained by CT findings (Diffuse axonal injury)
- i. Demyelination and dysmyelination disorders
- j. Encephalitis
- k. Headache
- l. Hydrocephalus (in pediatric patients MRI is preferred over CT for assessment of shunt malfunction)
- m. Inflammatory and infectious processes of the brain or meninges, and their complications
- n. Neurodegenerative disease
- o. Pituitary dysfunction/tumor
- p. Posterior reversible encephalopathy syndrome (PRES)
- q. Postoperative evaluation
- r. Primary tumors and metastasis
- s. Seizures
- t. Stroke and cerebrovascular disease
- u. Vascular malformations
- v. Vasculitis

EXTENDED INDICATIONS

- a. Blood flow and brain perfusion study
- b. Evaluation of chronic hemorrhage
- c. Functional imaging
- d. Image guidance for intervention or treatment planning
- e. Spectroscopy (including evaluation of brain tumor, infectious processes and ischemic conditions)
- f. Tractography
- g. Volumetry

INDICATIONS FOR MRA/MRV ⁱⁱⁱ

Indications include, but are not limited to:

- a. Congenital(developmental) vascular abnormality
- b. Dural sinus thrombosis and intracranial venous occlusive disease.
- c. Etiology of intracranial and spinal hemorrhage.
- d. Posttraumatic injury to cervico-cerebral vessels for evaluation of presence, nature, and extent, including dissection
- e. Presence and extent of atherosclerotic occlusive disease and thromboembolic phenomena.
- f. Presence and extent of dissection.
- g. Presence, location, and anatomy of extracranial and intracranial aneurysms and vascular malformations.
- h. Relevant vascular anatomy for preprocedural evaluation, determining the effect of therapeutic measures, including post-treatment evaluation of endovascular treatment of aneurysm and arteriovenous malformation (AVM) ablation.
- i. Staging of brain neoplasms contiguous to intracranial venous sinuses
- j. Vascular diseases, such as vasculitis, and moyamoya disease
- k. Vascular status following extracorporeal membrane oxygenation (ECMO)
- l. Vascular supply to tumors.

TECHNIQUE

MRI examination of the brain can be performed with a wide array of pulse sequences. The radiologist should protocol each study using the appropriate pulse sequences in order to address the clinical question based on the information provided by the referring physician. The most commonly accepted basic imaging protocols for MRI of the brain currently include a T1-weighted sequence in the sagittal plane, a T2-weighted fluid-attenuated inversion recovery (FLAIR) in the axial plane, a T2 fast-spin-echo or turbo-spin-echo (or equivalent) sequence as well as diffusion weighted imaging (DWI) in the axial plane are also obtained. Echo planar (EPI) gradient echo imaging is an additional sequence that is being used routinely in many centers as part of the basic protocol given its short acquisition time (10 seconds). This sequence is useful to detect calcification or hemosiderin deposition in the context of chronic hemorrhage.

Slice thickness, spatial resolution, signal-to-noise ratio, acquisition time, and contrast are all interrelated. To optimize spatial resolution, imaging of the brain should be performed with a slice thickness of no greater than 5 mm and an interslice gap of no greater than 2.5 mm. For certain pathologies in the posterior fossa, a high resolution heavily T2 weighted sequence with 3D reconstruction could be obtained (CISS, SPACE, or FIESTA depending on the vendor). Thinner slices are currently being used in the 3T magnets.

In the context of trauma, MRI is preferred for suspected shearing lesions and diffuse axonal injury (DAI) in closed head trauma, as well as for the subacute and chronic sequelae of head injuries.

The absence of ionizing radiation makes MRI a preferred modality for follow-up of intracranial shunt in the pediatric population.

Gadolinium-enhanced studies are performed when lesion diagnosis and improved conspicuity are required or when there is suspicion of breakdown of the blood-brain barrier. If flow compensation is available, it has been found to be useful in the evaluation of gadolinium-enhanced images in the posterior fossa which are otherwise degraded by flow artifacts arising from the transverse and sigmoid sinuses.

There are several additional techniques that may be used in the proper clinical context which include 3-dimensional imaging techniques, neuronavigation and intraoperative MRI, magnetization transfer imaging and cerebral spinal fluid (CSF) flow study using phase-contrast pulse sequences.

Magnetic resonance angiography (MRA) uses selected MRI pulse sequences in order to visualize the blood vessels (arteries). There are three major families of MRA techniques: time of flight (TOF) or inflow angiography, phase contrast (PC) angiography (related to the phase shift of the flowing proton spins) and dynamic gadolinium-enhanced (DGE) MRA. Quantification of flow is also possible using phase contrast acquisitions.

Similarly several methods are available to image the deep and superficial venous sinuses with MRI, including contrast-enhanced and non-contrast enhanced pulse sequences. The most common non contrast-enhanced technique is Time-of-flight (TOF) which relies on inflowing blood to provide vascular signal. TOF pulse sequences could be gradient echo (GRE) or spoiled gradient recalled (SPGR) acquisitions. To avoid in plane artifacts, coronal or sagittal oblique acquisitions are helpful. Contrast-enhanced MR venogram (CE-MRV) is a widely used technique that uses a 3D spoiled gradient echo sequence in conjunction with a bolus of gadolinium. The vascular contrast results from the T1 shortening effect and has relatively little dependence on inflow effects.

Diffusion weighted pulse sequences enable the study of proton motion with the use of powerful gradients. The most common clinical indication is for detection of acute ischemic stroke. Diffusion weighted images are acquired along 3 orthogonal axis (X, Y and Z) with respect to the magnet. A non-diffusion weighted image (which is a T2-weighted image) is also acquired with which to calculate the apparent diffusion coefficient (ADC). Diffusion tensor imaging (DTI) involves the acquisition of at least 6 diffusion encoding direction (e.g. X, Y, X, and XY, XZ, YZ). 3D information produces 3D virtual trajectory of white matter bundles called tractography. DTI is rotationally invariant which means the position of the head within the magnet bore does not influence the resulting DWI and ADC values as is true for simple DWI. Recent advances in diffusion sequences now include a family of motion and susceptibility insensitive sequences. These provide reasonable diffusion weighting in the presence of metallic implants and also during some degree of non-complex motion.

DWI is useful to characterize acute ischemic stroke, abscess, epidermoid cysts, highly cellular tumors including lymphoma and medulloblastoma, as well as active demyelination.

Perfusion studies use bolus injection of gadolinium and rapid acquisition of multiple brain volumes. Perfusion studies are usually done to determine regional cerebral blood flow and blood volume in patients presenting with acute ischemic stroke. In combination with diffusion imaging, perfusion/diffusion mismatch can be a powerful tool for assessment of potentially recoverable brain tissue with appropriate thrombolytic treatment.

The stroke protocols vary depending on the Institution and the available imaging resources, Head CT, CTA of the head and neck and if available CT perfusion (CTP) are usually the imaging modalities most commonly used. The diagnostic role of conventional MR is confined mostly to the subacute and chronic phases, and also to problem solving in acute cases. However, the introduction of thrombolytic therapies for acute stroke has changed the neuroimaging protocols, leading to the use of MR also in the emergency workup of these patients. Recent technological advances in hardware (magnet, gradients, coils) and software (ultrafast sequences, post processing) allow morphological and functional studies to be

performed with very short times of acquisition. In clinical practice, functional studies including diffusion weighted imaging (DWI) and perfusion weighted imaging (PWI) are increasingly being performed in combination with standard MRI. This is particularly true in symptomatic patients with normal head CT in whom brain stem, lacunar and deep white matter infarcts are suspected.

Perfusion imaging is also used for the evaluation of brain tumors. The increase in vascularity of certain cerebral neoplasms (high grade gliomas) could be quantified with relative cerebral blood volume (rCBV). Perfusion is an indirect measurement of angiogenesis and permeability within a neoplasm and both are important biological markers of malignancy, grade and prognosis, in particular in gliomas. Perfusion imaging is also helpful to differentiate between recurrent tumors and radiation necrosis in post therapy follow-up.

Magnetic Resonance Spectroscopy (MRS) can be used to evaluate dominant brain metabolites such as N-acetyl aspartate (NAA; a marker of neuron health, choline (a metabolite in cell membranes), creatine (involved in energy metabolism), and lactate (visible as the result of anaerobic metabolism). Some minor metabolites can sometimes also be visualized such as myo-inositol, glutamate/glutamine, and taurine, to name a few. However whether these will be visualized depends on the pulse sequence, parameters, SNR, and location.

MRS sequences may be point resolved spectroscopy sequence (PRESS) or stimulated echo acquisition mode (STEAM). PRESS is most often used, using variable echo times. The longer echo time removes short T2 species leaving only dominant peaks of choline, creatine, NAA, and lactate (if present). It should be noted that lactate will exhibit an inversion of the methyl doublet at 1.30ppm, as it undergoes J-modulation. However a number of other metabolites (e.g. glycine) and pharmaceuticals (e.g propylene glycol) also have methyl doublets near to 1.30ppm that will likewise invert. Hence care in positive identification of lactate is essential.

MRS has been used in a wide array of brain pathologies however it is mainly used clinically to investigate brain tumors.

While a detailed discussion of all the evolving advanced imaging techniques is beyond the scope of this standard, it should be noted that rapid pulse sequences and other advanced imaging techniques may provide added utility for MRI of the brain. These can include, but are not limited to: echo planar imaging, parallel imaging, rapid gradient-echo pulse sequences (capable of providing T1 or T2 information), susceptibility weighted imaging, functional imaging, and volumetric, morphometric, and other quantitative applications.

It is the responsibility of the supervising radiologist to determine whether additional pulse sequences or nonconventional pulse sequences and imaging techniques confer added benefit for the diagnosis and management of the patient.

B. HEAD AND NECK

With the advance of hardware and faster sequences including improved fat suppression technique MRI is being used as the primary method of head and neck imaging in many departments. However, CT could alternatively be used in preliminary assessment, especially assessment of lymph node size, bony detail and calcification. MRI definitely trumps CT regarding the outstanding soft tissue contrast, differentiating mucus / fluid from the tumor and evidence of perineural spread. Diffusion weighted imaging technique might be useful in differentiating abscess from necrotic tumor and is increasingly being used.

The drawbacks of MRI include the insensitivity to calcification, degradation of the images, especially in the lower neck, caused by motion artifacts (swallowing or respiratory movements) or by the presence of metallic dental appliances/fillings in the mouth. CT could also be a better choice in cases of fulminant infection, patient's inability to cooperate due to claustrophobia, altered mentation or medical condition such as congestive failure or a breathing disorder that makes lying flat difficult.

INDICATIONS FOR MRI IN THE HEAD AND NECK

Indications include, but are not limited to:

- a. Arterial dissection
- b. Brachial plexus pathology
- c. Evaluation of neck mass
- d. Nasopharyngeal and oral malignancy
- e. Orbital tumors
- f. Parathyroid adenoma
- g. Retrocochlear pathology
- h. Sinonasal malignancy
- i. Temporomandibular joint disorder

INDICATIONS FOR MRI ANGIOGRAM IN THE HEAD AND NECK

- a. Atherosclerotic and other occlusive arterial disease
- b. Thoracic outlet syndrome
- c. Vascular malformations in the neck

The supervising radiologist should have complete understanding of the indications, risks and benefits of the examination, as well as alternative imaging procedures, backed by proper clinical history and detailed clinical examination findings of the patient as well as the diagnostic question(s) to be answered.

The radiologist must also understand the pulse sequences used in regards to the appearance of different tissues and potential artifacts. The standard protocols should be tuned for each patient to improve image quality.

Patients, in whom neurological findings are present, in addition to the head and neck symptoms, often require a complete examination of the brain.

The MRI technique for scanning the head and neck should endeavor to maximize SNR and spatial resolution within a reasonable scan time. This is an evolving technology, with pulse sequences, protocols, contrast agents, techniques and indications continuously being modified and improved. Detailed and specific imaging protocols are thus not included here, as these vary with equipment, field strength, gradient strength, range of options and motion compensation techniques and may become obsolete during the tenure of the guideline. Instead, general concepts are included to aid in development of optimized protocols for evaluation of different anatomic areas and pathological conditions.

A dedicated head coil should be used in suprahyoid applications, a dedicated neck coil for infrahyoid applications. Dedicated surface coils may be helpful for the temporomandibular joint (TMJ).

T1-weighted images are the best for delineating fine anatomic detail when the structure in question is surrounded by soft tissue. For structures surrounded by cerebrospinal fluid, such as the cranial nerves in the cisterns and internal auditory canals, thin, 3D T2-weighted images provide excellent delineation of detail. A combination of T1-weighted and T2-weighted images in sagittal, axial and coronal planes is needed. For most head and neck lesions, axial and coronal imaging may suffice, although sagittal images are useful for tongue base, palate, nasopharynx, and larynx.

Fast imaging techniques are helpful to reduce physiological movements and to improve image quality. Fat suppression in T2 weighted images and post-gadolinium images are very helpful to highlight pathology. Fat suppressed axial T1 images are very helpful to diagnose wall hematoma in vascular dissection.

3D imaging techniques are becoming faster and may be utilized more frequently, especially in brachial plexus imaging. For brachial plexus imaging extra time should be spent to generate a better resolution scout image to visualize and prescribe the high resolution imaging along and across the plexus.

Gadolinium-enhanced studies are performed when lesion diagnosis and improved conspicuity are required, i.e. tumor characterization including assessment of perineural spread, aggressive inflammatory process or vascular anomalies. Fat saturation sequences are desirable in order to differentiate a subtle enhancing lesion from surrounding fat.

Though gadolinium enhanced MRI angiogram images generate excellent images of the neck arteries without flow artifacts and with possibility of dynamic flow information; there is ongoing improvement in time of flight (TOF) technology that might be adequate to assess neck arteries in most instances. Indirect flow information from TOF angiogram could be very helpful in identifying reverse flow in cases of vertebral steal phenomenon.

C. ADULT AND PEDIATRIC SPINE

The role of MRI in the spine has been well established by comparative studies with conventional imaging methods using surgical correlation as an objective measure of accuracy. The areas of greatest proven value include degenerative diseases involving the cervical and lumbar spine, vertebral inflammatory lesions, congenital malformations and intramedullary lesions such as syringomyelia and neoplasms. Equally useful are the applications of MRI in evaluating extradural, intradural and extramedullary neoplasms, trauma, and patients with signs and symptoms of cord compression. MRI is helpful to assess bone marrow, intervertebral discs, spinal canal, neural foramina and the neural element including spinal cord and nerves. Diffusion MRI, dedicated high resolution MRA of the spine and MR neurography are newer techniques that allows for detailed assessment of these structures in the spinal column.

INDICATIONS FOR SPINE MRI ^{iv}

Indications include, but are not limited to, the evaluation of:

- a. Arachnoiditis
- b. Congenital spinal abnormalities
- c. Degenerative disk disease and its sequelae in the lumbar, thoracic, and cervical spine
- d. Extradural soft tissue and bony neoplasms
- e. Intradural extramedullary masses
- f. Intradural leptomeningeal disease
- g. Intramedullary tumors
- h. Intrinsic spinal cord pathology, including demyelinating and inflammatory conditions
- i. Meningeal abnormalities
- j. Nature and extent of bony malalignment
- k. Nature and extent of injury to spinal cord, vertebral column, ligaments, and intraspinal and paraspinal soft tissues following trauma
- l. Postoperative intraspinal fluid collections
- m. Postoperative intraspinal soft tissue changes
- n. Preprocedure assessment for vertebroplasty and kyphoplasty
- o. Spinal abnormalities associated with scoliosis
- p. Spinal cord herniation syndrome
- q. Spinal infection, including disk space infection, vertebral osteomyelitis, and epidural abscess
- r. Spinal vascular malformations and/or the cause of occult subarachnoid hemorrhage
- s. Syringohydromyelia
- t. Treatment fields for radiation therapy

MINIMUM STANDARD MRI TECHNIQUE FOR IMAGING THE SPINE

- a. A dedicated neck coil (either posterior alone or in combination with an anterior neck coil) for the cervical spine and a dedicated spine surface coil or phased-array surface coils for the thoracic and lumbar spines.
- b. A combination of sagittal T1-weighted, T2-weighted and STIR might be obtained. Again, protocols should be tailored to answer specific clinical questions. For example, when evaluating nerve roots, axial T2- or occasionally T1-weighted images should be added. For pediatric scoliosis, congenital malformations of the spine and suspected tethered cord, it is advisable to image the whole spinal column. Coronal sequences may be helpful.
- c. A maximum slice thickness of between 3-5 mm and 1.5-2 mm for cervical spine and corresponding nerve roots.
- d. Slice gap should be kept to the minimum.
- e. Matrix and slice profile selection resulting in an in plane spatial resolution in the order of 1-2 mm.
- f. Depending on the indication, either the combination of gradient moment nulling, cardiac gating, and saturation pulses for spin echo imaging (conventional or fast spin echo), or gradient moment nulling, with or without cardiac gating and saturation pulses for gradient echo imaging, should be used. Sagittal or axial gradient echo proton density-weighted sequences may be used as substitutes for T2-weighted sequences, especially for cervical and thoracic spinal bio-mechanical clinical problems.
- g. Gadolinium chelates should be used in evaluation of intramedullary and leptomeningeal diseases especially in tumor involvement. For pediatric brain tumors known to metastasize by subarachnoid seeding, it is essential that gadolinium enhanced imaging of the whole neuraxis, down to the bottom of the thecal sac, be performed before surgery. Contrast should also be routinely utilized for the differentiation of scar from disk, especially in a recent post-operative failed back following discectomy.

D. ABDOMEN AND PELVIS ▼

Magnetic resonance imaging (MRI) of the abdomen and pelvis is a useful tool for initial diagnosis and assessment of disease severity, clarification of abnormalities demonstrated on other imaging modalities, staging evaluation of certain malignancies, and follow-up evaluation of a variety of disease processes. MRI of the abdomen and pelvis is an evolving technology, with pulse sequences, protocols, contrast agents, techniques and indications continuously being modified and improved. Detailed and specific imaging protocols are not included here, as these vary with equipment, field strength, gradient strength, range of options and motion compensation techniques, and may become obsolete during the tenure of the guideline. Instead, general concepts are included to aid in development of optimized protocols for evaluation of different anatomic areas and pathological conditions. MRI facilities should develop specific MRI protocols for each abdominal and pelvic area to be evaluated and for a variety of common pathologies. Protocols should be based on selecting technical factors to achieve an appropriate balance of spatial resolution, anatomic area coverage, signal to noise ratio (SNR), contrast and scan time. For optimal imaging, selection of the appropriate coil, field of view (FOV), imaging matrix, slice thickness, slice gap, number of signal averages, imaging planes and use of motion compensation or breathhold techniques must be made. Choice of phase encoding to allow partial FOV should be considered to reduce scan times. The need for intravenous or intracavitary contrast and post-contrast pulse sequences must be considered, either routinely for certain protocols or as needed, based on precontrast study evaluation. Abdominal and pelvic imaging protocols need to be developed for each abdominal organ, e.g. liver, kidney, pancreas, etc., and for common pathological entities in these areas, and general screening protocols for larger areas should also be available. Protocols may need to be adapted for specific groups of patients, e.g. pediatric, obese, uncooperative patients. Sedation may be required for extremely anxious or claustrophobic patients.

MRI systems operating at 1.5 Tesla are the main clinical workhorse for body MRI, but continuing developments in 3.0 T systems are giving promise for increasing variety of clinical indications.

Abdominal and pelvic MRI should be performed upon request from the patient's attending physician or licensed health care provider, for an appropriate indication. For each request received, the MRI radiologist or imaging specialist should assess the indication and determine that MR is the appropriate test and if so, prescribe the appropriate protocol and indicate the area for coverage and the need for IV or intracavitary contrast. If available, previous imaging test results should be reviewed and be evaluated at the time of reporting.

EXAMINATION TECHNIQUES

- a. Use of a phased array surface coil(s) where possible unless precluded by patient body habitus or condition. Arms should be positioned comfortably depending on imaging plane and direction of phase encoding utilized. For certain examinations such as rectum, prostate or female pelvis, intracavitary coils may be considered if available.
- b. Imaging matrix, FOV and slice thickness should be selected and appropriate to fully cover the anatomic area of interest, and optimized to produce a balance between area coverage and resolution. Generally, slice thickness should not exceed 1.0 cm, with 5 to 7 mm generally achievable. An axial in-plane spatial resolution of 3 to 5 mm is recommended for most protocols. An interslice gap of 20% is generally used, and should not exceed 30%.
- c. Protocols for most anatomic areas should include T1, T2, fat suppressed T2 or STIR (short-tau-inversion recovery) in opposed state sequences, generally in the axial plane. Imaging in the sagittal and coronal plane can be useful for further evaluation of complex anatomy and delineation of pathology. For pelvic imaging, sagittal and axial imaging planes are generally most helpful. For evaluation of uterine lesions, ideal imaging planes are along the long- and short axis of the uterine corpus.
- d. T1- and T2-weighted images may be obtained using conventional spin-echo (SE), echo train spin-echo (TSE or FSE) or gradient echo (GRE) sequences. TSE and GRE sequences may be obtained using breath-hold (BH) techniques. If non-breath-hold sequences are used, appropriate respiratory motion reduction techniques should be utilized. Fat suppression is often useful for T2-weighted imaging, using STIR or SPIR (spectral presaturation inversion recovery) and for precontrast T1-weighted imaging, generally using SPIR technique. A bowel peristalsis reduction agent such as buscopan or glucagon should be considered for certain examinations. Positive or negative oral contrast agents can be useful for gastrointestinal imaging, and negative oral contrast agents can be useful to suppress signal and decrease artefact from bowel contents when imaging other organs.
- e. For liver, renal and adrenal imaging, In-phase and Out-of-phase chemical shift imaging may be helpful for lesion characterization, as it is an effective technique for hepatic steatosis and detection of intracellular lipid in certain adrenal (adenoma) and renal (angiomyolipoma) lesions. Diffusion weighted imaging may have some utility in oncologic imaging assessment and treatment monitoring and is being evaluated.
- f. Where no contraindication exists, intravenous injection of gadolinium chelates (or newer tissue specific agents) can assist in enhancing lesion detectability, characterization, and staging, for direct assessment of the vascular system and the vascularity and vascular supply of organs and pathological lesions. Dynamic acquisition of images following contrast injection in arterial, portal venous, equilibrium and for renal lesions, nephrographic and pyelographic phases, and for suspected cholangiocarcinomas, delayed phase imaging, assists in lesion characterization. Fat-saturation techniques are recommended. 2D and 3D techniques may be utilized, and 3D techniques can be acquired with isotropic or near-isotropic resolution, and used for multiplanar reconstructions. Subtraction techniques may be helpful to detect subtle enhancements.
- g. For evaluation of the biliary ductal system and pancreatic duct (MRCP), and dilated renal collecting system, heavily T2-weighted sequences, are helpful. Thick slab acquisition in multiple planes or multiple thin slices in a single plane can be utilized.
- h. The use of vitamin E capsules to mark the skin and localise palpable soft tissue masses is helpful to confirm that these are included in the area of concern.

DETECTION, EVALUATION, AND/OR CHARACTERIZATION OF THE LIVER

- a. Diffuse liver disease
- b. Findings requiring clarification from other imaging studies or laboratory abnormalities
- c. Focal hepatic lesions
- d. Known or suspected congenital abnormalities
- e. Known or suspected metastasis
- f. Potential liver donor
- g. Tumour response to treatment
- h. Vascular patency

DETECTION, EVALUATION, AND/OR CHARACTERIZATION OF THE PANCREAS

- a. Chronic pancreatitis or complications of acute pancreatitis
- b. Indeterminate lesions detected with other imaging modalities
- c. Known or suspected pancreatic masses
- d. Pancreatic duct anomalies, obstruction or dilatation
- e. Pancreatic or peripancreatic fluid collections
- f. Surgical planning for pancreatic neoplasms

DETECTION, EVALUATION, AND/OR CHARACTERIZATION OF THE BILE DUCTS AND GALLBLADDER

- a. Bile duct and gallbladder cancer
- b. Bile duct or gallbladder stones
- c. Biliary ductal dilatation

OTHER

- a. Assessment of inflammatory disorders of the bowel
- b. Detection and characterization of intra-abdominal fluid collections
- c. Detection and characterization of retroperitoneal neoplasms other than above
- d. Detection and evaluation of primary and metastatic peritoneal neoplasms
- e. Evaluation of ureteral abnormalities
- f. Preoperative assessment of gastric neoplasms

DETECTION, EVALUATION, AND/OR CHARACTERIZATION OF THE SPLEEN

- a. Clarification of diffuse abnormalities of the spleen
- b. Indeterminate lesions detected with other imaging modalities

DETECTION, EVALUATION, AND /OR CHARACTERIZATION OF THE KIDNEYS AND URINARY TRACT

- a. Indeterminate lesions detected with other imaging modalities
- b. MR Urography for evaluation of the collecting system for abnormalities of anatomy or physiology
- c. Potential renal donor assessment
- d. Staging and preoperative assessment of renal neoplasms

DETECTION, EVALUATION, AND /OR CHARACTERIZATION OF THE ADRENAL GLANDS

- a. Indeterminate lesions detected with other imaging modalities
- b. Pheochromocytoma and functioning adrenal adenoma

OTHER

- a. Assessment of inflammatory disorders of the bowel
- b. Detection and characterization of intra-abdominal fluid collections
- c. Detection and characterization of retroperitoneal neoplasms other than above
- d. Detection and evaluation of primary and metastatic peritoneal neoplasms
- e. Preoperative assessment of gastric neoplasms

DETECTION, EVALUATION, AND/OR CHARACTERIZATION OF THE PELVIS: SOFT TISSUE COMPONENTS

- a. Assessment for recurrence of tumors of the bowel, bladder, prostate, or gynecologic organs following surgical resection or exenteration
- b. Assessment of fetal and placental abnormalities
- c. Assessment of pelvic floor defects associated with urinary or fecal incontinence
- d. Detection and staging of gynecologic malignancies, including those originating in the vulva, cervix, uterus, ovaries, and fallopian
- e. Detection and staging of malignancies of the bowel, prostate, bladder, penis, and scrotum
- f. Determination of arterial and venous anatomy and patency
- g. Determination of number, location, and type (solid or hemorrhagic) of fibroids prior to myomectomy, hysterectomy, or uterine artery embolization
- h. Evaluation of complications following pelvic surgery, including abscess, urinoma, lymphocele, radiation enteritis, and fistula formation
- i. Evaluation of pelvic pain or mass, including detection of adenomyosis, ovarian cysts, torsion, tubo-ovarian abscess and benign solid masses, obstructed fallopian tubes, endometriomas, and fibroids
- j. Identification and staging of soft-tissue origin sarcomas
- k. Identification of a congenital anomaly of the male and female pelvic viscera
- l. Identification of the source of lower abdominal pain in pregnant women, including appendicitis and ovarian and uterine masses

ABDOMINAL AND PELVIC MR ANGIOGRAPHY

MR angiography provides noninvasive and reliable assessment of primary vascular diseases involving the abdominal and pelvic vessels, the effects of tumors on vessels, vascular supply of tumors and source of hemorrhage. It can be done in patients who cannot tolerate iodinated or paramagnetic contrast. The technique continues to evolve and a variety of options are available including 2-dimensional, 3-dimensional, time-of-flight, phase contrast and contrast enhanced techniques.

MAJOR ABDOMINAL AND PELVIC INDICATIONS

- a. Assessment of etiology of hemorrhage
- b. Assessment of etiology, extent and severity of primary vascular processes, e.g. atherosclerotic occlusive disease, aneurysm, dissection, vascular malformations, venous thromboembolism
- c. Assessment of vascular supply of tumors
- d. Preoperative planning for transplantation, vascular surgery, tumor resection

E. MUSCULOSKELETAL

MRI is often the most sensitive, noninvasive diagnostic test for detecting anatomic abnormalities of the musculoskeletal system. Its findings may be misleading if not closely correlated with the clinical history, physical examination, physiologic tests such as nerve conduction analysis and electromyography, and other imaging studies.

GENERAL CONSIDERATIONS

- a. Dedicated coil is mandatory to maximize the signal to noise ratio and in plane resolution.
- b. Patients should be positioned appropriately in a comfortable position, thus allowing the patient to remain motionless. We should strive to place area of interest in the center of the magnetic field as homogeneity of the magnet is best at its center. Use of vitamin E capsules is recommended to locate subtle soft tissue masses in order to confirm that the examination has included the relevant area of clinical concern.
- c. The choice of sequences may be optimized to address specific clinical questions and may vary due to local preferences. A typical imaging protocol may be composed of conventional spin-echo, fast (turbo) spin-echo, STIR, and gradient-recalled echo pulse sequence types. The exact repetition time (TR), echo time (TE), and flip angle chosen will depend on the field strength of the magnet and the desired relative contrast weighting. It usually includes images acquired in multiple imaging planes.
- d. Field of view depend on the anatomic structure under consideration, e.g. for the knee the FOV should be 16 cm or smaller. A maximum slice thickness should be less than 4mm for knee and shoulder and between 1.5-3 mm for wrist and elbow. The slice gap should not exceed 10% and preferably with newer scanners and stronger gradients, no slice gap should be used.
- e. Imaging of articular cartilage disorders can be accomplished with a variety of pulse sequences, including fast spin-echo, proton-density weighted, T2- weighted sequences with or without fat suppression, or 3D gradient-recalled (GRE) sequences. The use of 3D isotropic sequences (GRE, turbo spin echo PD or T2) is gaining popularity given its multiplanar reformat capabilities.
- f. The use of gadolinium chelates for enhancement permits more specific detection, characterization, and staging of musculoskeletal masses, and their recurrence. Gadolinium also has a role in the evaluation of inflammatory disorders.
- g. In cases of MR arthrography, T1-weighted images with fat suppression – either 2D (fast) spin-echo or 3D spoiled gradient-echo sequence are utilized to assess labral pathology. At least one T2-weighted sequence is usually included with MR arthrography to show abnormalities that are not visible on T1 weighted images and to outline fluid that does not communicate with the injected joint. Additionally, a T1-weighted sequence without fat suppression is useful for evaluating bone marrow and characterization of soft tissue lesions.
- h. Axial oblique images parallel to the femoral neck or Radial reformatted images around the femoral neck are used to assess femoroacetabular impingement.
- i. In joints containing large metallic implants - metal reducing techniques including altering sequence parameters to include a combination of longer echo trains, increased receiver bandwidth, smaller fields of view (FOV), increased matrix size in the frequency-encoding direction, and control of the phase and frequency encoding directions are used to reduce, but typically do not completely eliminate, metal artifacts.

INDICATIONS FOR MRI IN THE MUSCULOSKELETAL SYSTEM

Primary indications for MRI of the musculoskeletal system include, but are not limited to:

- a. Arthritides: inflammatory, infectious, neuropathic, degenerative, crystal-induced and post- traumatic
- b. Congenital and developmental conditions: dysplasia, symptomatic and asymptomatic normal variants.
- c. Fractures: traumatic, insufficiency, stress and pathologic in etiology.
- d. Infections of bone, joint, or soft tissue
- e. Intra-articular bodies: chondral, osteochondral, osseous

- f. Marrow abnormalities: bone contusions, osteonecrosis, marrow edema syndromes, stress fractures and staging of marrow replacing disease (metastasis, myeloma and primary marrow disease staging).
- g. Meniscal and labral disorders: nondisplaced and displaced tears, discoid meniscus, meniscal cysts; complications of meniscal and labral surgeries.
- h. Muscle and myotendinous disorders: partial and complete tears, inflammatory, infectious, neuropathic and degenerative myopathies.
- i. Neoplastic disorders (benign and malignant): of bone, joint, or soft tissue
- j. Neurologic conditions: nerve entrapment and compression, denervation peripheral neuritis,
- k. Osteochondral and articular cartilage abnormalities: osteochondral fractures, osteochondritis dissecans, degenerative chondrosis, chondral fractures.
- l. Synovial-based disorders: inflammatory and nodular synovitis, tenosynovitis, bursitis, ganglion cysts
- m. Tendon disorders: partial and complete tears, tendonitis, tendinopathy, treated tears, and xanthomas .
- n. Vascular conditions: entrapment, aneurysm, stenosis, occlusion,

EXTENDED INDICATIONS

- a. Arthritides: monitor response to treatment
- b. Infectious disease: Monitor response to treatment and determine best site for sampling
- c. Inflammatory disorders: assess most appropriate site for sampling or biopsy and monitor response to treatment
- d. Neoplastic disease: Assess most appropriate site for sampling, monitor response to treatment and follow-up for recurrence
- e. Pelvis: Sports hernias (Athletic Pubalgia)

INDICATIONS FOR MR ARTHROGRAPHY IN MSK

- a. Hip: Nondisplaced and displaced labral tears, paralabral cysts.
- b. Knee: Nondisplaced and displaced meniscal tears, parameniscal cysts; Post-operative meniscus.
- c. Shoulder: Nondisplaced and displaced labral tears, paralabral cysts; Post-operative shoulder.

F. CARDIOVASCULAR ^{vi}

Cardiovascular MR (CMR) has seen tremendous developments over the past 10 years. It is now one of the most powerful tools to evaluate cardiac anatomy, function, perfusion and viability.

INDICATIONS FOR CARDIOVASCULAR MRI

Indications include the assessment of:

- a. Cardiac masses and thrombus
- b. Congenital heart disease
- c. Ischemic heart disease
- a. Coronary artery stenosis or anomalous origin
- b. Myocardial perfusion at rest and exercise or pharmacological stress
- c. Myocardial viability
- d. Non-ischemic cardiomyopathy
- e. Pericardial disease

- f. Valvular heart disease
- g. Vascular imaging
- h. Ventricular morphology, function and mass

Imaging techniques used in CMR depend on the specific indication and the question to be answered at the end of the scan. The minimum standard MRI technique should endeavour to maximize the signal to noise ratio (SNR) and fidelity of anatomic registration and should include the following:

- a. In adult cardiac applications the phased array body coil may be used but a dedicated cardiac coil is preferred for optimal SNR). The selected field of view (FOV) should be appropriate to the size of the thoracic cavity. For pediatric applications, volumetric coils appropriate to the child size and age should be used.
- b. Slice thickness of 5-10 mm is suitable for most applications (6-8 mm most common). Occasionally, thicker slices are used (eg 15mm for T2-weighted TIR black-blood sequences).
- c. Slice gap between 0-50%
- d. Matrix and slice profile selection resulting in an in-plane resolution of up to $< 1 \times 1$ mm
- e. Optimized cardiac gating and respiratory ordered phase encoding, motion reduction techniques should be employed. The vectorcardiogram (VCG) method improves the reliability of R-wave detection because it overcomes magnetohydrodynamic effects. When the ECG signal is suboptimal (due to patient's large body habitus or a large pericardial effusion, for example), peripheral pulse gating using a peripheral pulse monitor can be a useful alternative to vectorcardiogram gating. Imaging that is triggered by the peripheral pulse wave will begin after the onset of left ventricular systole and therefore imaging of systole may be missed during the trigger window in prospective gating. To include the full duration of systolic ventricular contraction, retrospective gating is required (rather than prospective gating). Most imaging techniques which acquire images at a single temporal phase of the cardiac cycle (black-blood TSE, first pass perfusion, delayed enhancement) use prospective gating while cine imaging techniques employ retrospective gating.
- d. Respiratory gating strategies are available which synchronize data acquisition to the respiratory cycle and/or prospectively adjust slice position to compensate for motion. Navigator echo respiratory gating techniques monitor and correct for respiratory motion of the heart. Respiratory gating is most useful in the sedated pediatric and dyspneic heart failure population but navigator echo respiratory gating is also useful in 3D coronary MRA.
- f. Parallel acquisition techniques can reduce scan time by deriving spatial encoding information from multi-element coil arrays. Generally a factor of 2 is used routinely and higher parallel factors can further reduce acquisition times and improve temporal resolution at the price of progressive SNR loss.

CARDIOVASCULAR MRI APPLICATIONS

a. BLACK-BLOOD IMAGING

- o Single shot turbo or fast spin-echo imaging is now standard for imaging of the heart and great vessels. This can be performed in multiple planes and is an excellent tool for anatomical surveys especially in the setting of congenital heart or pericardial disease. The advantages of this sequence is the relatively short acquisition time but due to the single shot technique, there is relatively low signal compared to turbo or fast spin echo sequences. Double inversion pulses can be added to these sequences to null the signal from blood and improve the "black blood" appearance.
- o Traditional T1 and T2-weighted turbo or fast spin-echo imaging with and without fat saturation can be used to assess structural abnormalities of the ventricles and pericardium as well as cardiac and pericardial masses.
- o T2-weighted turbo/ fast spin-echo sequences can be combined with double inversion recovery (DIR) pulses for improved nulling of blood signal (T2-weighted DIR FSE or TSE). They can be used without or with fat saturation that can be achieved using chemical fat saturation or spectral adiabatic pulse sequences (T2 SPAIR) or with a third inversion recovery pulse to null fat (so called "triple inversion or TIR"). All of these T2-weighted DIR fat saturated sequences can be used to detect myocardial edema in the setting of suspected acute myocarditis,

acute myocardial infarction as well as for tissue characterization in the setting of a suspected cardiac or pericardial tumour. It is also possible to add a T2 preparation pulse prior to a steady state free precession (SSFP) sequence to increase the T2 weighting and use this to assess for myocardial T2 signal abnormalities but this is not widely used.

- Myocardial T2* imaging is used to assess the presence of myocardial iron due to difficulties associated with myocardial biopsy (invasive procedure, sampling error etc). It is a segmented gradient multi-echo technique which enables the calculation of T2* for the myocardium typically assessed at the interventricular septum. T2* is an exponential decay constant which is affected by local magnetic field inhomogeneities as well as spin-spin relaxation (T2 relaxation or decay). T2* decay is accelerated by myocardial iron deposition due to the paramagnetic effects of iron. However, compared to the well established calibration curves correlating liver iron concentration with liver T2* values where liver iron can in fact be quantified, myocardial iron cannot be quantified.

b. WHITE-BLOOD IMAGING

- Single shot steady state free precession (SSFP) imaging in multiple planes (multiple long axis views and short axis stacks) can be used as an alternate to single shot turbo spin-echo (TSE) for anatomical delineation or as localizers.
- Breath-hold cine imaging using steady state free precession has replaced spoiled gradient echo cine imaging in most cases to assess cardiac anatomy and function due to its improved SNR, improved endocardial delineation and faster acquisition times. Atrial and ventricular volumes and myocardial mass can be calculated with a high degree of accuracy and reproducibility and MRI is considered the gold standard for assessment of ventricular size and function. Dobutamine infusion during image acquisition has been used to detect wall motion abnormalities as a result of inducible myocardial ischemia. This is generally performed in academic centres with close physician monitoring and its use in routine clinical practice has yet to be adopted. Adenosine stress perfusion MRI is also increasingly being used to evaluate myocardial ischemia. The safety of both methods of pharmacological stress CMR has been demonstrated when performed in experienced centers.
- Real time SSFP cine imaging can be used in the setting of suspected pericardial constriction or when ECG gating is impossible due to severe arrhythmia. Its clinical application will evolve over time.
- Myocardial tagging involves the placement of a saturation grid or lines across the heart and this is used in combination with cine imaging. The deformation of the lines may help in the assessment of wall motion for strain analysis and pericardial-myocardial adhesions that may be seen in constrictive pericarditis. Some centres use myocardial tagging to delineate myocardial tumours (which typically do not contract whereas normal myocardium does) but this is not widely used in clinical practice.
- ECG-triggered 3D SSFP imaging using free breathing with navigator tools to compensate for respiratory motion can be used to image the coronary arteries, but this application is not widespread. Gadolinium is not necessary but if gadolinium is being injected as part of the examination, this sequence is usually completed post gadolinium to take advantage of the improved CNR after contrast injection.

c. FLOW-SENSITIVE IMAGING TECHNIQUES

Phase contrast imaging is a gradient-echo (GRE) technique which is the cornerstone of flow velocity measurement in MRI. It is used for shunt quantification in congenital heart disease and to assess regurgitant fractions in valvular regurgitation and the severity of stenosis in aortic coarctation or valvular stenotic lesions. A breath-held (shorter acquisition with more accurate localization of slice if planning from images that were obtained in end expiration) or free-breathing (better temporal resolution and avoids potential altered physiology with breath-held technique) approach can be used. An appropriate encoding velocity must be used to avoid aliasing (when encoding velocity is set too low) or poor SNR (when encoding velocity set too high).

d. PERFUSION IMAGING TECHNIQUES

MR perfusion techniques are all based on the dynamic imaging of the first pass of Gadolinium based, T1-shortening contrast agents through the myocardium. Ultrafast imaging sequences are required to acquire images at three to five slice positions each heartbeat. Variations of GRE, SSFP and hybrid GRE-echo planar pulse sequences can be used along with parallel imaging to increase performance. Stress imaging can be done during adenosine or dipyridamole infusion and compared to first-pass rest imaging for the identification of reversible ischemia, followed by delayed enhancement imaging to assess for infarct. This is generally performed in academic centres with close physician monitoring.

e. LATE GADOLINIUM ENHANCEMENT TECHNIQUES

T1-weighted inversion recovery GRE imaging performed between 10 to 20 minutes after gadolinium injection is the mainstay for detecting the presence and extent of myocardial infarction. There is expanded extracellular volume of distribution in damaged myocytes found in infarction which leads to retention of gadolinium compared to normal myocardium in which the gadolinium has washed out. When the MRI signal intensity of normal myocardium has been effectively nulled, infarcted myocardium should appear bright or 'hyper-enhanced'. This technique is also valuable in the characterization of non-ischemic cardiomyopathies with specific enhancement patterns described in the presence of various myopathies and/or infiltrative diseases. Delayed hyper-enhancement can also occur in the setting of myocarditis and both the degree and area of enhancement can decrease over time as some of the hyper-enhancement may relate to edema rather than infarct.

For delayed enhancement imaging using T1-weighted inversion recovery gradient echo sequences, it is important to first determine the inversion time that selectively nulls the signal from normal myocardium. This TI is generally between 200-300 msec but this can vary depending on the specific gadolinium contrast agent used, the dose, and the field strength (1.5T vs. 3.0T). If a phase sensitive inversion recovery GRE sequence is utilized (often part of the same breath held acquisition as the magnitude images), image contrast is less vulnerable to improper choice of TI and is relatively stable for a wide range of TI times. Most vendors also provide a TI scout sequence which will systematically vary the TI to provide a preview to aid in the appropriate selection of TI time.

Another option for delayed enhancement imaging is to use an inversion recovery prepared 3D breath hold whole heart SSFP sequence. This has the advantage of faster acquisition time but at the price of reduced spatial resolution and SNR.

f. VASCULAR IMAGING TECHNIQUES

Magnetic resonance angiography is a robust and reliable technique that can be applied to visualize the extra-cardiac thoracic vasculature in routine clinical practice. Magnetic resonance coronary angiography is still considered a field of research as compensation of cardiac and respiratory motion cannot be achieved in all patients. However, it can be used successfully to image the coronary arteries in patients who have regular heart rates and consistent tidal volumes to visualize the proximal two thirds of the coronary arteries. MR coronary angiography is a reasonable option in young patients to exclude anomalous course because it avoids radiation that would be required with coronary CT angiography.

Specific Vascular Indications

- a. aortic disease for follow-up of acute aortic syndromes, aneurysms or vasculitis
- b. suspected congenital heart disease due to the frequent association of vascular variants and malformations

A rapid 3-dimensional spoiled gradient echo acquisition is obtained during the intravenous injection of a gadolinium-based contrast agent. A rapid 2-dimensional T1-weighted gradient echo sequence is run to detect the arrival of contrast agent either as a pre-scan using a small test bolus of contrast or immediately preceding the 3-dimensional MR angiogram which is manually or automatically triggered when the contrast agent arrives. Prospective gating can reduce cardiac motion artifacts but at the expense of increased scan time and therefore usually the MR angiograms are not

cardiac gated. This does lead to blurring of structures located in close proximity to the beating heart such as the aortic root and ascending aorta.

Time-resolved 3-dimensional MRA provides dynamic information with a temporal resolution of 0.5-3.0 seconds. In order to increase the speed of acquisition, through-plane spatial resolution is sacrificed using parallel imaging acceleration and data sharing techniques. This technique requires only a small amount of contrast (typically only 3-4 cc) and captures the dynamics of blood flow through the right and left circulation. This is particularly useful when temporal information is required such as outlining feeding and draining vessels in the case of arteriovenous malformations, AV fistulas, shunts and anomalous connections.

G. CHEST ^{vii}

MRI is presently used as a problem solving modality. The principle applications are evaluation of the chest wall, mediastinal and hilar structures. All other pertinent imaging studies should be reviewed before MRI imaging is undertaken.

The minimum standard MRI technique for scanning the chest should endeavor to maximization of SNR and fidelity of anatomic registration and should include the following:

In adults the body coil is suitable. The selected FOV should be appropriate to the size of the thoracic cavity. For pediatric applications, volumetric coils appropriate to the child size and age should be used.

INDICATIONS FOR IMAGING THE CHEST

- a. anterior mediastinal mass or pericardial mass to rule out mediastinal or cardiac invasion
- b. chest wall mass
- c. lung cancer (chest wall, diaphragmatic, or pericardial invasion)
- d. mesothelioma (chest wall, diaphragmatic, or pericardial invasion)
- e. pulmonary angiography
- f. thoracic outlet syndrome

For the evaluation of mediastinal and hilar structure adjacent to the heart cardiac gating may be required, with the relative weighting in a given image governed by required RR interval of the cardiac cycle. Relatively T1-weighted or PD-weighted images in a combination of axial, sagittal, coronal and oblique planes are suitable when evaluating anatomy. For evaluation of the superior mediastinum, cardiac gating is not always required, providing greater flexibility for T1 and T2 weighting.

Gadolinium chelates are required to distinguish cystic versus solid masses (where both cysts and solid masses may have homogeneously bright T2 signal) and may be helpful in demarcating tumour borders and possible invasion of vascular structures.

Repeat phases post gadolinium chelate injection may be helpful to distinguish from slow flow in the pulmonary veins vs. thrombus or tumour invasion.

When alternate mediastinal, hilar and chest wall pathologies are under evaluation T1 and T2-weighted images in a combination of axial, sagittal and coronal planes as well as; additional planes may be required in certain instances. Additional sequences (e.g. STIR) may be of value in specific instances to look for edema.

Slice thickness of between 7-10 mm is suitable for most applications but is also dependent on the size of the mass being evaluated and thinner slices may be necessary for small lesions.

Slice gap between 20-30%, preferably 20%.

Gadolinium chelates should be utilized in the evaluation of recurrent or post-therapy residual chest wall and mediastinal tumours.

Magnetic resonance angiography is a robust and reliable technique that can be applied to visualize the thoracic vasculature in routine clinical practice. To assess thoracic outlet syndrome, imaging with arms up and down is necessary for thoracic outlet syndrome where the kinking of the subclavian arteries may be positional. Imaging bilateral subclavian arteries is useful for comparison and time resolved MRA can be helpful in cases of steal phenomenon due to proximal subclavian stenosis resulting in retrograde flow in the ipsilateral vertebral artery.

In some cases, phase contrast imaging at the level of the vertebral arteries may also show the reverse direction of flow in cases of proximal subclavian stenosis. However, the small caliber of the vertebral arteries may be problematic for phase contrast imaging.

Magnetic resonance angiography may also be useful to rule out acute pulmonary thromboembolic disease in the setting of iodinated contrast allergy. It should be performed only in centers that routinely perform it and perform it well as investigators have found great variability in the sensitivity and specificity of the technique depending on the institution. The spatial resolution is limited to the detection of emboli in the segmental arteries. The accuracy of this technique is limited for subsegmental vessels.

LUNG PERFUSION

Information relating to pulmonary perfusion can be obtained using dynamic first-pass imaging of gadolinium-based contrast media. While 2D dynamic GRE sequences can be acquired with ultra-high temporal resolution (eg, 100 ms), 3D coverage is desired for maximizing sensitivity to segmental and sub-segmental perfusion defects (eg, pulmonary embolism). Recent advancements in parallel imaging and novel k-space acquisition strategies have improved the feasibility of obtaining 3D coverage of the entire lung in approximately 1.5 s, but with a penalty in SNR. Assuming optimal temporal resolution and SNR, quantitative estimates of perfusion in ml/min/g parenchyma can be obtained by sampling the changing signal intensity over the initial transit of the contrast agent for a given parenchymal region of interest. Perfusion and blood volume can be estimated for each region by applying a tracer kinetic model. These techniques are still investigational and not used routinely in clinical practice.

LUNG VENTILATION

It is also possible to assess regional ventilation with MRI. Most techniques are analogous to radionuclide imaging, whereby a radiolabelled gas or aerosolized tracer is inhaled and its distribution imaged. In MRI, hyperpolarized ^{129}Xe or ^3He is first created by applying a specialized laser light to amplify the fraction of magnetically active nuclei in the gas prior to inhalation by the patient. Images are typically acquired using a rapid train of low flip-angle pulses to track the rate at which the protons depolarize to their native state. In addition to the polarization equipment and gases, this approach requires hardware capable of multinuclear imaging and remains limited to a small number of academic centres. Alternatives such as oxygen-enhanced and aerosolized gadolinium-based techniques are also areas of active exploration. These techniques are still investigational and not used routinely in clinical practice.

H. BREAST IMAGING ^{viii}

Breast MRI has made many advances in clinical imaging in the past decade. While it was an imaging tool used chiefly to image breast implants when the last set of ACR guidelines was introduced, it has now become an essential component of breast imaging, and now forms a vital role in the investigation of breast cancer, as well as in screening women at high risk for developing breast cancer. Whether it is used as a problem-solving tool, a screening test, or for staging patients with breast cancer, it has the highest sensitivity for detecting breast cancer of any clinical breast imaging tool available. These guidelines include the current applications of breast MRI as well as fundamental requirements for breast MRI imaging in clinical practice.

INDICATIONS FOR IMAGING THE BREAST

- a. Breast implants: to determine presence of silicone implant rupture or other complications
- b. Definitive problem solving in equivocal mammographic clinical and/or US findings
- c. High risk screening: for screening women at high risk for breast cancer, with estimated lifetime risk of greater than 20-25% e.g. women who are BRCA 1 and 2 gene mutation carriers, women who received chest irradiation for treatment of another malignancy such as lymphoma between the ages of 10-30 years of age, PTEN Li-Fraumeni syndrome, Cowden syndrome, or Bannayan-Riley-Ruvalcaba syndrome, or one of these syndromes in first-degree relatives
- d. Neo-adjuvant chemotherapy: to assess response to chemotherapy
- e. Occult breast cancer: to determine the site of a primary carcinoma in a patient presenting with metastatic breast carcinoma such as axillary lymphadenopathy or other site of bony or body metastases when mammograms and breast ultrasound are negative; patients with suspicious bloody or serous nipple discharge and negative mammograms and breast ultrasound.
- f. Peri-operative evaluation: to assess for residual disease
- g. Preoperative staging: to assess extent of disease in the affected breast, and to screen for occult contralateral malignancy, expected in 3-6% of patients

PROTOCOLS

Breast MRI protocols should be used to provide information on high-spatial resolution morphology, functional information on perfusion and capillary leakage, and tissue T1 and T2 relaxation times.

A dedicated breast coil is required for all cases of breast MRI. Only indications of assessment of implant do not require the intravenous injection of gadolinium chelates; all other indications for breast MRI currently need an IV injection of gadolinium. The standard dose of 0.1 mg/kg gadolinium is used, and is optimized with a power injector at a rate of 2-3 mls/sec, followed by a 10-20 ml saline flush.

DYNAMIC CONTRAST ENHANCED SEQUENCES

The angiogenic activity of cancers constitutes the basis for breast cancer detection with breast magnetic resonance imaging.

HIGH-SPATIAL RESOLUTION SEQUENCES

Breast MRI is the most sensitive imaging method currently available for demonstration of invasive breast cancer. However, angiogenic activity is not the only factor responsible for enhancement of the breast, and other conditions such as inflammatory processes in the breast, and increased hormonal activity may result in enhancing lesions. High spatial resolution images are required to best evaluate the borders of enhancing lesions, similar to interpretation of mammographic images, and to determine the most likely diagnosis. Higher spatial resolution increases the specificity and sensitivity of the MRI. The sensitivity of Breast MRI is maximized by correlation with the timing of menstrual cycle, such that optimal imaging, when feasible, such as with screening MRI, is performed in menstruating females between days 7-14 of the menstrual cycle.

BASIC REQUIREMENTS FOR BREAST MRI

- a. A dedicated breast coil -there are several available coils on the market.
- b. Temporal resolution of less than 1-3 minutes per acquisition- ideally 60-90 seconds per acquisition.
- c. Dynamic imaging - acquiring a stack of images temporally 3 times; 1 pre and 2 post the bolus injection of contrast. The first post contrast should be no later than 180 seconds after the contrast injection. The last set of images should be no earlier than 6 to 8 minutes after the contrast injection.

- d. Spatial resolution that uses the largest imaging matrix within the acquisition window: in-plane pixel size of 0.5 X 0.5 to 1.0 X 1.0 mm and through plane pixel size of 1-3 mm.
- e. All dynamic contrast-enhanced breast MRI pulse sequences require a T1-weighted gradient echo (GRE) sequence that meets the requirements of adequate temporal resolution. This may be achieved with 2D multi-section or three-dimensional (3D), fast (turbo) or regular, spoiled or nonspoiled. Compared with 2D imaging, 3D imaging has the advantage of stronger T1 contrast, and uses a shorter repetition time than 2D, with a higher signal-to-noise ratio, which allows for thinner (higher spatial resolution) sections to be acquired.
- f. All 3D (2D T1 and T2 requires a certain range of TR to produce the appropriate contrast) pulse sequences should use the shortest possible repetition time and a large flip angle (larger with longer repetition times: usually 90 degrees for 2D and 25-50 degrees for 3D-GRE). Parallel imaging has enabled maximal spatial and temporal resolution.
- g. Current bilateral dynamic protocols use the transverse sagittal or coronal planes and may be vendor specific to optimise spatial and temporal resolution. If isotropic imaging is used, images can be successfully reformatted in all planes for viewing.
- h. Bilateral breast imaging protocols are required for all women undergoing screening (women at increased risk for breast cancer), and in all who undergo staging for a known breast cancer. This allows assessment of the contralateral breast and facilitates comparison to avoid diagnostic errors. There are very few indications where unilateral breast imaging is utilized.
- i. Fat suppression is ideally applied to the dynamic pulse sequences; but should not be used at the expense of temporal or spatial resolution. Fat suppression may be achieved by a number of methods, most commonly through active fat suppression or fat saturation, by eliminating signal from fatty tissue, or by choosing selective water excitation. Active fat suppression requires a very homogeneous field across the entire FOV, which may be difficult to achieve with breast imaging, given the structure of the breasts. Specifically manually choosing a region of fat in the breast by which to “shim” to fat signal greatly helps improve the fat saturation. Some of the inhomogenous fat suppression may also be subtracted out.
- j. Kinetic data is acquired by visual assessment of the enhancement pattern, and by placing a region of interest (ROI) over the enhancing area. No more than 3-4 pixels should be included in the ROI, to minimize inaccurate averaging of the enhancement. The edges or maximally enhancing areas are the best to evaluate. A kinetic curve is generated with dedicated software.
- k. GRE T2 with or without fat saturation – for evaluation of fluid, cysts, edema in the breasts

ADDITIONAL SEQUENCES

- a. GRE T1 without fat saturation- for evaluation of fat, lymph nodes, and architecture of the breast
- b. May use the body coil to evaluate lymph nodes in the axillary and internal mammary nodal stations, cervical and supraclavicular areas
- c. Axial and sagittal STIR with water saturation sequences may be used to determine the integrity of breast implants

QUALITY ASSURANCE ^{ix}

Each facility should establish and maintain a medical outcomes audit program to follow up positive assessments and to correlate pathology results with the interpreting radiologist’s findings. The audit should include evaluation of the accuracy of interpretation as well as appropriate clinical indications for the examination. Each center performing breast MRI should be able to obtain the correlative pathology results from either their own facility or one with whom they have a referral arrangement, by means of correlation with mammographic, sonographic and or MRI guided biopsies. Facilities must use the Breast Imaging Reporting and Data System (BI-RADS®)(ref) for final assessment codes and terminology for reporting and tracking outcomes.

For further Breast MRI requirements please refer to the CAR Standard on Breast Imaging.

I. FETAL IMAGING ^x

MRI is an effective noninvasive diagnostic test for characterizing many fetal abnormalities; however, it should be interpreted with the relevant clinical history and prior sonographic findings. This is a specialized test and practiced in few institutions. It is used mainly for problem-solving and only in select circumstances for screening.

MEASURES FOR FETAL MOTION REDUCTION

- a. Clinical measures such as keeping mother from consuming anything for 4 hours before the MR examination in allowable circumstances, and making sure that she is comfortable during the scan.
- b. Use of benzodiazepines to sedate the pregnant patient for the purpose of decrease fetal motion can be used in extremely limited and specialized situations.

INDICATIONS FOR FETAL IMAGING

Neurologic Indications

- a. Congenital anomalies of the brain or injury is anomalies of the brain or injury are suspected
e.g. Ventriculomegaly, Agenesis of the corpus callosum, Holoprosencephaly, Cerebral cortical malformations, parenchymal injury in monochorionic twin
- b. Congenital anomalies of the spine, e.g. Neural tube defects, Sacrococcygeal teratomas
- c. Vascular abnormalities of the brain

Non-Neurologic Indications

- a. Fetal Abdominal or pelvic mass
- b. Fetal masses in the thorax, e.g. Congenital diaphragmatic hernia, Pulmonary sequestration, Congenital cystic adenomatoid malformation, Airway obstruction
- c. Fetal orbital malformations and growth, e.g. anophthalmia, micophthalmia, colobomatous cyst, quadratic growth model for lens, orbit and interocular distance.
- d. Masses of the face and neck, e.g. venolymphatic malformation, Hemangiomas, Goiter, Teratomas, Facial clefts

Technical and Maternal Indications

- a. Evaluation of placenta accreta (including its variants, placenta increta and placenta percreta) especially in presence of posterior upper segment and myomectomy scar.
- b. Fetal surgery assessment
- c. Maternal factors where fetus cannot be adequately assessed by sonography e.g. decreased amniotic fluid, large maternal body habitus, difficult position of the fetal head, and advanced gestational age, where shadowing from the calvarium can interfere with ultrasound images.

Present data have not conclusively documented any deleterious effects of MRI at 1.5 T on the developing fetus. However, MR scans at any stage of pregnancy should potentially affect the care of the patient or fetus during the pregnancy and the information cannot be acquired by ultrasonography. Intravenous contrast should not be used for fetal MRI.

APPENDIX A - Sample Safety Questionnaire

Please answer all questions carefully and completely. The following items can interfere with the MRI study and your safety.

To be completed by patient or family member with knowledge of patient history.

Name:		Date of Birth:		
Weight:		Height:		
	YES	NO	What, When, Where (if applicable)	
Do you now, or have you ever, had a pacemaker or defibrillator?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Have you had heart surgery?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Have you had surgery for an aneurysm?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Do you have an implanted pump, stimulator, electrodes or electronic device?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Do you have stents, coils, filters or grafts?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Have you had ear or eye surgery?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Have you ever sought medical attention to have metal removed from your eyes?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Is there a possibility you are pregnant?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Do you have any kidney problems or are you on dialysis?	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
Do you have diabetes, Lupus, history of kidney or heart disease, TIA, stroke or poor circulation to the legs or other parts (excluding varicose veins)? Please specify.	<input type="checkbox"/> Yes	<input type="checkbox"/> No		
If you have any allergies, please list them:	1.		5.	
	2.		6.	
	3.		7.	
	4.		8.	
Do you have:			YES	NO
Breast implants/ penile implant			<input type="checkbox"/> Yes	<input type="checkbox"/> No
Hearing aid			<input type="checkbox"/> Yes	<input type="checkbox"/> No
Permanent eye liner or tattoo			<input type="checkbox"/> Yes	<input type="checkbox"/> No
Body piercing			<input type="checkbox"/> Yes	<input type="checkbox"/> No
Nicoderm or medication patch			<input type="checkbox"/> Yes	<input type="checkbox"/> No

Do you have:		YES	NO
Removable dental work		<input type="checkbox"/> Yes	<input type="checkbox"/> No
Shrapnel/bullets		<input type="checkbox"/> Yes	<input type="checkbox"/> No
A shunt		<input type="checkbox"/> Yes	<input type="checkbox"/> No
I.U.D. (Intrauterine device)		<input type="checkbox"/> Yes	<input type="checkbox"/> No
Are you breast feeding?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
Have you ever had an MRI?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
If yes, did you have an injection of contrast?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
If yes, did you have any reaction to the contrast?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you have any type of prosthesis or metal in your body that has not been covered in this questionnaire?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
Are you taking medications for your heart, bronchitis, asthma or high blood pressure?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
If yes, please list them:			
1.	3.	/	
2.	4.		
Are you taking blood thinners?		<input type="checkbox"/> Yes	<input type="checkbox"/> No
Signature of person who completed the form:			
Date:			
Relationship to patient:			
TO BE COMPLETED BY TECHNOLOGIST:			
eGFR calculated value (if applicable):			
Date of blood test:			
The risk of the contrast/exam has been explained to the patient.			
Verbal consent was obtained and venipuncture performed by:			
Comments:			
Questionnaire reviewed by:			
Injection performed by:			
Contrast used:		Reaction? <input type="checkbox"/> Yes <input type="checkbox"/> No	
Other drugs used:		Reaction? <input type="checkbox"/> Yes <input type="checkbox"/> No	
Technologist Signature:			

APPENDIX B - Sample Pre-Sedation Questionnaire

The information you supply below assists in the development of your anesthesia care. This form should be completed by each adult patient or by the parent/guardian if the patient is a child.

Please complete this questionnaire accurately and completely.

Name:					
Date of Birth:		Weight:		Height:	
Blood Pressure:		Respirations:		Pulse:	
Allergies (please list name and reaction):	Name		Reaction		
	1.				
	2.				
	3.				
Current Medications (please include over-the-counter, herbal and non-prescription meds):	1.		4.		
	2.		5.		
	3.		6.		
Prior Operations and Approximate Year:	1.				
	2.				
	3.				
BODY SYSTEM REVIEW					
Do you have any of the following medical conditions?				YES	NO
High Blood Pressure				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Treatment for Heart Attack Date: _____.				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Chest Pains / Angina				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Heart Murmur / Valvular Heart Disease /History of Rheumatic Fever				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Congestive Heart Failure				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Irregular Pulse / Palpitations / Atrial Fibrillation				<input type="checkbox"/> Yes	<input type="checkbox"/> No
History of Angioplasty / Stent Insertion / or Heart Surgery				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Pacemaker or I.C.D. Insertion Date: _____.				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Poor Circulation / Peripheral Vascular Disease				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Asthma, Wheezing, Chronic Cough				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Recent Chest Cold or Pneumonia				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Recent Steroid Use (e.g. prednisone) Date: _____.				<input type="checkbox"/> Yes	<input type="checkbox"/> No
Diabetes Date Diagnosed: _____.				<input type="checkbox"/> Yes	<input type="checkbox"/> No

Do you have any of the following medical conditions?	YES	NO
Hepatitis, Liver Disease, or Jaundice	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Thyroid gland problems / thyroid replacement medications	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Kidney Problems / Dialysis / Transplant / Stones	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Easily nauseated / motion sickness / migraine headaches	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Any injury or disease involving neck, spine or joints	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you have numbness, weakness, or paralysis of your extremities?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Mental health problems – depression / anxiety / needle phobia	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Blood problems (e.g. anemia / low platelets)	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you have any oral piercings, (such as studs or rings) in your tongue or lip?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you wear contact lenses?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Have you ever received a blood transfusion?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
(Women) Are you pregnant? Due date: _____.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you (or did you) smoke? Packs/day: _____. Smoked for how many years? _____. Quit date: _____.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you consume alcohol? Drinks/week _____.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you take or have you ever taken recreational drugs?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Do you or your close relatives have a history of malignant hyperthermia (MH) or pseudo-cholinesterase deficiency?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Have you had a serious problem with previous anesthesia?	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I have been told not to drive myself home or to operate heavy machinery within a 24-hour period of receiving an anesthetic drug.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Signature of person who completed this form:		
Relationship to patient (if applicable):		
Date:		

APPENDIX C - Acronyms

For health professionals consulting with this document, please note that a list of vendor technical descriptions, comparisons and specifications can be accessed on the Siemens Global Website. The link to the MRI Acronyms document produced by Siemens Medical is the following:

http://www.medical.siemens.com/siemens/en_US/gg_mr_FBAs/files/MAGNETOM_World/Application_Tips/MRI_Acronyms.pdf

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