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Cardiovascular Magnetic Resonance

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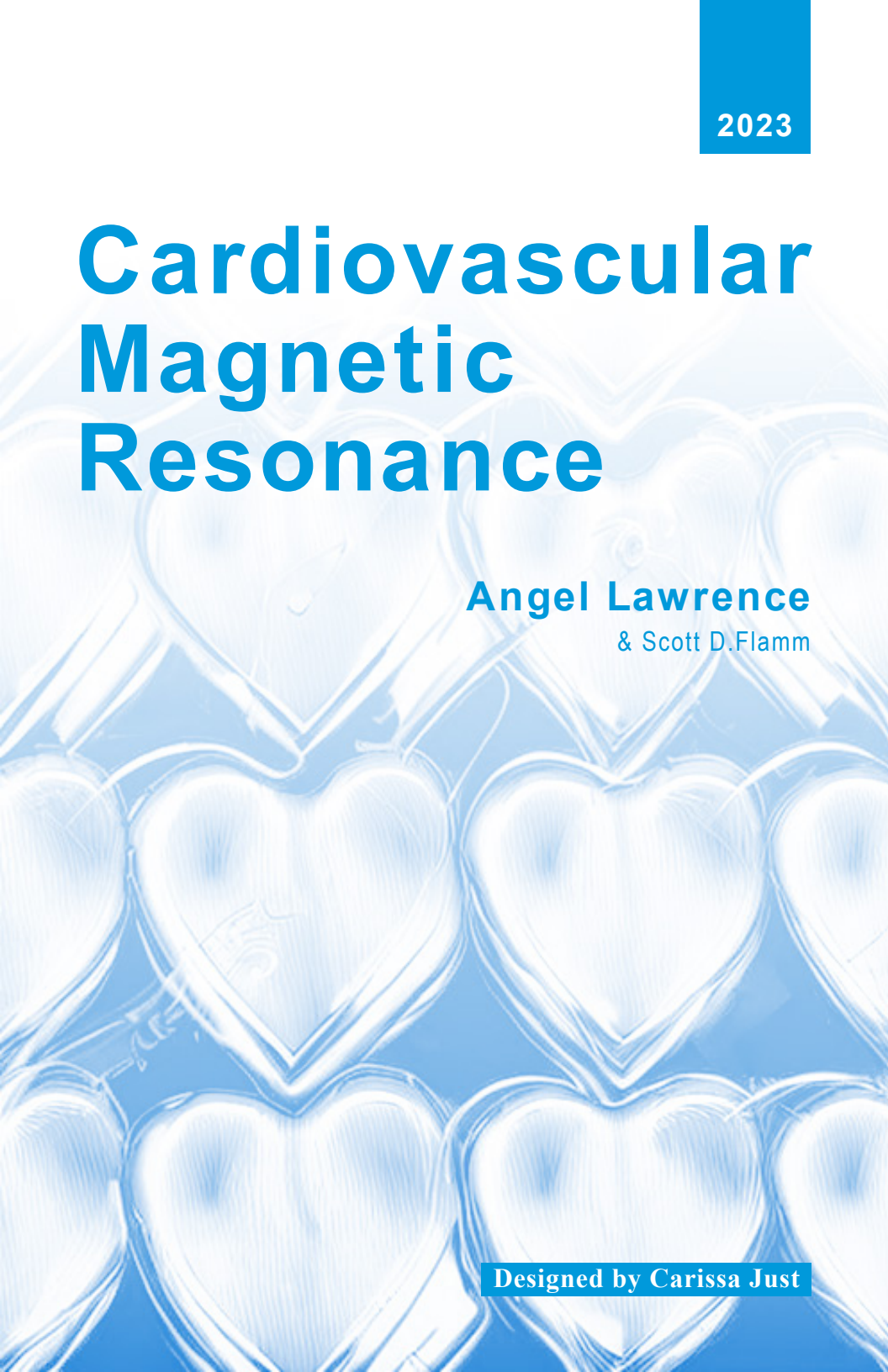

Designed by Carissa Just

Cardiovascular Magnetic Resonance

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This booklet is designed to serve as an easily digestible primer on CMRI that provides guidelines and helpful hints to get you on your way.

Preface

With this book I'd like to have a "heart to heart" discussion with you, the reader, on how to acquire images of the heart.

Cardiovascular Magnetic Resonance imaging (CMR) is an incredibly useful cardiac imaging modality that continues to gain in both popularity and clinical utility. CMR has become one of, if not the most informative noninvasive imaging modalities to evaluate structure and function of the cardiovascular system.

This booklet is aimed to provide a step-by-step guide for MRI technologists new to cardiovascular imaging, and CMR in particular, and to those who may be interested in a concise reference guide to keep by the scanner.

Further, with this information I hope to help you gain the foundation needed to achieve proficiency in CMR.

We will do so with a stepwise approach including cardiac MRI pulse sequences, acquisition approaches, clinical indications, and tips and tricks for CMR that I have learned through clinical practice. Join me as we explore the exciting world of CMR.

Acknowledgements

Words cannot express my deepest gratitude for my advisor and teacher, and the former Section Head of Cardiovascular Imaging at the Cleveland Clinic, Dr. Scott Flamm.

Thank you for generously imparting your knowledge and expertise over the years. Your patience, motivation, constructive feedback, and constant guidance has helped shape all of us around you.

As well, I am grateful for the assistance of, and could not have made this booklet without the kindness and help of Dr. Paul Schoenhagen. Your ever-present willingness to help does not go unrecognized.

And lastly, I need to thank Dr. Deborah Kwon for her encouragement and endless support.

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Abbreviations

2 CH	2 Chamber view-VLA
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3D	3 Dimensional
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ACCF	American College of Cardiology Foundation
AHA	American Heart Association
ALCAPA	Anomalous Left Coronary Artery from PA
APC	Aorto-pulmonary collaterals
AR	Aortic regurgitation
ARCAPA	Anomalous RCA from PA
ASD	Atrial septal defect
AV	Atrioventricular
AVSD	Atrioventricular septal defect
BSA	Body surface area
bSSFP	Balanced steady- state free- precession
BT	Blalock- Taussig (shunt)
CAD	Coronary artery disease
CBTS	Classic BT shunt
CCTGA	Congenitally corrected TGA
CMR	Cardiac Magnetic Resonance
DCRV	Double chamber right ventricle
Desc	Descending
DICOM	Digital Imaging and Communications in Medicine
ECG	Electrocardiogram
EDV	End-diastolic volume
EF	Ejection fraction
ESV	End-systolic volume
FOV	Field of view
FWHM	Full-width half maximum
HLA	Horizontal long axis
HR	Heart rate
HRS	Heart Rhythm Society
IVA	Inferior vena cava
LAD	Left anterior descending (coronary artery)
LA	Left atrium/atrial
LCx	Left circumflex (coronary artery)
LGE	Late gadolinium enhancement
LPA	Left pulmonary artery
LVEDP	LV end-diastolic pressure
LV	Left ventricle
MAPCA	Major aorto-pulmonary collateral artery
MBTS	Modified BT shunt
MIP	Maximum intensity projection
MPA	Main pulmonary artery
MR	Mitral regurgitation
MRA	Magnetic resonance angiography
MV	Mitral valve

NASCI	North American Society for Cardiovascular Imaging
NSA	Number of signal averages
PACS	Picture Archiving and Communication System
PA	Pulmonary Artery
PDA	Persistent ductus arteriosus
pHLA	Pseudo HLA
PR	Pulmonary regurgitation
pSA	Pseudo short axis
PSIR	Phase sensitive inversion recovery
PS	Pulmonary stenosis
pVLA	Pseudo vertical long axis
RA	Right atrium
RCA	Right Coronary Artery
RF	Regurgitant fraction
ROI	Region of interest
RV	Right ventricle
RVOT	Right ventricular **o**utflow tract
RWMA	Regional wall motion abnormality
SA	Short axis
SCMR	Society for Cardiovascular Magnetic Resonance
SVC	Superior Vena Cava
SD	Standard deviation
SI	Signal Intensity
SNR	Signal-to-noise ratio
STIR	Short-tau inversion recovery
SV	Stroke volume
TE	Time to Echo (aka Echo time)
TEE	Transesophageal echocardiogram
TOF	Tetralogy of Fallot
TR	Time to Repetition (aka Repetition time)
TSE	Turbo spine echo
TVR	Tricuspid valve replacement
TV	Tricuspid valve
VENC	Velocity encoding
VLA	Vertical long axis
VR	Volume rendering

PART I:

Applications & Techniques

Double Inversion Recovery & Black Blood Pulse Sequences

Double Inversion Recovery (DIR) is an inversion recovery variant that uses not one, but two nonselective 180°-inverting pulses.

The earliest applications of this type of DIR technique were in brain imaging, particularly for detection of multiple sclerosis plaques and lesions of the cerebral cortex.

CMR takes advantage of this tissue contrast weighting and includes a component to produce **"black blood"** that allows improved visualization of the soft-tissue structures.

In this method, two 180°-pulses are applied close together in time. The first 180°-pulse is nonselective, meaning that it inverts the magnetization for all tissue within the imaging volume.

Black Blood Pulse Sequences:

- The second 180°-pulse, following immediately after the first 180°-pulse, is slice selective, meaning that it returns the magnetization of the tissues only in that slice back to the +z-direction.
- Thus, the myocardium and other relatively stationary tissues in the imaging slice plane have their signal preserved, but the blood flowing from adjacent slices has an inverted magnetization.

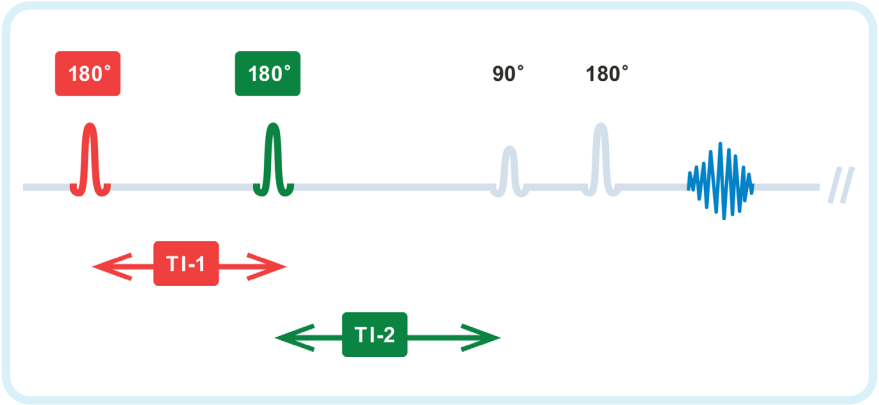


Fig. 1.1 - Black Blood Pulse Sequence

SSFP Pulse Sequence

Steady-state free-precession (SSFP) pulse sequences are a class of rapid magnetic resonance imaging techniques in which a steady, residual transverse magnetization is maintained between successive cycles.

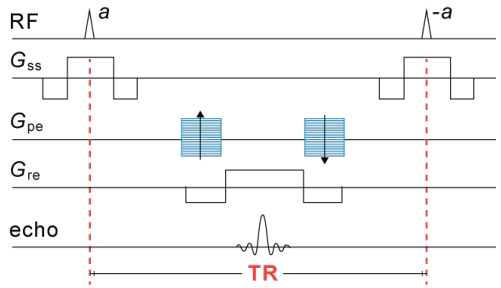
The basic idea of SSFP is to apply a series of excitation pulses with a short TR that is shorter than the T2 relaxation time of the tissue. As a result, the transverse magnetization does not fully decay before the next pulse and reaches a steady-state after a few cycles. The flip angle of the pulses is typically between 50° and 80°.

Image Contrast:

- **Bright blood sequence** with relatively uniform signal intensity of both slowly and rapidly flowing blood.
- Considered T2/T1-weighted. The T2-weighting generally dominates, except after the administration of gadolinium-contrast agent when the T1 effects dominate.

Clinical Utility:

- Best sequence to assess cardiac function.
- Bright blood even with slow flow.
- Typically, shorter TRs and TEs than with gradient-echo imaging.
- Typically has shorter breath-holds and higher spatial resolution for the same breath-hold time compared to gradient-echo images.
- Less sensitive for detecting turbulent flow due to valvular disease or intracardiac shunts as a result of the very short TEs.



In bSSFP sequences, flow and banding artifacts are increased due to the heightened requirement for field homogeneity.

These artifacts are worst with longer TRs,

Fig. 1.2 - bSSFP Sequence

Real-time Cine

Real-time cine comprises a group of single-shot echo-planar methods that allow acquisition of bright blood cardiac images continuously, and without breath holding. The trade-off for increased speed is decreased spatial resolution, as can be appreciated from the somewhat blurry images, and coarser temporal resolution.

Cine SSFP Pulse Sequence

Cine SSFP pulse sequences are typically obtained as one or two slices obtained in a single breath hold. **Echoes** are grouped into cardiac phases with retrospective ECG-gating, then reconstructed and played in a loop.

To fully evaluate the entire heart, separate cine image sets at various locations must be obtained. For example, a standard cine study will include a contiguous set of short-axis slices through the ventricles from base to apex, along with three long-axis images through the left ventricle (2-, 3-, and 4-chamber views). Additional views may include valvular and outflow tract images, as needed.

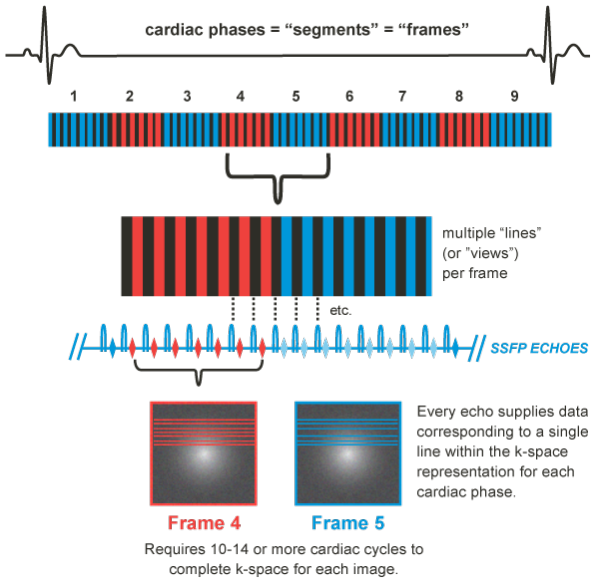


Fig. 1.3 - Cine SSFP Pulse Sequence

Myocardial Perfusion Pulse Sequences

Imaging Sequence Type:

- A variety of base pulse sequences are used including gradient-echo, gradient-echo variants hybridized with echo-planar readouts, and SSFP sequences.
- A **Saturation Recovery (SR)** preparatory pulse is used to tip the longitudinal magnetization of all tissues in the imaging volume into the transverse plane. After being tipped into the transverse plane tissues begin to recover longitudinal magnetization as a function of their T1 values. Gadolinium-containing blood and myocardium have short T1s and recover quickly, while non-enhancing myocardium or ischemic myocardium, and other tissues remain relatively saturated or darker appearing.
- Typical image sets obtained are 3-6 short-axis images preferentially acquired over a single heartbeat, though may be acquired over two heartbeats for greater myocardial coverage, and may include selected long-axis images. Anywhere from 30-60 image dynamics are acquired for each imaging slice during a breath hold. These images are acquired after (or during) the administration of a pharmacologic vasodilator, such as adenosine.

Image Contrast:

- Bright blood (following gadolinium/ contrast)
- T1-weighted

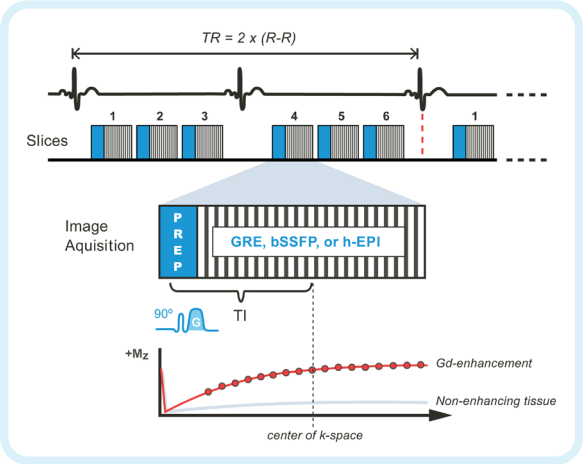


Fig. 1.4- Saturation Recovery (SR) preparatory pulse

Cardiac Stress Agents:

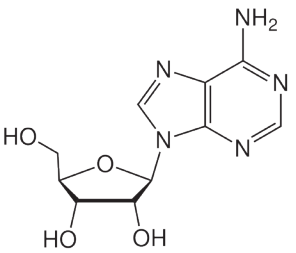


Fig. 1.5 - Adenosine

Adenosine is a strong vasodilator for coronary and most vascular beds, has a short half-life, and is administered continuously over 3-4 minutes. Two separate IV lines are typically necessary so that bolus administration of adenosine does not occur. Caution must be exercised when considering administration of adenosine to patients with a history of valvular stenosis, cerebrovascular insufficiency, or autonomic dysfunction.

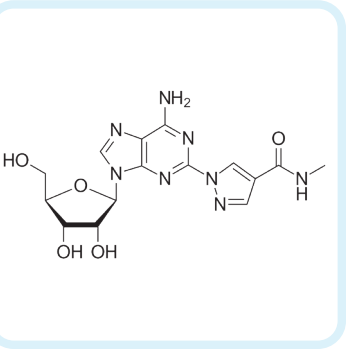


Fig. 1.6 - Regadenoson

Regadenoson, commercially known as Lexiscan, is a systemic vasodilator, similar in action to adenosine, and available in a pre-filled syringe. It specifically acts as an A2A receptor agonist and is recommended for patients with obstructive airway disease or asthma. Regadenoson has a substantially longer half-life than adenosine, and its effects may endure for up to 30 minutes.

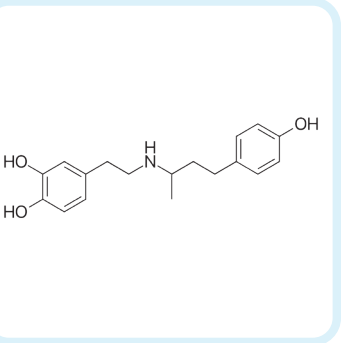


Fig. 1.7 - Dobutamine

Dobutamine, in contrast to Adenosine and Regadenoson, is a positive chrono-trope, and can induce myocardial ischemia by increasing demand for oxygen. Dobutamine may be administered either as “low dose” to determine myocardial viability, or a “high dose” to induce myocardial ischemia manifested as myocardial wall motion abnormalities. Wall motion and perfusion irregularities that might not be evident under non-stressed conditions.

Late Gadolinium Enhancement (LGE) Pulse Sequences

The standard LGE pulse sequence typically is performed using a T1-weighted rapid GRE sequence combined with an inversion- recovery pre-pulse designed and timed to null the signal of normal myocardium.

The images from this sequence demonstrate high contrast between normal myocardium (that is dark or “nulled”) and abnormal myocardium (that is bright or "hyper-enhanced").

The sequence relies on choosing a correct inversion time (TI) to optimally suppress the signal from the normal myocardium, and is typically on the order of ~250ms, though can be longer with greater time from administration of contrast agent and image acquisition.

Phase Sensitive Inversion Recovery:

- A newer version of the sequence, called **Phase Sensitive Inversion Recovery (PSIR)**, has gained in usage as it requires less precision in choice of T1, thereby allowing more consistently optimized image quality.
- The change in the **longitudinal magnetization (Mz)** in the infarcted and normal myocardium after a non-selective RF pre-pulse.
- The **optimal inversion time (TI)** is the time between the RF pulse to the time when the Mz of the normal myocardium is zero (null point). The image data acquisition occurs at this null point so that the signal of the normal myocardium appears dark, whereas the signal of the infarcted myocardium appears bright.

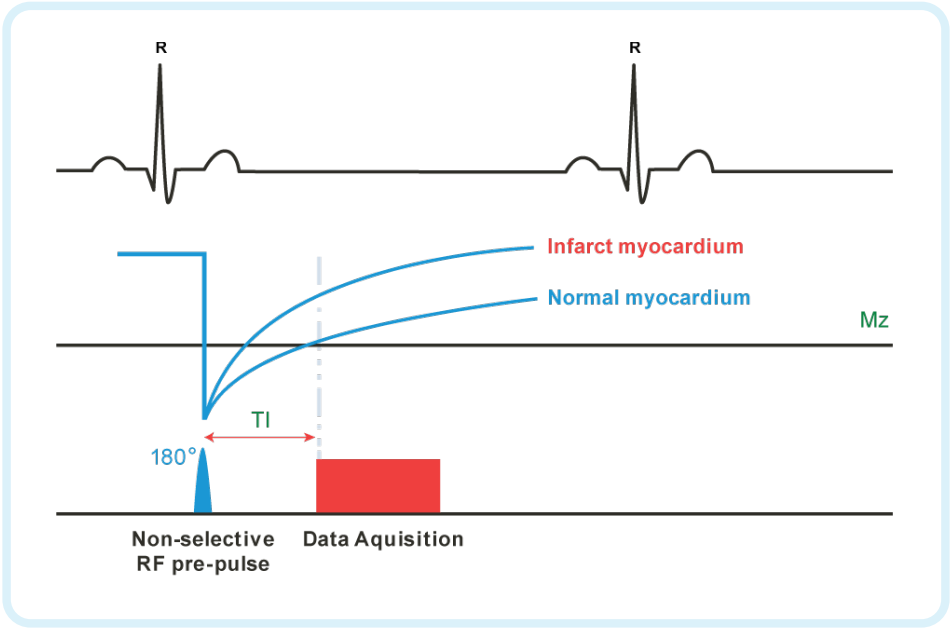


Fig. 1.8 - Phase Sensitive Inversion Recovery (PSIR) Sequence

Phase-Contrast Flow Sequence

A **2D phase-contrast velocity-encoded MRI sequence** is a type of MRI technique that can measure the velocity of moving protons, such as those in blood vessels. It works by applying a pair of phase encoding pulses that are opposite in polarity, though equal in magnitude. Stationary protons will have no net change in phase, while moving protons will collect a net phase change between the pulses with the difference being proportional to the velocity of the protons.

The sequence requires the selection of a **velocity encoding (VENC)** parameter, that determines the maximum velocity that can be measured without aliasing. The VENC should be chosen according to the expected flow velocity in the region of interest. For example, typical flow in the ascending aorta may be 1-1.5 meters/sec, but higher velocities may be encountered in patients with hyperdynamic circulation.

The sequence typically also requires the selection of an imaging plane ("through **plane**") that is perpendicular to the main direction of flow, to avoid errors due to flow obliquity. Imaging may also be performed "in plane", such as to measure aortic stenosis velocity, or in coarctation of the aorta.

The sequence generates two types of images: magnitude, and phase images.

- The **magnitude image** is comparable in appearance to a gradient-echo cine image.
- The **phase image** contains the velocity information and shows the flow as high or low signal depending on direction, and the background stationary tissue as intermediate grey.

The sequence quantifies the flow by plotting the velocity versus time for a region of interest and calculating the net flow for each cardiac cycle.

The velocity-encoded imaging data is usually acquired over several cardiac cycles during a breath-hold, though free-breathing and single cardiac cycle data can be acquired, though with coarser temporal resolution.

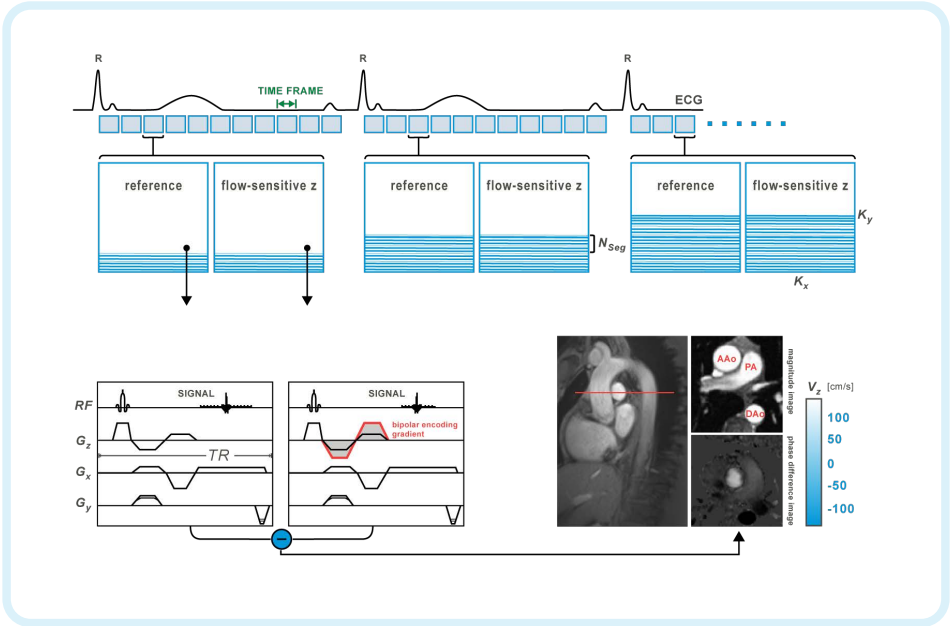


Fig. 1.9 - Phase-Contrast Flow Sequence

"Whole Heart MRA" Pulse Sequence

A **Whole Heart MRA** is a type of gradient echo MRI pulse sequence (otherwise known as an SSFP MRA sequence) that can generate high-resolution images of blood vessels without using contrast agents. It works by maintaining a steady residual transverse magnetization (Mxy) between successive cycles of radiofrequency pulses and gradients.

The sequence has various clinical applications, such as evaluating the aorta and coronary arteries, and detecting vascular anomalies.

The sequence can also be modified by using inversion recovery (IR) pulses or T2-preparation pulses to enhance the arterial signal and suppress the venous signal. The sequence has some advantages over contrast-enhanced MRA, such as avoiding contrast-related risks, potentially reducing scan time, and improving image quality.

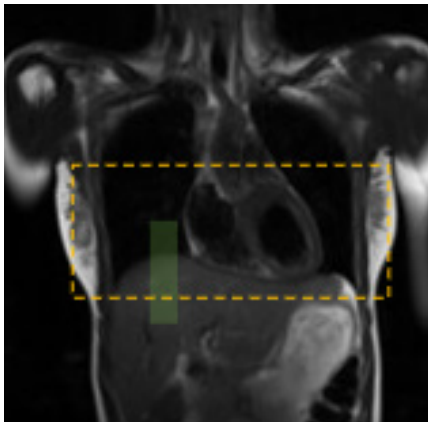


Fig. 1.10 - How to Set up for Whole Heart

Simplified pulse diagram for SSFP MRA:

- The **balanced steady-state free precession sequence** employs symmetrical gradients to reverse phase shifts and signal variations (depicted as the black box). This process results in minimal signal loss and the merging of stimulated echoes with free induction decay.

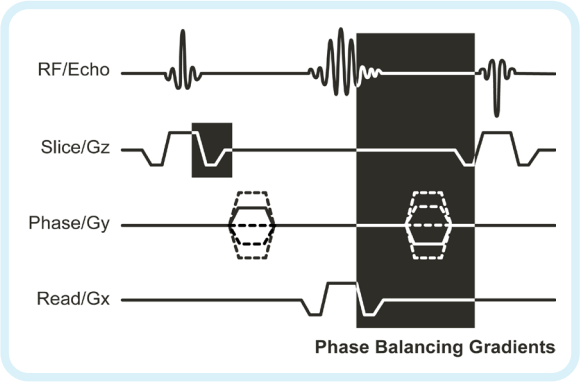


Fig. 1.11 - bSSFP Diagram

Contrast-Enhanced MRA Pulse Sequence

Contrast-enhanced MR angiography (CE-MRA) is similar to contrast-enhanced CT angiography, though is performed following intravenous injection of a gadolinium-based contrast agent (instead of an iodine-based compound, as in computed tomographic angiography).

Once the contrast bolus arrives in the vessel of interest, imaging is performed using a rapid 3D T1-weighted spoiled gradient-echo pulse sequence. TR and TE are generally made as short as possible, and gradient-moment nulling is not used.

A wide receiver bandwidth (resulting in a short sampling time) is typically employed in conjunction with partial k-space acquisition and parallel imaging.

T1- Mapping

T1-mapping is a technique performed to quantify the T1 values of tissue before or after contrast administration. The most commonly used techniques are **Look Locker imaging:** Modified Look Locker Inversion recovery (MOLLI), and shortened MOLLI (ShMOLLI).

The number and orientation of slices obtained will depend upon the indication, though the most common approach is 3-5 short-axis slices that are 6-8 mm thick and have in-plane spatial resolution of 1.6–2.0 mm. Diastolic acquisition is best with the exception of patients in atrial fibrillation where systolic acquisition may be preferred. In patients with higher heart rates, specific sequences designed for these higher heart rates may be used.

When T1-mapping is performed in the absence of contrast agents it is known as "*native*" T1-mapping. T1-mapping can also be performed both prior to contrast and again between 10- and 30-min post gadolinium contrast administration.

When this T1 data is integrated with the patient's hematocrit value the **Extracellular Volume (ECV)** fraction can be determined. Note that the hematocrit should be measured ideally within 24 h of imaging for the most accurate (ECV) measurement.

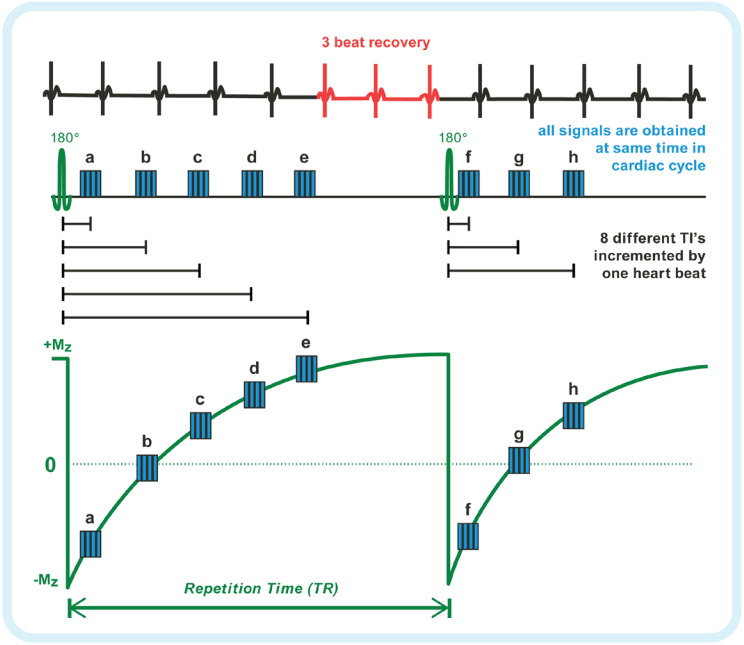


Fig. 1.12 - T-1 Mapping

T2 STIR-Weighted Imaging:

Black-blood T2-weighted imaging with **Short Tau Inversion Recovery (STIR)** is a technique used to preferentially highlight areas of myocardial edema, such as in the setting of myocarditis or acute myocardial infarction

The sequence may be performed in either long- or short-axis, and is acquired during a breath-hold in diastole.

However, note that this sequence may be prone to artifacts as a result of field heterogeneity, motion, or inadequate thickness of the preparatory pulse, particularly in short-axis slices at the base of the left ventricle. Further artifacts may occur as bright signal intensity in areas of slow flow, such as along the subendocardial border in the left ventricular apical region.

T2-mapping & T2-weighted (T2w) Imaging

T2-mapping, similar to T1-mapping, is performed where quantitation of T2 values is desired, typically in settings where myocardial edema is suspected.

There are two primary pulse sequences employed: a T2-prepared SSFP sequence (T2prep), and a fast Gradient and Spin-Echo (GraSE) pulse sequence. In general, the T2prep sequence may be preferred, as it can be performed in a breath-hold.

The number and orientation of slices obtained, again similar to T1-mapping, will depend upon the indication, though the most common approach is 3-5 short-axis slices that are 6-8 mm thick and have in-plane resolution of 1.6–2.0 mm. Diastolic acquisition is again preferred with the exception of patients in atrial fibrillation where systolic acquisition may be optimal.

T2* Imaging

T2* (pronounced T2-"star") is a technique optimized for rapid determination of tissue iron deposition. This sequence is typically used in patients who have had multiple blood transfusions and are at risk of excessive iron deposition in the myocardium, which can lead to heart failure and death. These patients include those with beta thalassemia, sickle cell disease, and other rare anemias.

The pulse sequence is a single breath-hold, gradient-echo scan with a series of 6–9 iterated echoes typically beginning at ~2 msec and extending to ~ 16 msec. A single short-axis slice at the mid ventricular level is acquired with a slice thickness of 8mm and an in-plan spatial resolution of ~2mm.

Optional: determination of liver iron deposition can also be obtained by acquiring an axial slice through the mid-hepatic level. As the liver does not move no ECG-gating is required, and the echo times may be slightly shorter and more closely spaced. This tighter spacing of echo times may be useful for more accurate determination of iron quantification in those patients with severe iron deposition.

PART II:

Tips & Tricks

Patient Preparation

For cardiac imaging the typical field strength of MRI scanners employed is 1.5 T or 3 T. However, promising work is being performed on both lower and higher field strength systems, which may usher in newer capabilities.

1. Screen the patient for devices, implants and other patient-specific risks/safety considerations.
2. Request the patient to use the rest room before the study.
3. Clean skin for optimal ECG lead contact. Shave hair as needed.
4. Attach the ECG leads to the patient, and check the ECG trace to ensure adequacy of the ECG signal.
5. Position the respiratory bellow, as appropriate.
6. A cardiac imaging specific surface coil with multiple coil elements (typically ≥8 elements) is highly recommended, and is required to employ parallel acceleration techniques that reduce scan and breath-hold times.
7. ECG-gating hardware and software are required, and in our experience the inclusion of vector-cardio graphic gating is preferred. ECG-gating capabilities should include the ability to perform prospective, retrospective, and triggered gating techniques.
8. A 20- or 22-gauge Intravenous (IV) catheter is often sufficient. When there is need for rapid injection of contrast, such as in myocardial perfusion exams or MRA acquisitions, an 18-gauge IV catheter may be preferred.
9. An MRI compatible power injector is preferred for rapid injection of contrast agent.
10. Prepare the injector with an appropriate dose of contrast.
11. Inform the patient about breath-holding steps and have them practice. Our preference for breath-holding instructions is to have the patient breathe in, breathe out, breathe in again, and breathe out half way and hold. This allows the patient to have enough air remaining in the lungs to not struggle with the breath-hold, and to allow them to be consistent in their efforts.
12. Place the surface coil over the patient's chest.
13. Provide the patient with disposable earplugs or MR-compatible headphones.

Electrocardiographic Gating:

Cardiac gating uses the electrical signal detected by leads placed on the patient's chest to trigger and coordinate the MRI pulse sequence data collection. For example, the data acquisition is triggered by each R-wave and is stopped after the prescribed imaging data has been collected. In this way, each image, or image phase is acquired at the same portion of the cardiac cycle, so that blurring from cardiac motion is minimized or eliminated.

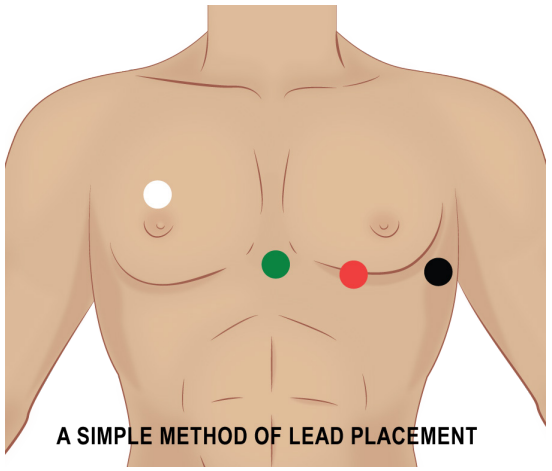


Fig. 2.1 - Lead Placement Chart

Accurate ECG gating is crucial to optimize image quality.

1. Clean patient skin by removing grease, or natural oils that may prevent leads from proper attachment
2. Ensure that electrodes are firmly attached to the chest wall.
3. In male patients shave any chest hair in the region of the interest.
4. There are usually four leads that are color-coded for easy use. Some systems may only use three leads. Directions on lead placement are usually given by the manufacturer.
5. If the trace on the ECG monitor is poor try re-positioning of the leads in different order or different locations on the chest in an effort to improve the trace.
6. Keep electrodes packed/unopened until you need them. By doing this, we prevent the contact gel from drying out.
7. Patient body habitus, previous surgery, and pathology can affect the cardiac axis, potentially impacting your trace. Reposition lead placement accordingly.
8. Leads should not form a loop, as this could potentially cause a radiofrequency burn.
9. Electrodes must be MRI safe, as radiofrequency burns have been associated with electrodes featuring metal connectors.

After the above steps have been taken, if the ECG trace remains poor, consider changing to peripheral pulse gating, or consider single-shot techniques for static imaging, real-time cine imaging to improve image quality.

Fig. 2.2 - Normal ECG

Different Types of Arrhythmias:

Atrial Fibrillation (A-Fib, or AF) is the most common sustained arrhythmia, and presents unique challenges to CMR. Patients with small beat-to-beat variability may be imaged with minimal adjustments, while those with large beat-to-beat variability can be challenging to image well.

Fig. 2.3 - Atrial Fibrillation

Premature Ventricular Contraction (PVC) denotes a heartbeat that happens earlier than it should, and can result in blurring, particularly for cine imaging.

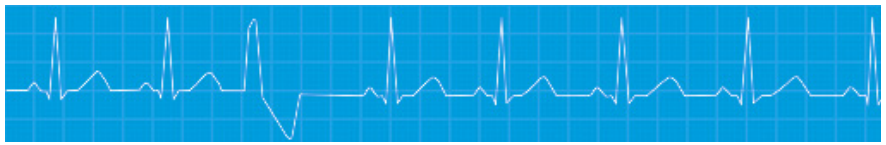


Fig. 2.4 - Premature Ventricular Contraction

Bigeminy is a heart rhythm where a normal beat and an ectopic beat occur in pairs repeatedly.

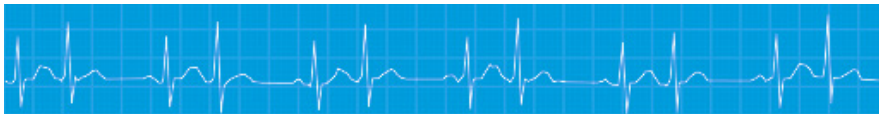


Fig. 2.5 - Bigeminy

The quality of MRI ECG traces vary according to rate, rhythm, cardiac output, and body habitus.

Factors that affect and alter the ECG trace:

- Poor cardiac output
- Arrhythmias
- Early repolarization
- Left ventricular hypertrophy
- Myocardial ischemia and infarction
- Left ventricular aneurysm
- Pericarditis
- Hyperkalemia
- Hypothermia
- Pulmonary Embolism

Tips & Tricks

Patient unable to hold breath-holds consistently

- Reduce number of slices acquired per breath-hold
- Reduce number of phases for each breath-hold
- acquisition matrix (increases voxel size)
- Reduce FOV (reduces number of phase-encoding steps)
- Use parallel imaging
- Acquire images in inspiration instead of exhalation
- Increase NSA (performing non-breath-hold scans)
- Provide supplemental oxygen via nasal cannula

Arrhythmias

- Use arrhythmia rejection
- Use **Prospective triggering** (acquires data during a specific acquisition window between R-waves)
- Use Real-time imaging
- Use **Peripheral pulse gating** (note that peripheral pulse gating detects the pulse wave of the blood at the tip of the fingers or toes. As there is a delay in the beginning of image acquisition, cine data will start being acquired typically during mid-diastole. For static images, such as black-blood imaging, or LGE, there will be a need to incorporate an altered trigger delay to acquire images in the appropriate portion of the cardiac cycle.

Devices: Pacemakers & ICDs

There has been increasing demand to scan patients with implanted devices such as pacemakers and implantable cardioverter-defibrillators (ICDs). As a result of their metal components and associated artifacts, these devices can pose additional challenges in CMR. Prior to and after the CMR exam the pacemaker or ICD must be checked, and placed into an appropriate mode for MRI scanning by an experienced device technician, electrophysiologist or device representative.

During the CMR exam, for safety purposes, the patient ideally will have continuous ECG, BP, and oxygen saturation monitoring, and will be in frequent communication with the MRI technologist.

The imaging challenges that are faced include pronounced susceptibility and other artifacts.

To minimize these artifacts, a number of approaches can be used including:

1. Use of a frequency scout to demonstrate the optimal center frequency off-set
2. Use of specially designed wide bandwidth ("wide band") pulse sequences
3. For cine imaging limiting the use of SSPF sequences and instead switch to GRE cine sequences that are less susceptible to field heterogeneities.
4. Have the patient raise their arm over their head in an effort to move the generator box farther away from the heart.
5. Consider using skin tape to move the generator box more superiorly and/or laterally to be farther from the heart.
6. Retained, temporary epicardial pacing wires are fine, thin wires placed during surgery that are typically removed a few days post-surgery. Occasionally these wires are not able to be removed and are instead cut off at the skin surface with the wires remaining in the chest. These fine, thin wires are not felt to pose any significant hazard and patients with such retained wires can safely undergo a CMR examination.
7. Temporary transvenous pacing systems are considered to pose a significant risk due to their long, bulky leads along with the presence of an external generator box. Patients with transvenous pacing systems should not undergo MRI examinations while the device and lead(s) are in place.

CMR Safety

The magnetic resonance imaging environment has the potential to pose serious risks to patients and facility staff in several ways.

To promote awareness and understanding of MR safety guidelines adhere to ACR and Institution safety policies and procedures.

MR Safe - A designation indicating that the object or device is safe in all MR environments, without conditions. It is reserved for nonmetallic, nonconducting, and nonmagnetic objects that pose no known hazards in any MR environment.

MR Conditional - A designation indicating that the object or device may be safely used in the MR environment, provided the conditions for safe use are met. Decisions based on published MR Conditional or safety claims should recognize that all claims apply to specifically tested static field and spatial gradient field strengths and only apply to the precise model, make, and identification of the tested object.

MR Unsafe - A designation indicating that the object or device is known to present safety risks in the MR environment. These are primarily ferromagnetic objects, implant, device, or objects discovered during MR examination.

Fig. 2.6 - CMR Safety

MRI Zones

Zone I: Facility Entrance - This region includes all areas that are freely accessible to the general public. This area is typically outside the MR environment itself and is the area through which patients, health care personnel, and other employees of the MR facility access the MR environment.

Zone II: Reception - This area is the interface between the publicly accessible, uncontrolled Zone I and the strictly controlled areas of Zones III and IV. Typically, patients are greeted in Zone II and are permitted to move freely throughout. under the supervision of MR Personnel, prior to entry into Zone III. It is recommended that patient preparation for the MRI examination take place in Zone II. This preparation includes MRI screening, medical history, and appropriate patient gowning.

Zone III: Reception - The MR control room only approved MR personnel and patients that have undergone MRI screening are allowed in this zone.

Zone IV: Magnet - The MR scanner room

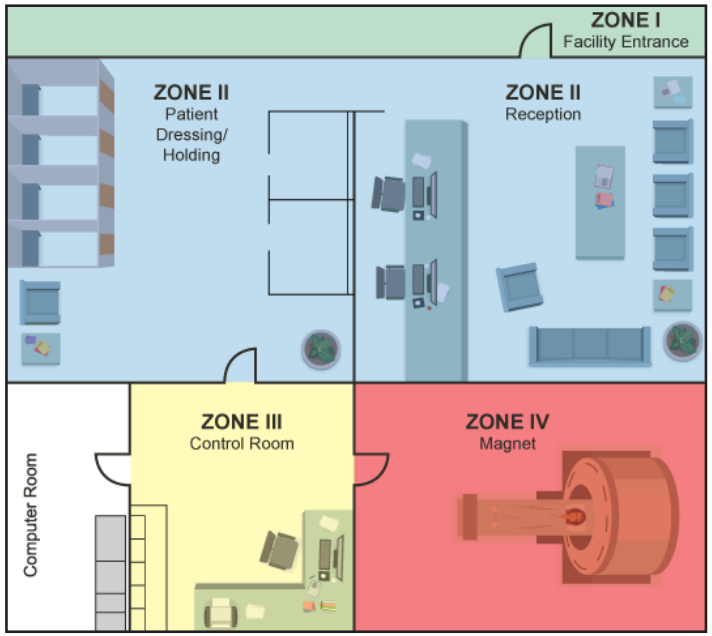


Fig. 2.6 - MRI Zones

Gadolinium Based Contrast Agents (GBCA)

MRI contrast agents are used to improve the detection and visualization of both normal and abnormal anatomy and conditions. The contrast agents that are commonly used in CMR incorporate a rare earth metal called Gadolinium.

This metal is from the Lanthanide series, has seven unpaired electrons, and strong paramagnetic properties that markedly reduces the T1 relaxation of the surrounding protons, thus increasing the signal intensity on T1-weighted images.

Care must be taken when using contrast agents, as free Gadolinium is toxic to the body when injected, and can deposit in multiple tissues with wide-ranging effects on those tissues.

To make Gadolinium safe for injection into the blood stream for CMR exams, the Gadolinium is "chelated" with larger molecules that bind the Gadolinium tightly, yet allow it to exert its paramagnetic properties and reduce the T1 relaxation on surrounding protons.

There are two categories of commonly used CMR Gadolinium-chelate contrast agents: those with a **linear** structure, and those with a **macrocyclic** structure, the latter of which are considered to be the most stable, and therefore safest for use.

Below is a table of some commercially available contrast agents that includes their structure, reflexivity, and some physicochemical properties.

Brand Name	T1 Relaxivity	Osmolality (mOsm/kg)	Viscosity (cP)	Structure
Magnevist	4.1	1960	2.9	Linear
MultiHance	6.3	1970	5.3	Linear
Omniscan	4.3	789	1.4	Linear
OptiMARK	4.7	1110	2.0	Linear
Dotarem	3.6	1350	2.4	Macrocyclic
ProHance	4.1	630	1.3	Macrocyclic
Gadavist	5.2	1603	5.0	Macrocyclic

Fig. 2.7 - GBCA Contrast

Contrast Enhancement

Gadolinium based contrast agents distribute in the interstitial and extracellular spaces in the myocardium within minutes after intravenous injection.

- Both healthy and diseased myocardium will take up gadolinium contrast and exhibit enhancement depending on the pulse sequence used.
- Contrast washout and uptake within the myocardium can depend on multiple factors such as acute heart disease, myocardial blood supply, heart rate, hematocrit, and renal function.
- **Hyper-enhancement** is a term used to denote the increased signal intensity of irreversibly damaged myocardium (whether chronic scar tissue or acutely infarcted myocardium), in contrast to the "nulled" or dark normal myocardium.
- Within the first 3 minutes the signal intensity related to contrast concentration in tissues is significantly different between and among the blood pool, normal myocardium, and ischemic myocardium (when a vasodilator has been given). Later, that differentiation diminishes substantially among these tissues, while the slower wash-in and wash-out rate of infarcted myocardium allows gadolinium to accumulate and demonstrate a clear contrast between the blood pool and healthy myocardium.

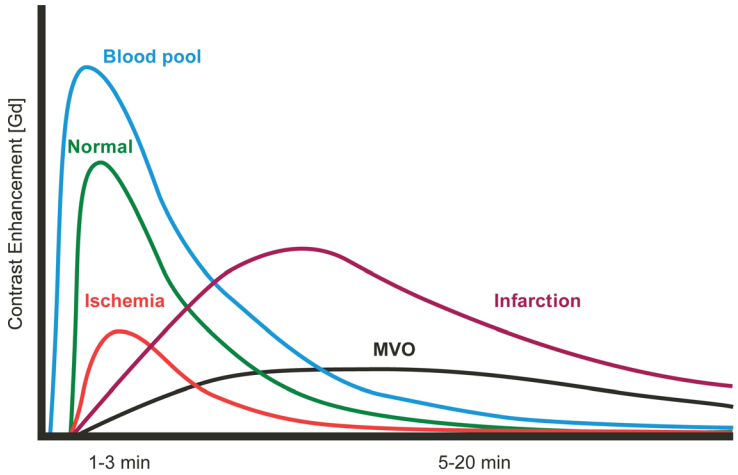


Fig. 2.8 - Contrast Enhancement

Obtaining accurate conventional 3D contrast

Enhanced MRA for assessing the arterial system with minimal venous contamination relies on the precise timing of contrast material injection. To optimize the quality of images, several parameters must be adjusted, including the volume of contrast material and the amount of saline to follow, delivery rate, scan timing, and sequence duration.

- To ensure excellent image quality and a satisfactory contrast- to-noise ratio, the timing of the sequence is crucial. This means that the acquisition of the center of K-space should align with the peak phase when the contrast material reaches its maximum concentration in the vessel of interest.
- Filling the center portion of K-space prior to peak contrast concentration can lead to artifacts such as ringing or banding. Alternatively, if the images are acquired too late, the blood pool will be in an equilibrium phase and the arterial and venous anatomy will have lesser signal intensity than is optimal.

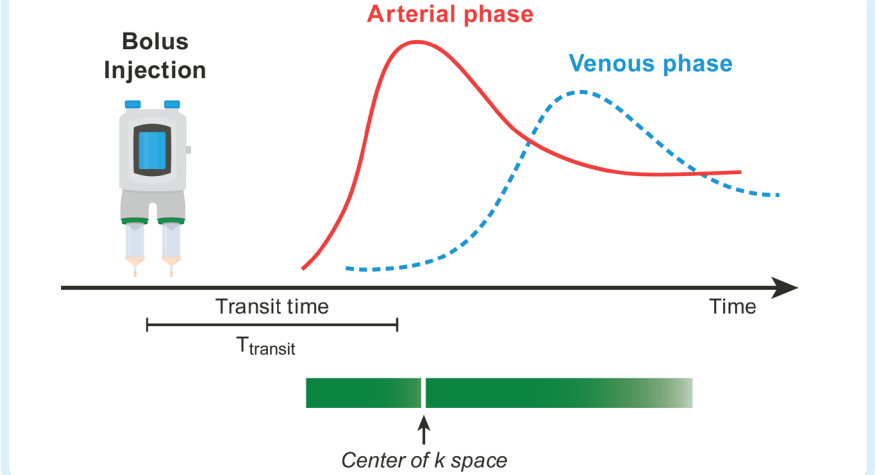


Fig. 2.9 - Enhanced MRA

CMR in Pregnancy

Pregnant patients are able to undergo an MRI at any stage of pregnancy, however, both the American College of Gynecology and Obstetrics and the American College of Radiology recommend that performance of MRI in pregnant patients should be evaluated on a case-by-case basis. While there are no known deleterious effects of MRI on a developing fetus, potential effects can not be completely excluded. As a result, any MR imaging performed should be kept to the minimum necessary to answer the relevant clinical question and provide medical benefit to the patient and/or fetus.

In general, gadolinium should not be administered to a pregnant patient. The administration of a gadolinium–based contrast agent is associated with an increased risk of a broad set of rheumatological, inflammatory, and infiltrative skin conditions, and for as well as, stillbirth or neonatal death, according to a recent Canadian study (Ray JG, et al. JAMA 2016;316(9):952-961).

When considering an MRI in a pregnant patient, following appropriate assessment of the clinical question, a risk-benefit analysis should be documented in the patient's medical record and in the imaging physician's report indicating that the study being performed was warranted. Patient informed consent should be obtained for studies performed in the first and second trimesters, and considered when in the third trimester.

The scans should be as short as possible, with only the essential images acquired. Every attempt should be made to minimize the delivery of FR energy to the pregnant patient. SSFP sequences should be avoided due to the higher RF power deposition.

Artifacts

I. Bo-field heterogeneity

- Causes signal loss and spatial distortion due to resonance frequency offsets and causing distortion between tissues, and frequently noted involving the heart and lungs.
    1. Tighten shimming around the heart and use center frequency adjustment
    2. Offset frequency (=50Hz) of the scanner center-frequency
    3. Apply wideband, which can reduce banding artifacts

II. Cardiac Motion

- Caused by ectopic heart beats or arrhythmias
    1. Apply signal averaging
    2. Motion compensated pulse sequences

III. Breathing Motion

- Inconsistencies between different segments of the acquisition can lead to the appearance of ghosting artifacts on the reconstructed images.
    1. Use parallel imaging to shorten acquisition time
    2. Signal averaging
    3. Decrease scan time

IV. Blood flow

- Caused by increased phase shifts between lines of k-space acquisition.
    1. Using pulse sequences with flow compensation gradients
    2. Suppression of the blood signal with saturation pulses applied parallel to slices
    3. Cardiac triggering
    4. Swapping phase and frequency encoding directions

V. Gibbs Ringing

- This artifact manifests as fine parallel lines adjacent to high-contrast interfaces.
  1. Increasing the number of phase-encode steps
  2. Use of fat suppression

VI. Aliasing

- When blood flow velocity exceeds the chosen velocity encoding
  1. Increase velocity encoding setting

VII. Chemical shift

- Mis-registration between fat and water
  1. Shortening the echo time
  2. Decrease the voxel size

VIII. Susceptibility artifacts

- Can be caused by sternal wires, artificial heart valve, coils, stents, etc.
  1. Shorten the echo time
  2. Decrease voxel size
  3. Increase bandwidth
  4. Aligning the phase-encoding direction with susceptibility gradients
  5. Parallel imaging
  6. If using SSFP sequences switch to GRE sequences (less sensitive to field distortion and heterogeneity)

At 3T artifacts are more problematic due to Bo and B1 field inhomogeneities.

IX. Black Bounding Artifacts

- Also known as India Ink, result from the presence of fat and water protons within the same imaging voxel.
- This artifact is present in bSSFP sequences.
- The different resonant frequencies of fat and water spins result from their different chemical compositions. When fat and water spins are imaged together, their resonant fr quencies can be slightly offset from each other, resulting in their signals being out of phase. This leads to signal cancellation in areas where fat and water are closely adjacent to each other, creating a dark band or loss of signal and image distortion. This effect is more pronounced at higher magnetic field strengths.
  1. Increasing the bandwidth can help minimize these artifacts.
  2. Switch to GRE sequence (solid gradient echo).
  3. Implementing tighter shimming can also be beneficial.

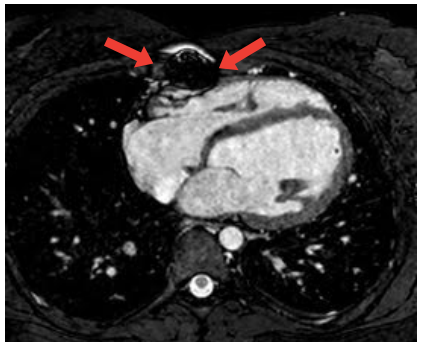


Fig. 2.10 - Sternal Wires

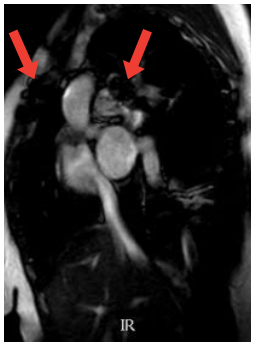


Fig. 2.11 - Sternal Wires and Pulmonary Coils

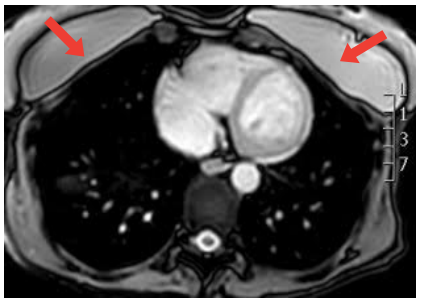


Fig. 2.12 - Breast Implants

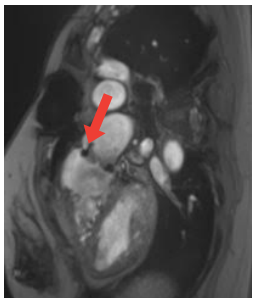


Fig. 2.13 - Pulmonary Valve