

# Cardiovascular Magnetic Resonance

## Pocket Guide

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# CMR Pocket Guide

Foreword

Safety

Normal Values

Acquisition

Artifacts

Ischemic CHD

DCM

HCM

LVNC

ARVC

Myo-/Pericarditis

Amyloidosis

Sarcoidosis

Fibrosis

Iron Overload

Tako-Tsubo

Effusion

Constriction

Coronaries

Aortic Disease

Valve Disease

Cardiac Masses

Terminology

References

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**John Greenwood**  
**Sven Plein**



# Foreword

**The clinical indications for Cardiovascular Magnetic Resonance (CMR) continue to expand. This pocket guide aims to provide a day-to-day companion for those new to CMR and for those looking for a quick reference guide in routine practice. The booklet gives an overview of established normal ranges for CMR measurements, common acquisition methods and clinical indications for CMR. For each indication we provide typical scan protocols, tips and tricks and a guide for reporting.**

**Bernhard Herzog**

**John Greenwood**

**Sven Plein**

The Cardiovascular Magnetic Resonance Pocket Guide represents the views of the ESC Working Group on Cardiovascular Magnetic Resonance and was arrived at after careful consideration of the available evidence at the time it was written. Health professionals are encouraged to take it fully into account when exercising their clinical judgment. This pocket guide does not, however, override the individual responsibility of health professionals to make appropriate decisions in the circumstances of the individual patients, in consultation with that patient and, where appropriate and necessary, the patient's guardian or carer. It is also the health professional's responsibility to verify the applicable rules and regulations applicable to drugs and devices at the time of prescription.

For more detailed information on CMR protocols, current evidence, and with extensive examples on CMR cases we recommend the CMR-Update book, available through [www.herz-mri.ch](http://www.herz-mri.ch).

We acknowledge the support and advice we have received from Regina Herzog, Gavin Bainbridge, Ananth Kidambi, Manish Motwani and Akhlaque Uddin.

**Index**

# Safety

## Common Devices

### MR unsafe

- Any device which is known to threaten or pose hazard in all MR environments
- Most pacemakers
- Insulin pumps
- Most implantable cardioverter / defibrillators
- Metal foreign bodies in the eye



### MR conditional

- Any device which is demonstrated to pose **NO** hazard in a **specific** MR environment with **specified** conditions
- Most metallic heart valves
- Intra-coronary stents
- Prosthetic joints
- Dentures



### MR safe

- Any device which is known to pose **NO** hazard in **all** MR environments
- Only assume that a device is MR safe if it has this logo on it



### Tips & Tricks

Any doubt? Check online: [www.mrisafety.com](http://www.mrisafety.com)

# Safety

## Nephrogenic Systemic Fibrosis

### General

- Thought to be related to toxic effects of Gd ions in patients with advanced renal failure / haemodialysis
- Causes fibrosis of skin, joints, eyes, and internal organs
- Very rare, but serious syndrome

### Contrast media and safety

#### Safest (cyclical structure):

- Dotarem, Gadovist, ProHance

#### Intermediate safety (ionic linear structure):

- Magnevist, MultiHance, Primovist, Vasovist

#### Lowest safety (linear non-ionic structure):

- Omniscan, OptiMARK

**Note: No cases of NSF have been reported in patients with normal renal function**

### Tips & Tricks

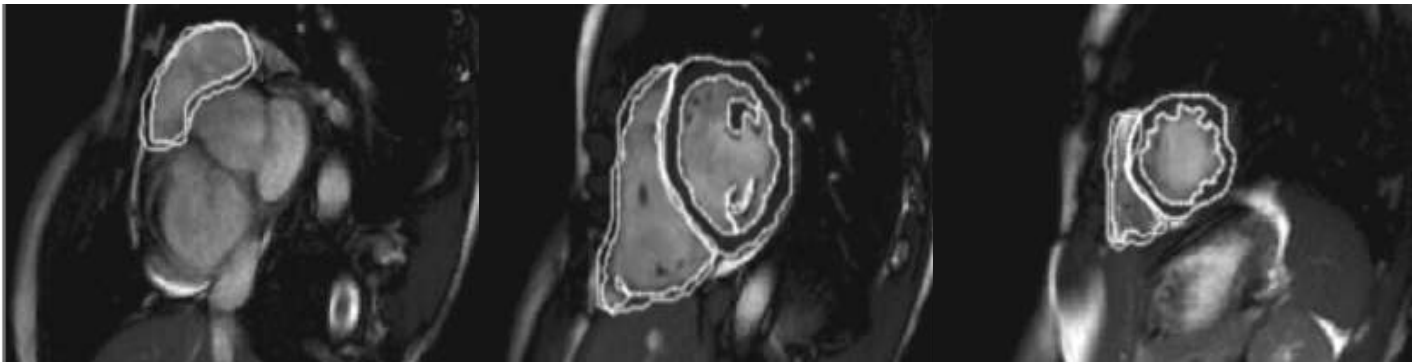
- **eGFR 30-60ml/min/1.73m<sup>2</sup>:** choose safest contrast agent, use only with caution
- **eGFR <30ml/min/1.73m<sup>2</sup>:** linear structured contrast agents contraindicated
- **In patients with severe renal failure:** consider haemodialysis within 2 hours after contrast agent administration – not proven to prevent NSF

# LV Volumes, Function and Mass

## Male Adults

| Absolute Values | <35 years          | ≥35 years         |
|-----------------|--------------------|-------------------|
| EDV (ml)        | 173 ± 29 (115–231) | 149 ± 25 (99–199) |
| ESV (ml)        | 7 ± 15 (27–87)     | 43 ± 13 (17–69)   |
| SV (ml)         | 118 ± 18 (82–154)  | 106 ± 19 (68–144) |
| EF (%)          | 67 ± 5 (57–77)     | 71 ± 6 (59–83)    |
| Mass (g)        | 131 ± 21 (89–173)  | 120 ± 23 (74–166) |

| Indexed to BSA               | <35 years        | ≥35 years       |
|------------------------------|------------------|-----------------|
| EDV/BSA (ml/m <sup>2</sup> ) | 90 ± 11 (68–112) | 75 ± 11 (53–97) |
| ESV/BSA (ml/m <sup>2</sup> ) | 30 ± 7 (16–44)   | 22 ± 6 (10–34)  |
| SV/BSA (ml/m <sup>2</sup> )  | 60 ± 8 (44–76)   | 53 ± 8 (37–69)  |
| Mass/BSA (g/m <sup>2</sup> ) | 67 ± 10 (47–87)  | 60 ± 9 (42–78)  |



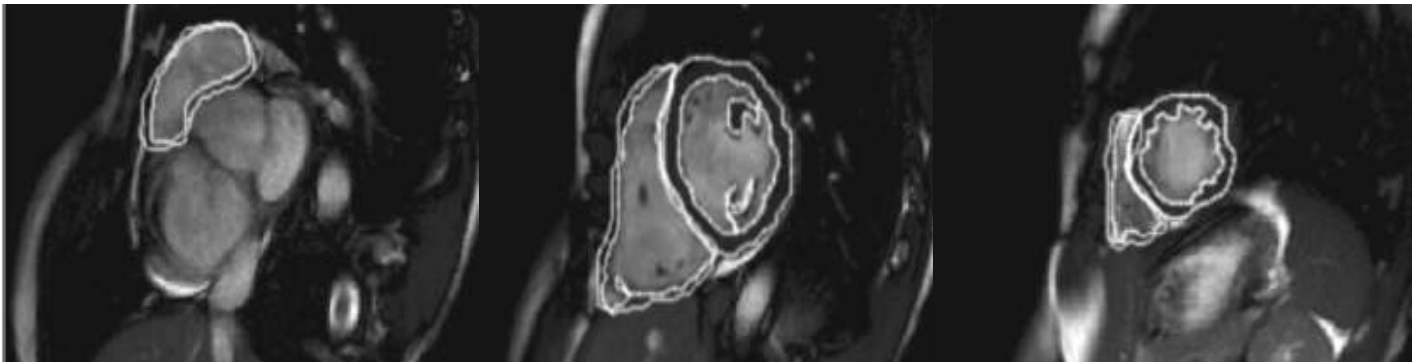
Reference 2). Values are given as mean ± SD; reference ranges in brackets, calculated as ± 2SD of the mean. Analysed with Argus software from short axis SSFP cine images. These values may vary depending on image sequence, acquisition technique and contouring.

# LV Volumes, Function and Mass

## Female Adults

| Absolute Values | <35 years         | ≥35 years         |
|-----------------|-------------------|-------------------|
| EDV (ml)        | 137 ± 25 (87–187) | 128 ± 23 (82–174) |
| ESV (ml)        | 43 ± 11 (21–65)   | 40 ± 12 (16–64)   |
| SV (ml)         | 96 ± 18 (60–132)  | 89 ± 16 (57–121)  |
| EF (%)          | 69 ± 6 (57–81)    | 69 ± 6 (57–81)    |
| Mass (g)        | 92 ± 20 (52–132)  | 92 ± 19 (54–130)  |

| Indexed to BSA               | <35 years      | ≥35 years       |
|------------------------------|----------------|-----------------|
| EDV/BSA (ml/m <sup>2</sup> ) | 80 ± 9 (62–98) | 73 ± 11 (51–95) |
| ESV/BSA (ml/m <sup>2</sup> ) | 25 ± 6 (13–37) | 23 ± 6 (11–35)  |
| SV/BSA (ml/m <sup>2</sup> )  | 55 ± 6 (43–67) | 51 ± 8 (35–67)  |
| Mass/BSA (g/m <sup>2</sup> ) | 53 ± 9 (35–71) | 52 ± 9 (34–70)  |

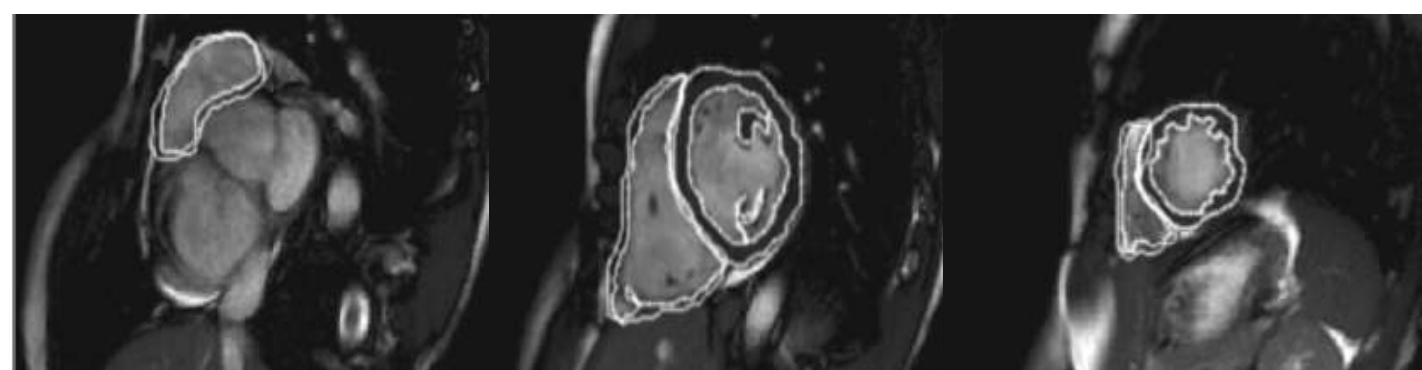


Reference 2). Values are given as mean ± SD; reference ranges in brackets, calculated as ± 2SD of the mean. Analysed with Argus software from short axis SSFP cine images. These values may vary depending on image sequence, acquisition technique and contouring.

# RV Volumes, Function and Mass Male Adults

| Absolute Values | <35 years          | ≥35 years          |
|-----------------|--------------------|--------------------|
| EDV (ml)        | 203 ± 33 (137–269) | 181 ± 28 (125–237) |
| ESV (ml)        | 87 ± 20 (47–127)   | 71 ± 17 (37–105)   |
| SV (ml)         | 116 ± 19 (78–154)  | 110 ± 18 (74–146)  |
| EF (%)          | 57 ± 5 (47–67)     | 61 ± 6 (49–73)     |
| Mass (g)        | 42 ± 8 (26–58)     | 39 ± 7 (25–53)     |

| Indexed to BSA               | <35 years         | ≥35 years        |
|------------------------------|-------------------|------------------|
| EDV/BSA (ml/m <sup>2</sup> ) | 104 ± 15 (74–134) | 89 ± 11 (67–111) |
| ESV/BSA (ml/m <sup>2</sup> ) | 44 ± 9 (26–62)    | 34 ± 7 (20–48)   |
| SV/BSA (ml/m <sup>2</sup> )  | 59 ± 9 (41–77)    | 55 ± 8 (39–71)   |
| Mass/BSA (g/m <sup>2</sup> ) | 22 ± 4 (14–30)    | 20 ± 3 (14–26)   |



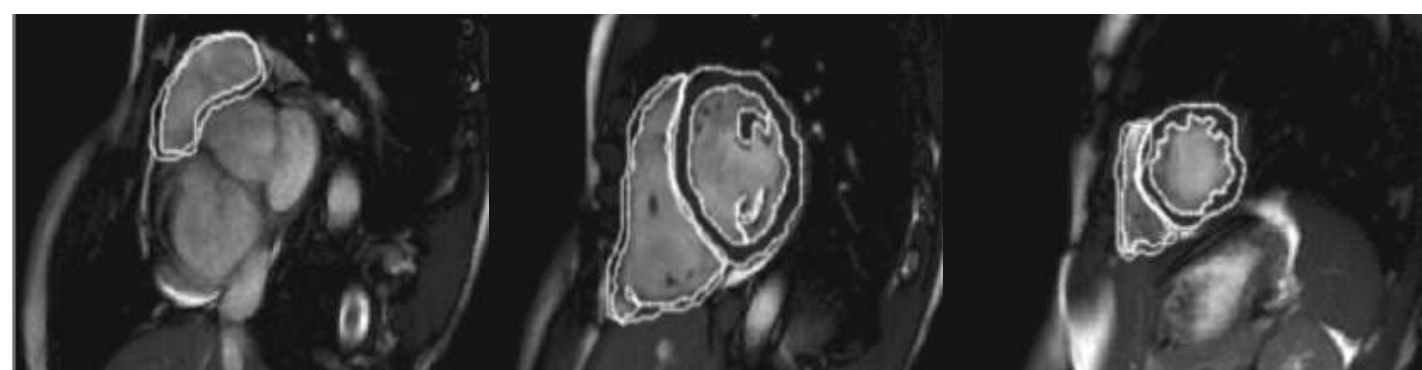
Reference 2). Values are given as mean ± SD; reference ranges in brackets, calculated as ± 2SD of the mean. Analysed with Argus software from short axis SSFP cine images. These values may vary depending on image sequence, acquisition technique and contouring.



# RV Volumes, Function and Mass Female Adults

| Absolute Values | <35 years         | ≥35 years         |
|-----------------|-------------------|-------------------|
| EDV (ml)        | 152 ± 27 (98–206) | 140 ± 37 (66–214) |
| ESV (ml)        | 59 ± 12 (35–83)   | 52 ± 22 (8–96)    |
| SV (ml)         | 93 ± 17 (59–127)  | 93 ± 17 (50–126)  |
| EF (%)          | 61 ± 3 (55–67)    | 64 ± 7 (50–78)    |
| Mass (g)        | 36 ± 7 (22–50)    | 33 ± 7 (19–47)    |

| Indexed to BSA               | <35 years        | ≥35 years        |
|------------------------------|------------------|------------------|
| EDV/BSA (ml/m <sup>2</sup> ) | 89 ± 11 (67–111) | 80 ± 19 (42–118) |
| ESV/BSA (ml/m <sup>2</sup> ) | 35 ± 5 (25–45)   | 30 ± 12 (6–54)   |
| SV/BSA (ml/m <sup>2</sup> )  | 54 ± 7 (40–68)   | 54 ± 7 (32–68)   |
| Mass/BSA (g/m <sup>2</sup> ) | 21 ± 3 (15–27)   | 19 ± 3 (13–25)   |



Reference 2). Values are given as mean ± SD; reference ranges in brackets, calculated as ± 2SD of the mean. Analysed with Argus software from short axis SSFP cine images. These values may vary depending on image sequence, acquisition technique and contouring.

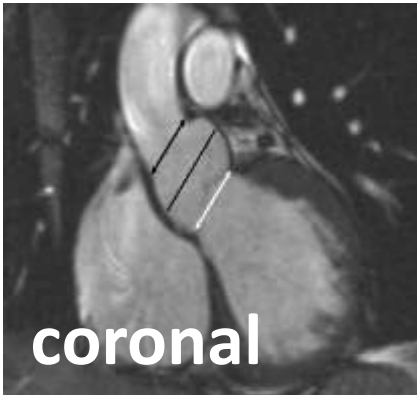
# Aortic Root Dimensions

## Male

|                          | 20-29 years | 30-39 years | 40-49 years |
|--------------------------|-------------|-------------|-------------|
| Annulus (s)              | 21.4 ± 2.4  | 20.7 ± 1.7  | 21.6 ± 2.0  |
| Annulus (c)              | 26.5 ± 1.8  | 25.2 ± 2.4  | 25.8 ± 1.5  |
| Aortic sinus (s)         | 30.5 ± 3.9  | 29.8 ± 3.8  | 32.0 ± 2.4  |
| Aortic sinus (c)         | 32.5 ± 3.4  | 31.8 ± 4.8  | 33.6 ± 2.6  |
| Sinotubular junction (s) | 23.3 ± 3.4  | 22.2 ± 4.0  | 24.4 ± 3.3  |
| Sinotubular junction (c) | 23.7 ± 3.5  | 22.2 ± 3.0  | 24.5 ± 2.4  |

|                          | 50-59 years | 60-69 years | 70-79 years |
|--------------------------|-------------|-------------|-------------|
| Annulus (s)              | 22.8 ± 2.8  | 23.5 ± 1.8  | 23.3 ± 2.7  |
| Annulus (c)              | 26.4 ± 3.7  | 26.5 ± 1.8  | 26.6 ± 1.9  |
| Aortic sinus (s)         | 33.3 ± 6.1  | 33.6 ± 2.7  | 35.1 ± 3.7  |
| Aortic sinus (c)         | 34.7 ± 6.4  | 35.7 ± 3.3  | 36.1 ± 3.5  |
| Sinotubular junction (s) | 26.6 ± 3.1  | 27.6 ± 3.6  | 28.3 ± 2.7  |
| Sinotubular junction (c) | 26.5 ± 3.7  | 27.5 ± 2.4  | 27.8 ± 1.7  |



Reference 3). Data measured in diastole and presented as mean ± SD in mm. Analyzed from sagittal (s) and coronal (c) SSFP LVOT cines

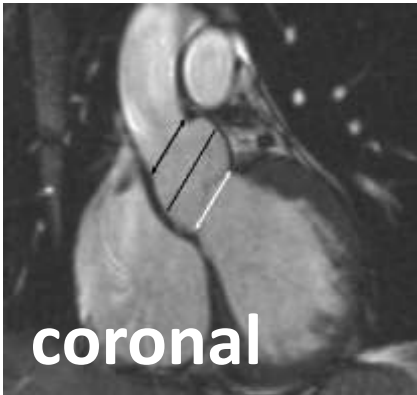
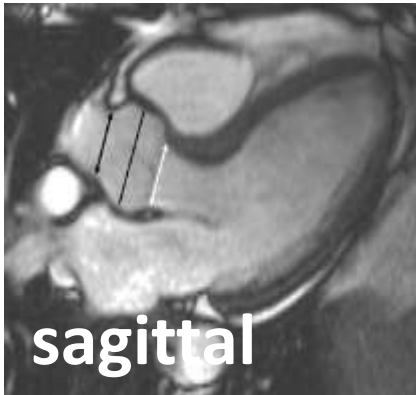
# Aortic Root Dimensions

## Female

|                          | 20-29 years | 30-39 years | 40-49 years |
|--------------------------|-------------|-------------|-------------|
| Annulus (s)              | 19.5 ± 2.4  | 19.2 ± 2.3  | 19.9 ± 2.2  |
| Annulus (c)              | 23.6 ± 3.0  | 22.9 ± 2.3  | 23.3 ± 1.5  |
| Aortic sinus (s)         | 26.5 ± 4.0  | 26.9 ± 3.1  | 31.5 ± 2.8  |
| Aortic sinus (c)         | 28.5 ± 4.9  | 28.2 ± 3.1  | 32.0 ± 2.5  |
| Sinotubular junction (s) | 21.1 ± 3.3  | 21.8 ± 2.8  | 25.7 ± 2.3  |
| Sinotubular junction (c) | 21.5 ± 2.7  | 22.1 ± 2.7  | 25.5 ± 2.1  |

|                          | 50-59 years | 60-69 years | 70-79 years |
|--------------------------|-------------|-------------|-------------|
| Annulus (s)              | 20.1 ± 1.9  | 20.4 ± 1.1  | 20.2 ± 1.5  |
| Annulus (c)              | 22.7 ± 2.1  | 22.3 ± 1.5  | 23.3 ± 1.5  |
| Aortic sinus (s)         | 29.1 ± 2.5  | 30.1 ± 2.5  | 30.2 ± 2.0  |
| Aortic sinus (c)         | 30.2 ± 2.3  | 31.0 ± 2.7  | 31.3 ± 1.8  |
| Sinotubular junction (s) | 24.1 ± 1.9  | 25.1 ± 3.0  | 25.0 ± 2.0  |
| Sinotubular junction (c) | 23.4 ± 2.1  | 24.7 ± 1.6  | 25.1 ± 1.3  |



Reference 3). Data measured in diastole and presented as mean ± SD in mm. Analyzed from sagittal (s) and coronal (c) SSFP LVOT cines

# Imaging Poor Breath-Holders

| Acceleration technique   | Comment   |
|--|---|
| <ul style="list-style-type: none"><li>• Reduce <b>number of slices</b> acquired per breath-hold</li><li>• Reduce <b>number of phases</b> for each breath-hold:<ul style="list-style-type: none"><li>- by reducing <b>acquisition matrix</b> (scan or phase percentage)</li><li>- by reducing <b>FOV</b></li></ul></li><li>• Increase <b>voxel size</b></li><li>• Use <b>parallel imaging</b></li><li>• Use <b>respiratory navigator</b></li><li>• Acquire images in <b>inspiration</b></li><li>• Consider <b>general anaesthesia</b></li></ul> | <ul style="list-style-type: none"><li>• Increases overall scan time</li><li>• Reduces SNR</li><li>• Increases spatial resolution</li><li>• Decreases spatial resolution</li><li>• Prone to artefacts</li><li>• Increases overall scan time</li><li>• Varying slice position with each breath-hold</li></ul> |

# Imaging Patients With Arrhythmia

| Technique   | Comment  |
|---|--|
| <ul style="list-style-type: none"><li>• <b>Heart rate</b> and/or <b>rhythm control</b> before scanning</li><li>• Use <b>Arrhythmia Rejection</b></li><li>• Use <b>Prospective triggering</b></li><li>• Use <b>Real-time imaging</b></li></ul> | <ul style="list-style-type: none"><li>• Use beta-blockers or other antiarrhythmic medication</li><li>• Increases breath-hold time</li><li>• Reduces SNR</li><li>• Reduces temporal and spatial resolution as well as SNR</li></ul> |

# Anatomy, LV and RV Function Module

1/2

## Anatomy Module

1. **T1w** axial black blood imaging (diaphragm to above aortic arch)  
**Free breathing or breath-hold (high resolution)**  
**Slice thickness: 8-10mm (contiguous)**

## LV function Module

1. **Cine SSFP** pulse sequence (parallel imaging as required)
2. **2-ch, 4-ch, SA and LVOT** (2 orthogonal) cine images
3. **SA cine stack** (from mitral valve to apex)  
**Slice thickness 6-10mm**  
**Inter-slice gap 0-4mm to equal 10mm**
4. **Temporal resolution  $\leq 45\text{ms}$**

## RV function Module

1. **Cine SSFP** pulse sequence (parallel imaging as required)
2. **Trans-axial cine stack** (from diaphragm to pulmonary bifurcation) or **SA cine stack as for LV module**  
**Slice thickness 6-8mm, inter-slice gap 0mm**
3. **Temporal resolution  $\leq 45\text{ms}$**

Index

# Anatomy, LV and RV Function Module

2/2

## Tips & Tricks (Anatomy Module)

1. **Scan in diastole** to reduce motion artefacts

## Tips & Tricks (LV / RV Function Module)

1. **To reduce breath-hold times use acceleration techniques**
2. **Contouring:**
  - In a healthy heart there is usually one less slice to contour in end-systole at the base of the heart (longitudinal LV shortening). Correlate SA to long axis view if available to identify mitral valve plane.
  - Use the movie function of the analysis software for correct alignments
  - Different methods have been proposed to deal with trabeculation and papillary muscles. Use a consistent approach and the correct normal values for the chosen method.
3. **RV volumes** are more reproducible when calculated from an axial imaging plane.

# Perfusion Module

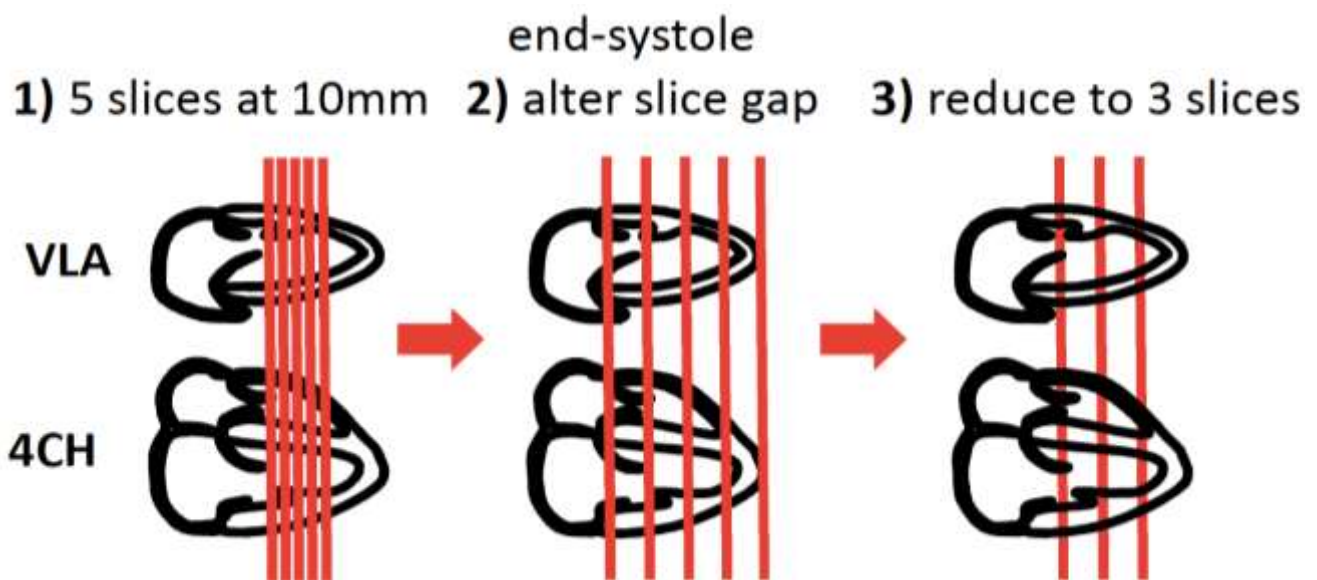
1. **Scout imaging** as per LV function module
2. **Saturation-recovery gradient echo pulse sequence** (GRE, gradient echo-echo planar (GRE-EPI), or SSFP readout)
3. **Parallel imaging** (twofold acceleration, if available)
4. **SA view imaging** (at least **three slices** per heartbeat);
  - **Slice thickness 8-10mm**
  - **In-plane resolution < 2.5mm**
  - Ideally obtain data **every heart beat**
5. **Contrast (0.05 - 0.1mmol/kg, rate: 3 - 7ml/s)** followed by 30ml saline flush (3-7ml/s)
6. **Breath-hold** starts during early phases of contrast infusion **before contrast reaches the LV cavity**
7. Image for **>40 heartbeats**



# Perfusion Module

## Tips & Tricks

1. **“Dummy” scan** to check
  - Correct slice positioning
  - Artefacts
  - ECG triggering at every single heartbeat
2. Switch to alternate heartbeat acquisition if HR is too high or reduce number of slices
3. **Field of View**
  - As small as possible
  - Parallel to the anterior chest wall
4. Use **“3 out of 5” technique** to position slices



# Early and Late Gd Enhancement Module

1/2

1. **2D-segmented IR GRE imaging during diastolic rest period**
2. **4-ch, 3-ch, 2-ch, SA images**
3. **In-plane resolution : <2mm**
4. **EGE: image 1-3min after contrast, TI >400ms**
5. **LGE:  $\geq 10$ min after Gd injection (0.1 – 0.2mmol /kg)**
  - The delay may be shorter if lower Gd doses are used
  - The delay may be increased in a low output state
6. **TI set to null normal myocardium:**
  - TI scout or Look Locker sequence
  - Phase-sensitive sequence with fixed TI as alternative
7. **Readout:**
  - Usually every other heartbeat
  - Every heartbeat in the setting of bradycardia
  - Every third heartbeat in the setting of tachycardia

# Early and Late Gd

# Enhancement Module

2/2

## Tips & Tricks

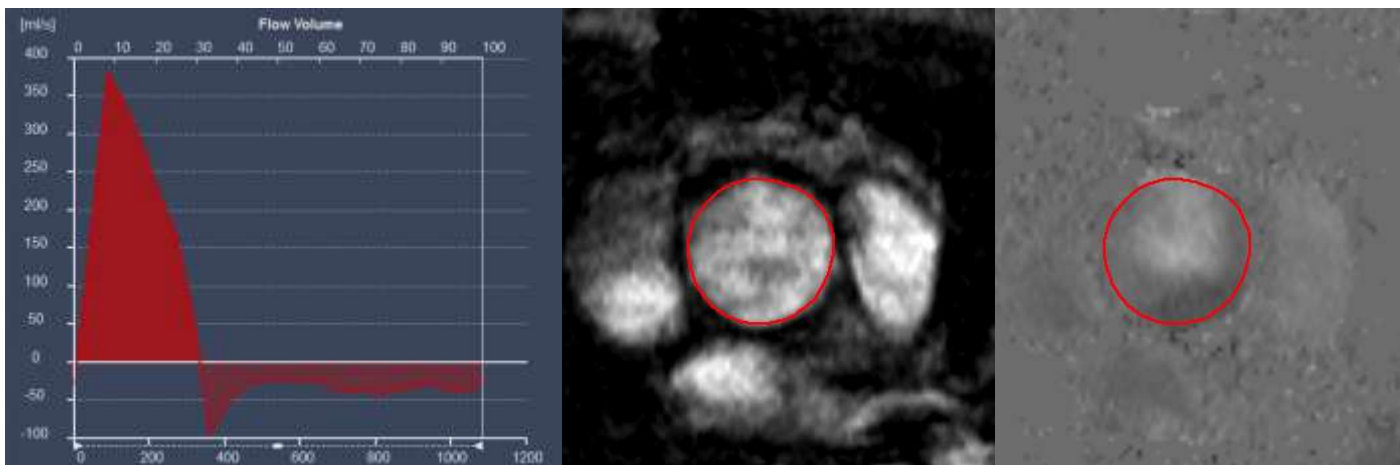
1. **Scan in mid- or late-diastole** to minimize motion artefacts
2. Use **saturation bands** across the spinal column and the anterior chest wall to reduce ghosting artefacts
3. **Late enhancement on images:**
  - Use “**Phase Swap**” (changing the phase encoding direction) to confirm pathology/detect artefact
  - Always consider a different plane cross-cutting through the enhanced area
4. **Increase TI times by 10 – 15ms every couple of minutes**, because the correct TI for “nulling” of normal myocardium slowly changes over time
5. **To reduce breath-hold times use acceleration techniques**
6. Acquiring the images during every second or third heartbeat can help if there are problems with arrhythmia
7. Consider infiltrative disease (**amyloidosis**) if normal myocardium is hard to null despite correct technique

Index

# Phase Contrast Velocity Encoded Module

1/2

1. Choose the **appropriate imaging plane perpendicular to direction of flow**
2. **Consider orthogonal acquisition** to define peak velocity
3. Set required **direction of flow**
4. Choose **appropriate VENC**:
  - **Normal systemic flow: 150cm/s**
  - **Normal right-sided flow: 100cm/s**
  - Adjust in pathological situations  
(severe valve stenosis > 400cm/s)
5. Choose **adequate spatial resolution**
  - **minimum of 4-6 pixels per vessel diameter**



*Volume time curve from flow velocity encoding through the ascending aorta in a patient with severe aortic regurgitation*

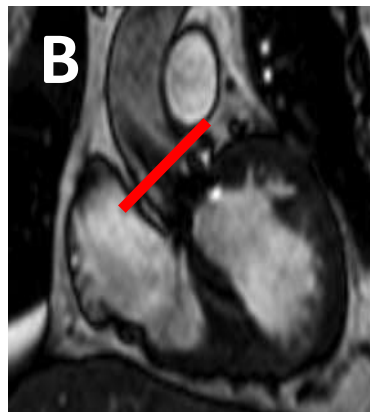
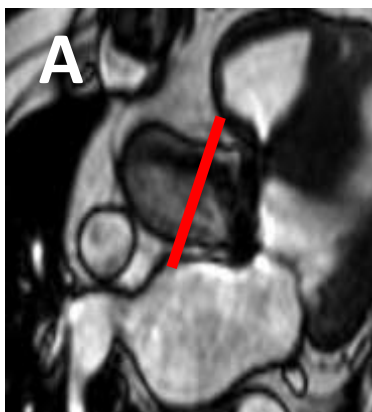
**Index**

# Phase Contrast Velocity Encoded Module

2/2

## Tips & Tricks

1. **VENC settings:**
  - Optimal within 25% of the true peak velocity
    - Too low: flow aliasing
    - Too high: underestimating velocity
  - Correct direction of flow (R-L, F-H)
  - Image plane distal from valve leaflet tips
  - Flow assessment: perpendicular to the vessel
  - Max. velocity assessment: perpendicular to the jet
2. **Avoid underestimation of velocities. Check:**
  - Adequate temporal resolution (phases)
    - Free-breathing acquisition: 30 phases
    - Breath-hold acquisition: 20-25 phases
3. Rotate FOV - orthogonal to the direction of flow
4. Slice thickness: <7mm

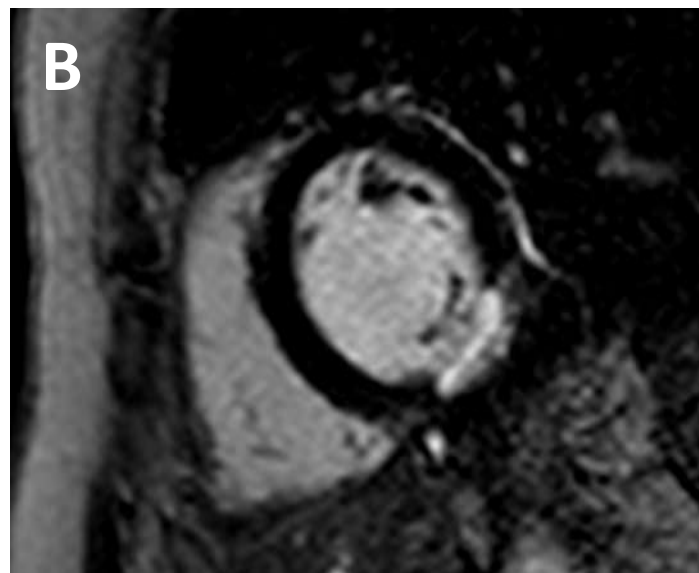
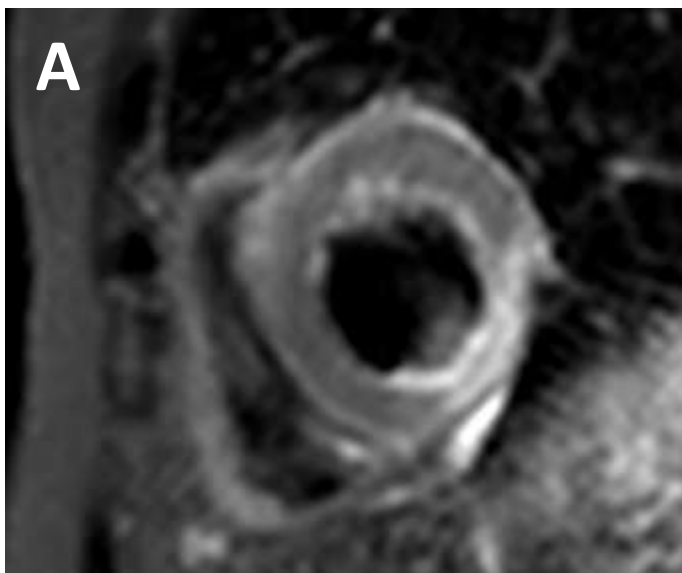


*Sagittal (A) and coronal (B) slice positioning for aortic stenosis*

[Index](#)

# Edema Module

1. **T2w imaging**
2. **Prior to contrast administration**
3. **Slice thickness:**
  - $\geq 10\text{mm}$  to ensure good SNR
  - **Slice thickness** of the dark blood pre-pulse should be greater than the longitudinal shortening of the LV
4. **Mid-diastolic readout**
5. Use **body coil** or alternatively **functional surface coil** intensity correction algorithms to correct for coil-related signal differences
6. Slow flow artefacts may cause high signal at endocardial border



*Myocardial infarction with inferior edema on T2w images (A) and LGE (B)*

# Angiography Module

1. Prepare **infusion pump** with contrast agent and flush  
Gd dose: 0.1–0.2mmol/kg
2. Define **3D target region** (usually a very large volume)
3. Define required **timing of acquisition** (arterial / venous)
4. Determine best **timing parameters** for data acquisition (pre-bolus or automatic triggering)
5. Perform a **dummy** acquisition
6. Perform **acquisition** with contrast administration

## Tips & Tricks

1. Optimize timing technique:
  - Ensure that the centre of k space is acquired at the same time as the bolus of contrast arrives in the vessel of interest
2. Ensure that the FOV covers the whole area of interest including any collateral or aberrant vessels

# Coronary Artery Imaging Module

1/2

1. Determine coronary **rest period**
  - Acquire **HLA** with **high temporal resolution** (50 phases)
2. **Navigator-gated, free-breathing 3D pulse sequence:**
  - **Trans-axial slices** (from the proximal main pulmonary artery to the middle of the right atrium; entire cardiac coverage if desired).
  - **Slice thickness: 1-1.5 mm**
  - **Spatial resolution in-plane: 1.0 mm** or less
  - **Slices: typically 50 – 80**
  - **Adjust trigger** delay and **acquisition window** according to observed coronary artery rest period
  - **Parallel acquisition** preferred
  - Navigator placed over the right hemi-diaphragm
3. **Optional:**
  - Consider contrast to increase vessel conspicuity
  - Breath-hold techniques if poor image quality or if navigators are unavailable or are of poor quality
  - T2-prepared sequence may be useful

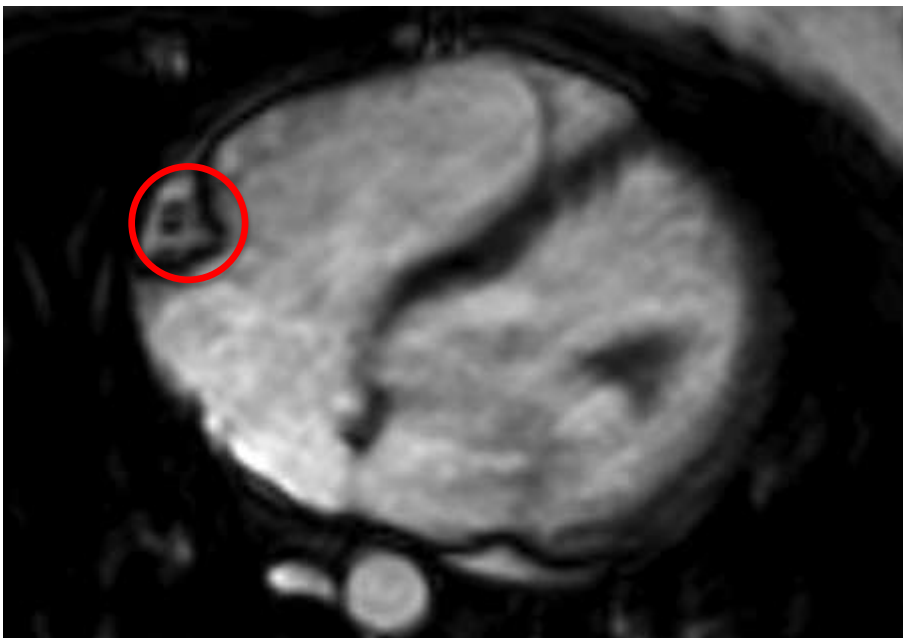


# Coronary Artery Imaging Module

2/2

## Tips & Tricks

1. **Problems identifying coronary rest period:**
  - repeat high temporal resolution 4-ch scan at the **correct HR**
  - **Consider cine scan during free-breathing** if HR changes significantly during breath-hold
  - **Check during systole** with a tight window (<50 ms)
  - As a compromise, scan **with longest trigger delay and a tight window** (<50 ms)
2. Coronary rest period may differ between LCA and RCA
3. **High HR** ( $\geq 90$ bpm): Use shortest scan window possible to minimize blurring
4. **Keep scan times to a sensible limit**
5. Higher spatial resolution equals longer scan times



*4-ch view showing the RCA in diastole*

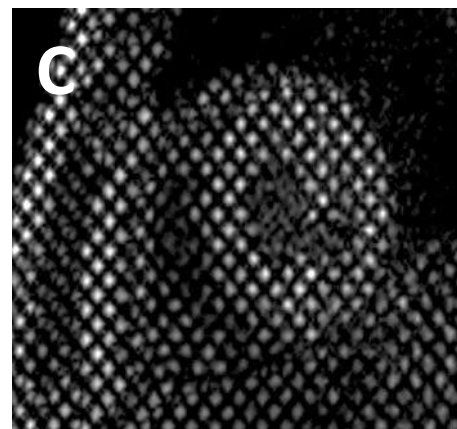
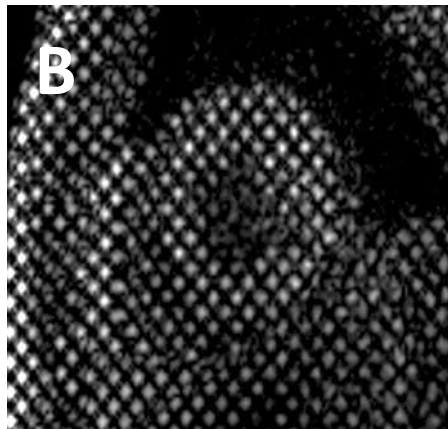
[Index](#)

# Tagging Module

1. **Scout imaging** as per LV function module
2. Choose **line tagging or grid tagging** pattern
3. Choose **slice orientation from cine study**
4. Acquire data in **breath-hold**

## Tips & Tricks

1. Reference modality for evaluating multidimensional strain
2. **Temporal resolution about 15-20ms**
3. **Acceleration techniques** used to shorten the breath-hold time are the same as for cine imaging
4. Use a low **flip angle** to reduce tissue saturation and prolong the tagging pattern throughout the cardiac cycle
5. Mid-myocardial circumferential strain from SA is most reproducible



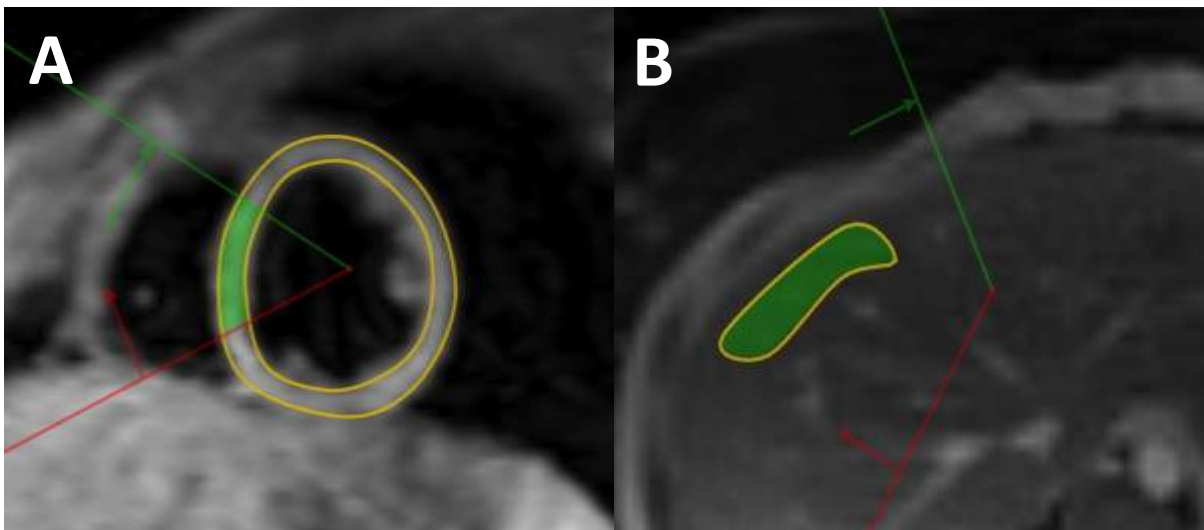
*Apical (A), mid-ventricular (B) and basal (C) grid-tagging*

# T2★ Module

1. T2★ quantitation is a standard CMR technique for **disease monitoring** and **guiding chelation therapy** in cardiac iron-loading conditions
2. **Single breath-hold, multi-echo, T2★ sequence**  
(gradient echo or modified black blood sequence)
3. **Single mid-ventricular slice**
4. **Single transaxial slice of the liver**

## Tips & Tricks

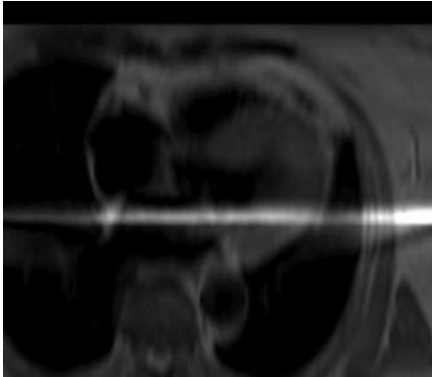
1. **Ensure good patient breath-holding for the heart and the liver scans** by coaching as the scan duration is long
2. **Make sure the septum is of good image quality** as this is where quantification is most reproducible
3. Position the transverse liver slice correctly:
  - Avoid large hepatic vessels for correct T2\* measurement in the liver tissue



*ROIs are placed in the ventricular septum (A) and the liver (B)*

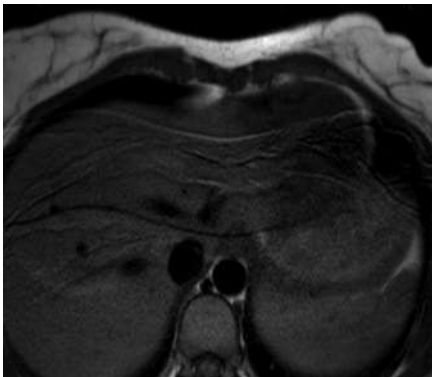
**Index**

# Artefacts



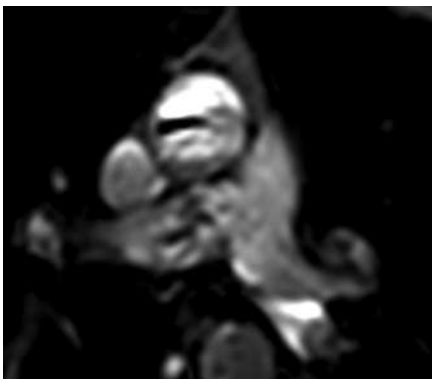
## Wrapping artefact (fold-over, back-folding)

- Increase FOV
- Add phase encoding (phase-oversampling, foldover suppression, no phase wrap)
- Swap phase and frequency direction
- Use selective tissue saturation bands
- Use a surface coil



## Ghosting artefact from motion (respiratory)

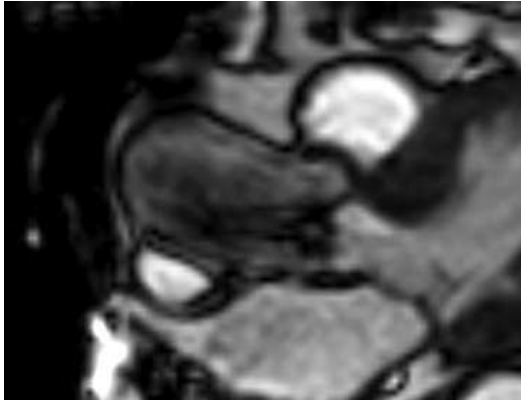
- Strict breath-holding plus acceleration techniques
- Respiratory gating or navigator echoes
- Swap phase and frequency direction
- Use selective tissue saturation bands to suppress the signal from the anterior abdominal wall



## Ghosting artefact from motion (pulsatile flow)

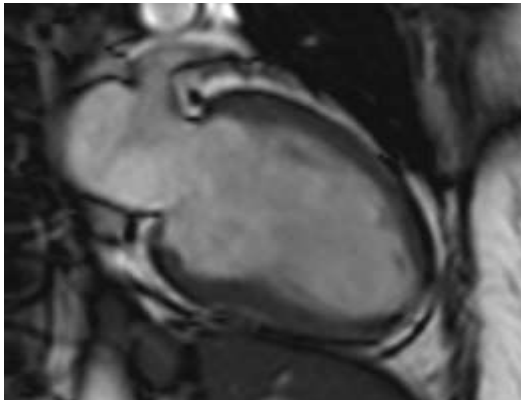
- Use ECG triggering / gating
- Use flow compensation (gradient moment nulling, gradient motion rephasing)
- Use selective tissue saturation bands to suppress the blood signal
- Swap phase and frequency direction

# Artefacts



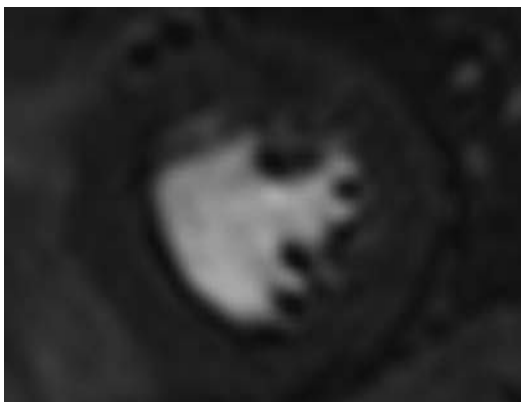
## Flow-related signal loss and flow jets

- Reduce echo time
- Use flow compensation
- Use bSSFP acquisition



## Chemical shift artefact

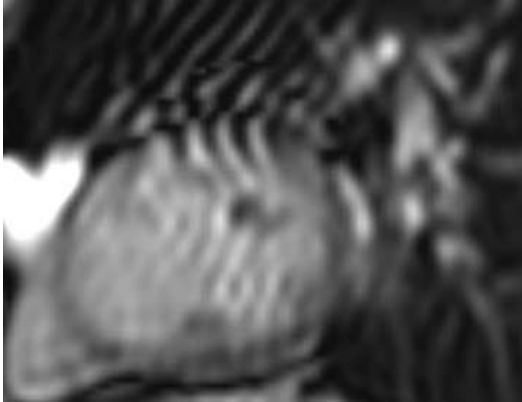
- Compare with other images as they are sequence dependent



## Dark rim artefact

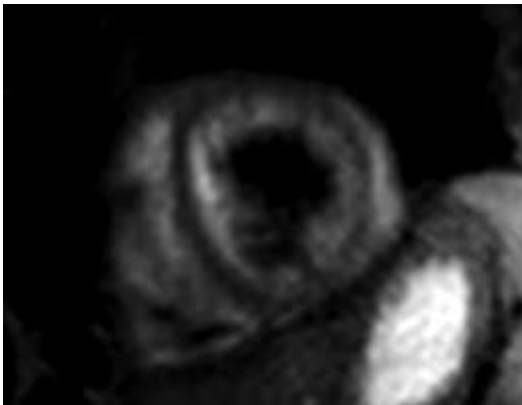
- Often seen in perfusion imaging
- Reduce contrast dose/infusion speed
- Increase in-plane spatial resolution

# Artefacts



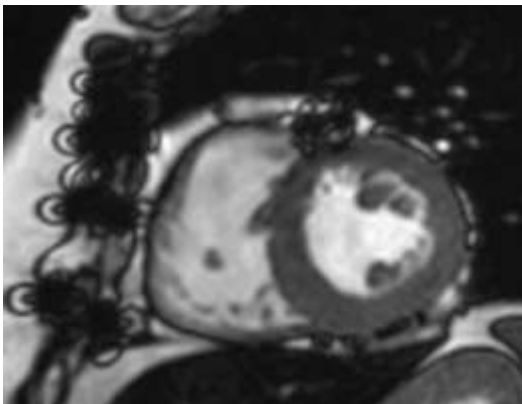
## Radiofrequency interference artefact

- Check for sources of interference and eliminate (e.g. make sure scan room door is closed)



## Slow flow artefact

- Usually in T2w images
- Increase black blood pre-pulse slice thickness



## Metallic artefact

- Usually less prominent on spin echo images than gradient echo images

# Ischemic Heart Disease 1/9

## Perfusion

### Protocol

1. **Anatomy** module
2. **Myocardial perfusion** module “dummy”
3. **Myocardial perfusion** module **STRESS**
4. **LV function** module
5. **Myocardial perfusion** module **REST**
6. **LGE** module

### Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF / RV: EDV, ESV, SV, EF
  - **Regional wall motion abnormalities** (17 segments)
2. Presence and transmural extent of **scar**
  - ≤25%, 26-50%, 51-75%, 76-100%
3. Presence and transmural extent of inducible **perfusion defect**
4. **Correlation** between **scar** and **perfusion defect**
5. Comment on **suitability of revascularization** based on ischemia and viable myocardium
6. (Presence and location of **artefacts**)

# Ischemic Heart Disease 2/9

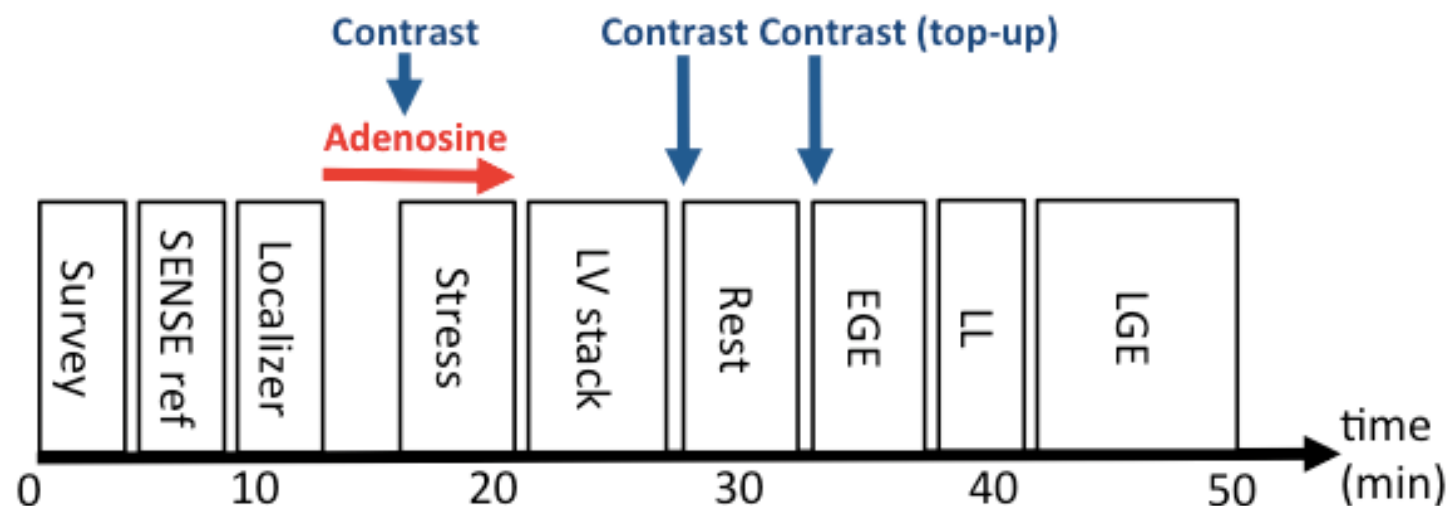
## Perfusion

### Key Issues

1. **Check BP /monitor ECG during adenosine perfusion**
2. **Adenosine dose:**
  - **140mcg/kg/min**
  - Consider **170 or 210mcg/kg/min**, if hemodynamic response is inadequate or after caffeine intake
3. **Contraindications for adenosine:** known hypersensitivity, 2nd /3rd AV nodal block, severe reversible airways disease

### Tips & Tricks

1. **One i.v. cannula (Y connector) for Adenosine and Gd is safe**
2. **Use “3 out of 5” technique to position perfusion slices**
3. Note: Segment 17 is not visualized on 3 slice SA perfusion scan





## Wall Motion

### Protocol

1. **Anatomy** module
2. **LV function** module - 3 SA, 2-3 LA views
3. **Dobutamine Stress**
  - 3min-intervals: 10 / 20 / 30 / 40 mcg/kg/min
  - HR target =  $0.85 \times (220 - \text{age})$
  - Consider 0.5 mg atropine x 2 to increase HR
  - Repeat cine images at each stress level
4. **LGE** module

### Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV, SV, EF / RV: EDV, ESV, SV, EF
  - **Regional wall motion abnormalities** (17 segments)
    - Improvement during low-dose stress (=viability)
    - Improvement or biphasic response during high-dose stress (=ischemia)
2. Presence and transmural extent of **scar**
3. Summarize: **resting function, contractile reserve, wall motion index, ischemia** for coronary territories
4. Comment if any **valvular regurgitation** worsens

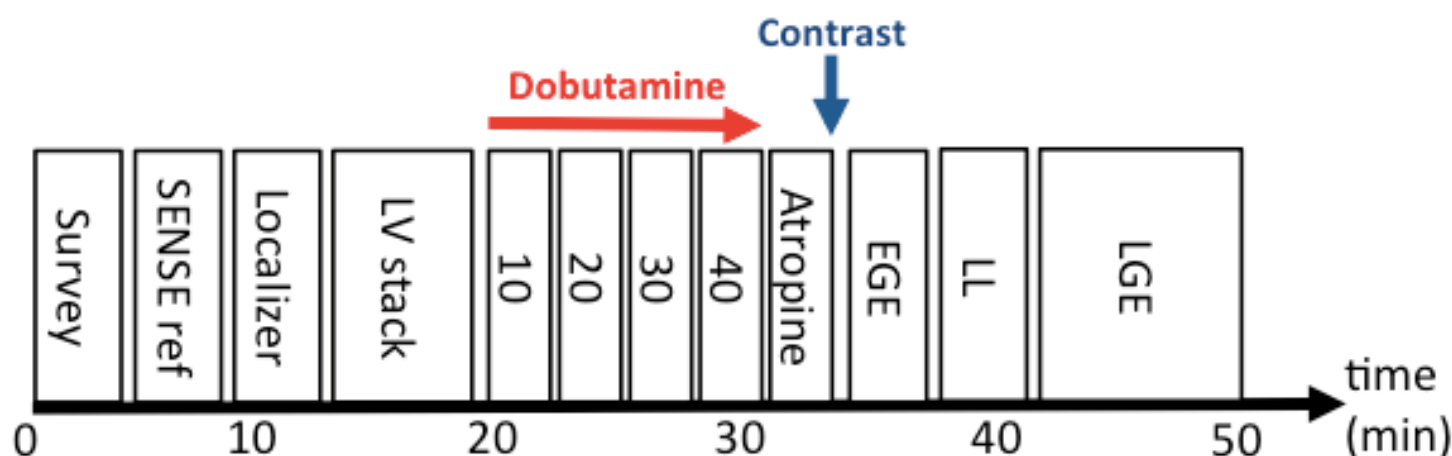
# Wall Motion

## Key Issues

1. **Check BP** at each stage of protocol / **monitor ECG**
2. **Always view cine loops during stress online**
3. **Stop test, if any of the following occurs:**
  - New wall motion abnormalities
  - Serious side effects
  - Achievement of peak HR
4. **Contraindications for dobutamine:** narrow-angle glaucoma, myasthenia gravis, obstructive uropathy, obstructive gastrointestinal disorders
















## Tips & Tricks

1. Use “3 out of 5” technique (perfusion module) to position SA slices



Ischemic Heart Disease5/9

Wall Motion

| Ischemic Conditions | Myocardial Wall Motion  |  |   |
|---------------------|---|--|---|
|                     | Rest  | Low-Dose Dobutamine  | High-Dose Dobutamine  |
| Normal              |    |    |    |
| Ischemia            |    |    |    |
| Hibernation         |   |   |   |
| Subendocardial Scar |  |  |  |
| Transmural scar     |  |  |  |

Wall Motion Score Index (WMSI)

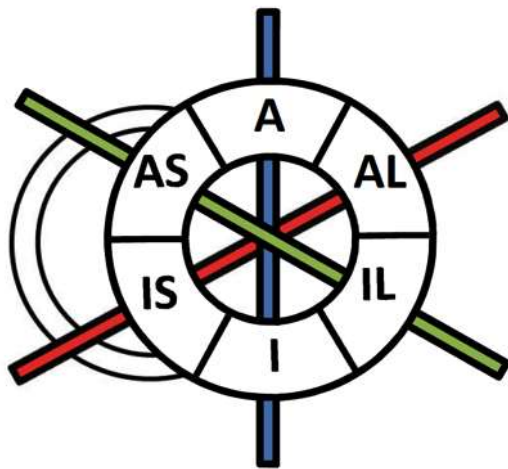
(sum of wall motion scores / number of segments)

|             |   |
|-------------|---|
| Normal      | 1 |
| Hypokinetic | 2 |
| Akinetic    | 3 |
| Dyskinetic  | 4 |
| Aneurysmal  | 5 |

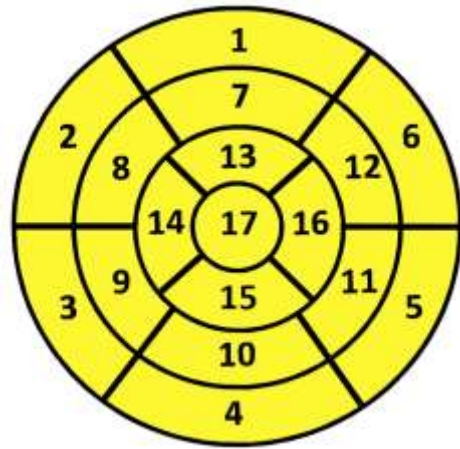
A WMSI of 1 is considered normal

# Ischemic Heart Disease 6/9

## 17 Segment Model

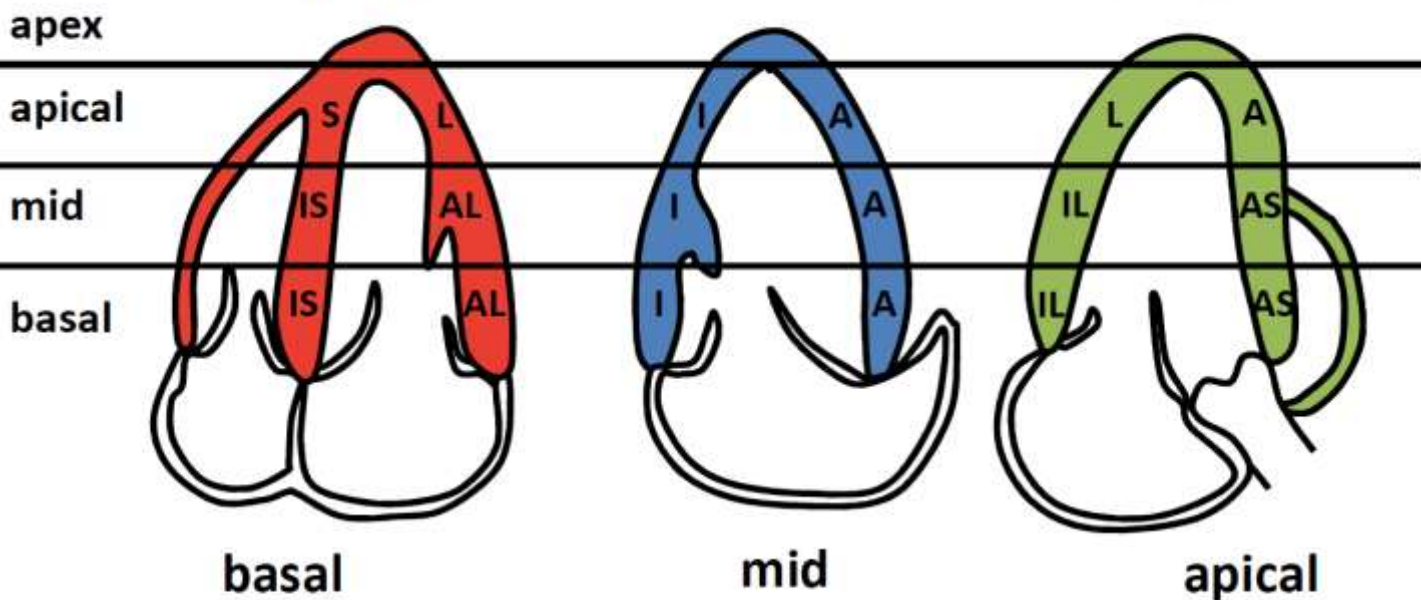


4 chamber



2 chamber

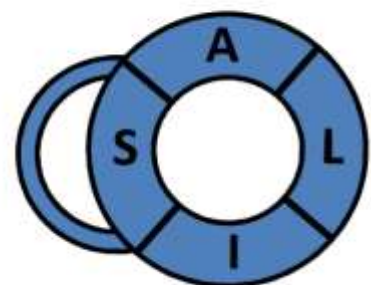
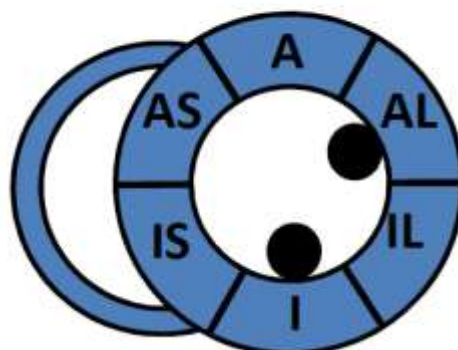
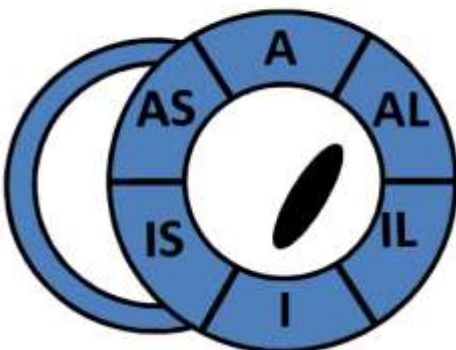
3 chamber



basal

mid

apical



Modified from reference 4)

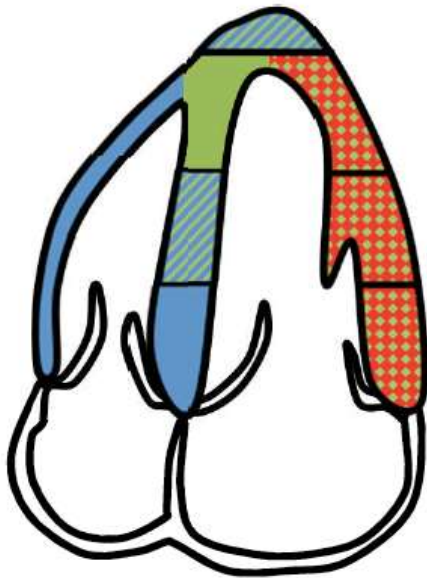
1: basal anterior A; 2: basal anteroseptal AS; 3: basal inferoseptal IS; 4: basal inferior I; 5: basal inferolateral IL; 6: basal anterolateral AL; 7: mid-anterior A; 8: mid-antersseptal AS; 9: mid-inferoseptal IS; 10: mid-inferior I; 11: mid-inferolateral IL; 12: mid-antrolateral AL; 13: apical anterior A; 14: apical septal S; 15: apical inferior I; 16: apical lateral L; 17: apex

[Index](#)

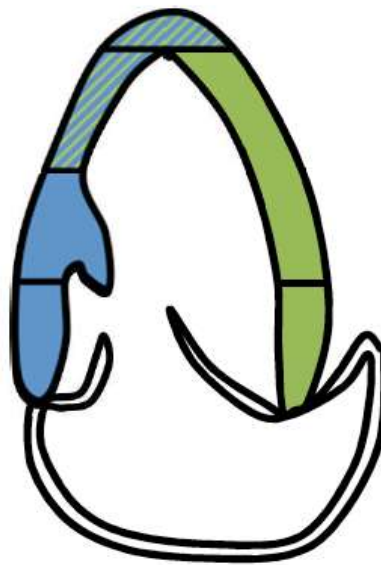
# Ischemic Heart Disease 7/9

## Coronary Supply

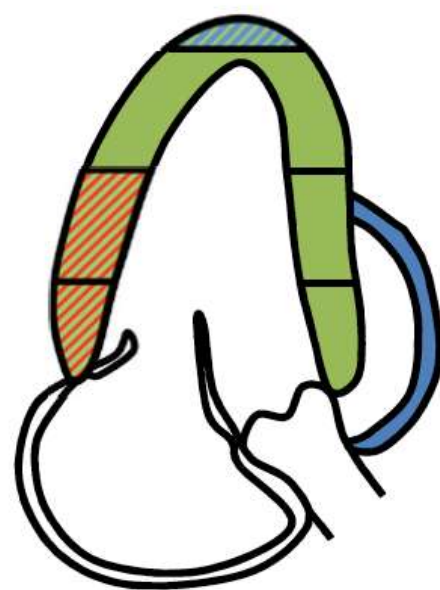
4 chamber



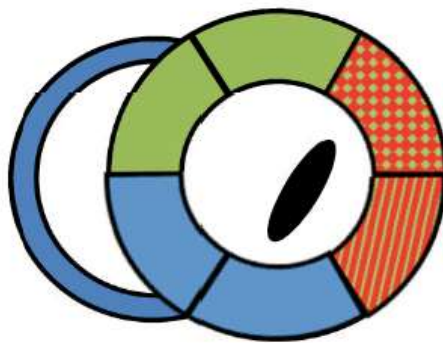
2 chamber



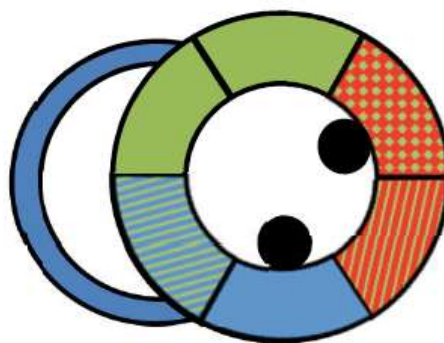
3 chamber



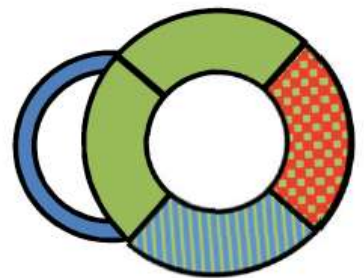
basal



mid



apical



LAD



LAD or CX



CX



LAD or RCA



RCA



CX or RCA

[Index](#)



# Ischemic Heart Disease 8/9

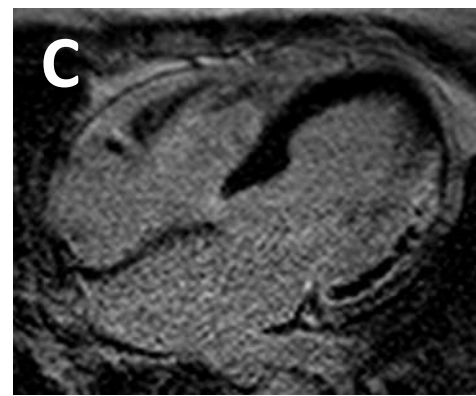
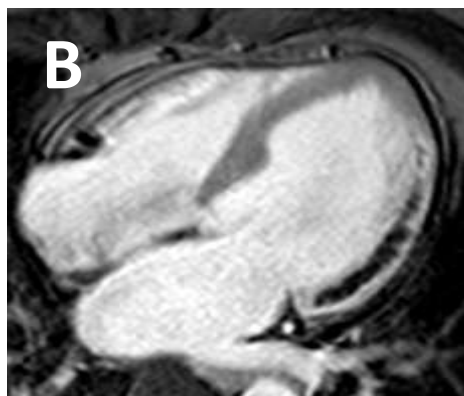
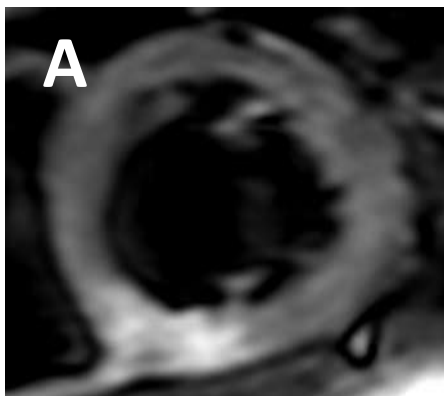
## Acute Myocardial Infarction

### Protocol

1. **Anatomy** module
2. **LV function** module
3. **Edema** module
4. **EGE – LGE** module

### Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF
  - RV: EDV, ESV, SV, EF
  - Regional wall motion abnormalities
2. **Presence of edema (=area at risk)**
3. Presence and transmural extent of **scar**
4. Presence and extend of **microvascular obstruction (MVO)**



*Acute myocardial infarction: A) inferoseptal edema on T2w SA B, C) MVO on 4-ch EGE, LGE*

**Index**

# Ischemic Heart Disease 9/9

## Acute Myocardial Infarction

### Key Points

1. T2w imaging may differentiate **acute** from **chronic myocardial infarction**
2. **Microvascular obstruction:**
  - Equates to angiographic “no reflow” appearance
  - High risk feature
3. **Risk assessment:**
  - Infarction size
  - LV / RV function
  - MVO
4. Assessment of **LV thrombus** on EGE images

### Tips & Tricks

1. **MVO** best seen on **EGE** images at **TI > 400ms**
2. **T2w** images must be acquired **before contrast** administration
3. Compare LGE images with cine images if unsure about differentiation between blood pool and endocardial late enhancement

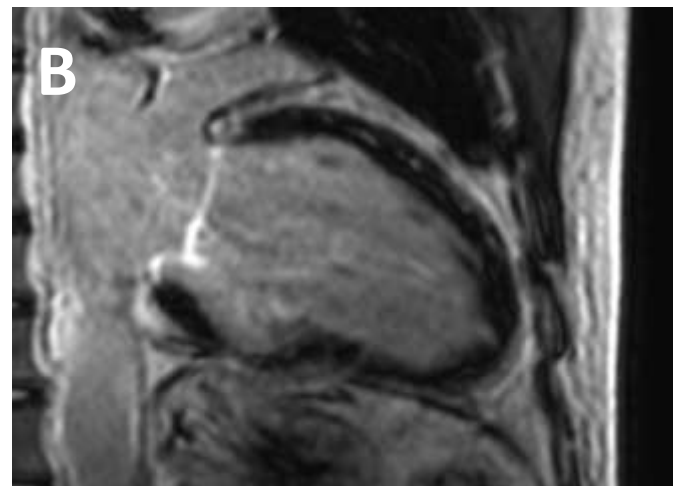
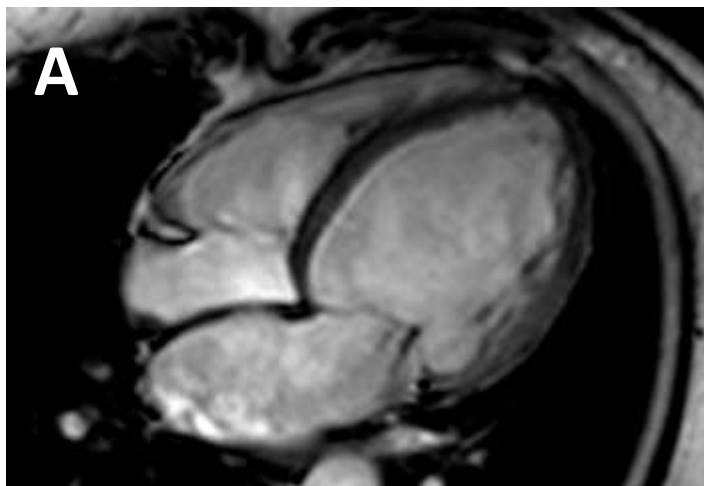
# Dilated Cardiomyopathy<sup>1/2</sup>

## Protocol

1. **Anatomy** module
2. **LV function** module
3. **Edema** module
4. **RV function** module
5. **LGE** module

## Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF, end-diastolic diameter
  - RV: EDV, ESV, SV, EF
2. Presence and severity of **valvular regurgitation**
3. Presence, location, and extent of **fibrosis**



*Dilated LV with MR (A) and mid-wall fibrosis on LGE images (B)*

**Index**



# Dilated Cardiomyopathy<sup>2/2</sup>

## Key Points

1. Mid-wall fibrosis indicative of DCM
2. **Risk factors for sudden cardiac death:**
  - LV impairment, EF <35%
  - Frequent repetitive NSVT
  - Presence and extent of mid-wall fibrosis

## Tips & Tricks

1. Use **acceleration techniques** to reduce breath-hold times
2. **Consider unrecognized CAD** if you identify:
  - Marked regional wall motion abnormalities
  - Subendocardial or transmural hyperenhancement on LGE
3. Consider abnormal vascular connections / shunts
4. **Tagging** may help identify wall motion abnormalities
5. Perfusion imaging can be difficult to interpret (thin myocardium, presence of scar and slower flow)

# Hypertrophic Cardiomyopathy

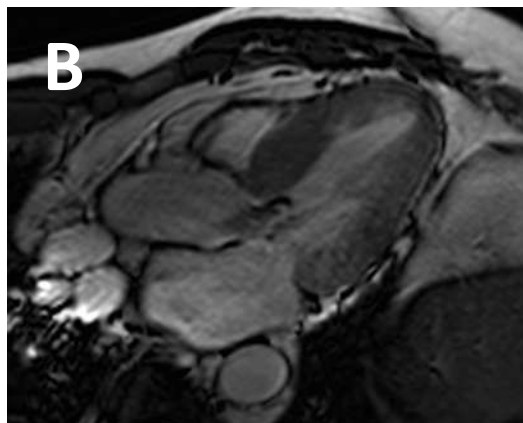
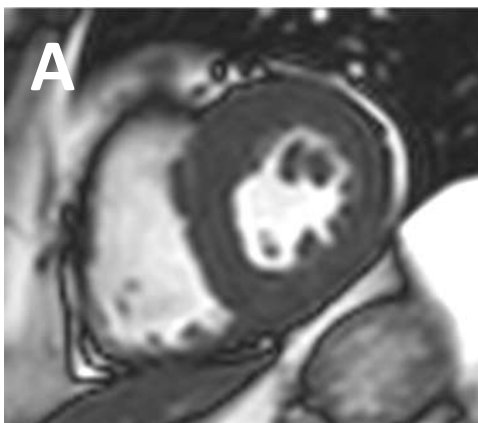
1/2

## Protocol

1. **Anatomy** module
2. **LV function** module
3. **LVOT** cines (2 orthogonal views)
4. **Velocity encoding** module in- and through- LVOT planes
5. **LV tagging** (3 SA slices, 4ch) - optional
6. **LGE** module

## Report

1. **Dimensions, mass** (corrected for BSA) and **function**  
EDV, ESV , SV, EF and mass
2. **Thickening and function of myocardial segments**
3. Presence of **LVOT obstruction at rest**
4. Presence of systolic anterior motion (**SAM**)
5. Presence and extent of **fibrosis**



*HCM: Septal hypertrophy and SAM of anterior mitral leaflet on SA (A) and 3-ch (B)*

Index

# Hypertrophic Cardiomyopathy

2/2

## Key Points

1. **Risk factors for sudden cardiac death in HCM:**
  - Positive family history
  - Syncope
  - Frequent repetitive NSVT
  - Blood pressure drop during exercise
  - Massive LV hypertrophy  $\geq 30\text{mm}$
  - Presence and extent of LGE
2. Consider possible obstruction under stress conditions

## Tips & Tricks

1. **LGE at the insertion points** of the RV to the LV are non-specific and often seen even in normal subjects
2. **Suggestive for HCM:**
  - Localized hypertrophy
  - Reduced contraction of hypertrophied segments
  - Presence of LGE
3. **Tagging** may help identify wall motion abnormalities

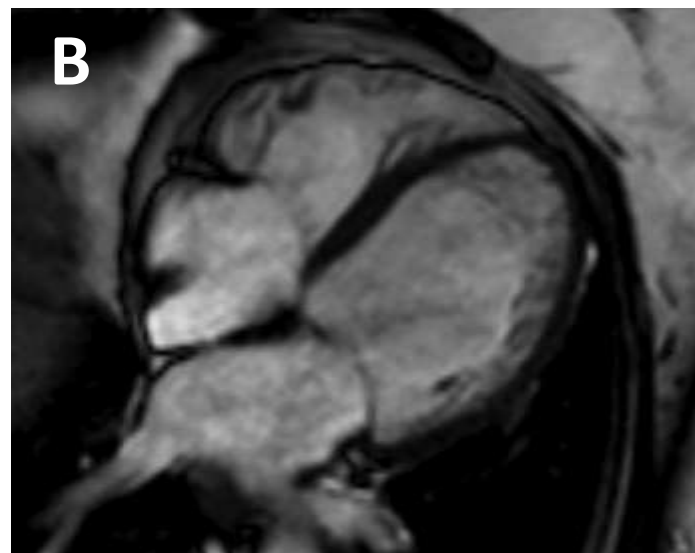
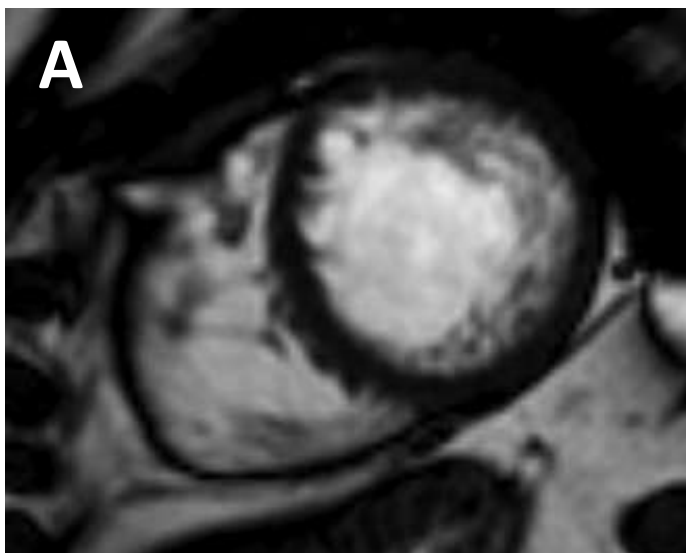
# Left Ventricular Non- 1/2 Compaction Cardiomyopathy

## Protocol

1. **Anatomy** module
2. **LV function** module
3. **LGE** module

## Report

1. **Dimensions, mass** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF
  - Mass of non-compacted and compacted layer
2. **Regional wall motion abnormalities**
3. Location and extent of segments with **increased non-compacted to compacted (NC/C) myocardial ratio**



*IVNC: Significant non-compacted myocardial layer, primarily in the lateral wall on SA (A) and 4-ch (B)*

**Index**

# Left Ventricular Non-Compaction Cardiomyopathy

2/2

## Key Points

1. **Current diagnostic criteria:**
  - **NC/C  $\geq 2.3 : 1$  on end-diastolic image\***  
**Note:** NC/C 2:1 on end-systolic echo images
  - **Non-compacted LV mass above 20%** of the global mass
2. **LGE** may represent **severe or late forms** of LVNC
3. **Diagnosis may not be based on imaging criteria alone**
  - Often over-diagnosed, particular in DCM (thin compacted myocardium) and in patients of Afro-American descent
  - Current diagnostic criteria may overdiagnose LVNC and new guidance is anticipated

## Tips & Tricks

1. Consider associated congenital defects (Ebstein anomaly, coarctation of the aorta, bicuspid aortic valve...)

\*Measured on 4-ch, 3-ch and 2-ch long axis cines

# Arrhythmogenic Right Ventricular Cardiomyopathy 1/5

## Protocol

1. **Anatomy** module
2. **LV function** module
3. **RV function** module (axial and RVOT)
  - **Slice thickness 6-8mm without inter-slice gap**
4. T1w axial **black blood** images (optional)
5. T1w axial **fat suppressed black blood** images (optional)
6. **LGE** module in same orientations
  - T1 nulling for RV

## Report

1. **Dimensions, mass** (corrected for BSA) and **function**
  - LV: EDV, ESV, SV, EF, longitudinal function, mass
  - RV: EDV, ESV, SV, EF, longitudinal function
  - **RV regional wall motion abnormalities**  
(inflow, apex, outflow)
2. Presence of **morphological RV abnormalities** (aneurysms, outpouchings)
3. Presence of **fatty RV or LV infiltration** (if acquired)
4. Presence and extent of **fibrosis**

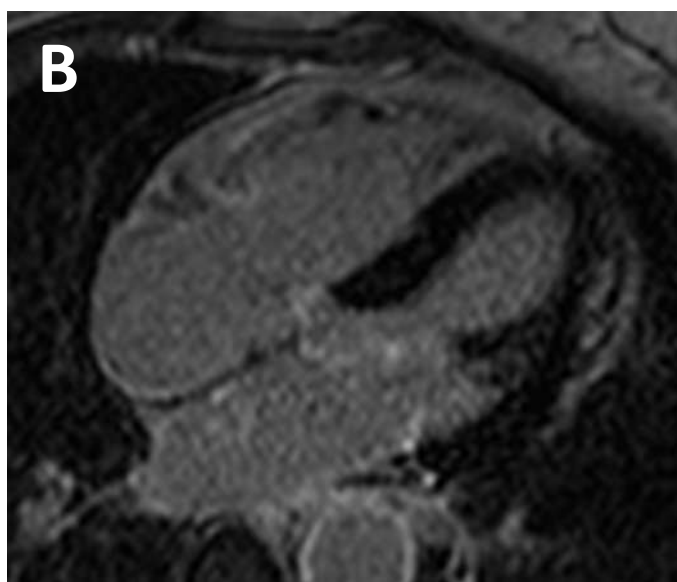
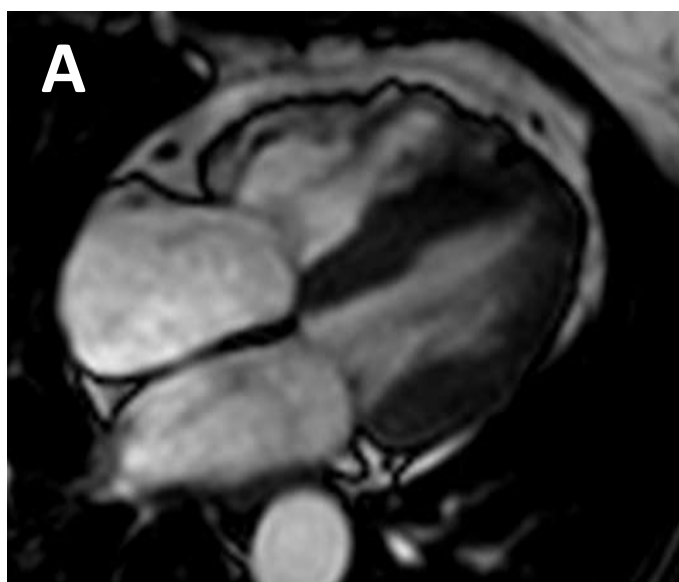
# Arrhythmogenic Right Ventricular Cardiomyopathy 2/5

## Key Points

1. **Diagnosis cannot be based on imaging criteria alone**
  - See modified Task Force ARVC criteria
2. RV wall motion abnormalities at the moderator band insertion point is common in normal subjects

## Tips & Tricks

1. **Focus on RV volumes and functional RV abnormalities**
2. Consider antiarrhythmic drugs in patients with VES
3. Consider alternative causes (abnormal vascular connections / shunts) in patients with dilated RV



*ARVC: Dilated, aneurysmatic RV with LG enhancement on 4-ch (A), LGE (B)*

[Index](#)

# Diagnostic Criteria

## 1. Global or regional dysfunction and structural alterations

- Major**
- Regional RV akinesia or dyskinesia or dyssynchronous RV contraction
  - and 1 of the following:
    - Ratio of RV EDV to BSA  $\geq 110\text{mL/m}^2$ (male) or  $\geq 100\text{mL/m}^2$ (female)
    - or RV ejection fraction  $\leq 40\%$
- Minor**
- Regional RV akinesia or dyskinesia or dyssynchronous RV contraction
  - and 1 of the following:
    - Ratio of RV EDV to BSA  $\geq 100$  to  $<110\text{mL/m}^2$  (male) or  $\geq 90$  to  $<100\text{mL/m}^2$  (female)
    - or RV EF  $>40\%$  to  $\leq 45\%$

## Definite diagnosis

- 2 major or 1 major and 2 minor criteria
- 4 minor criteria

## Borderline diagnosis

- 1 major and 1 minor
- 3 minor criteria

## Possible diagnosis

- 1 major or 2 minor criteria

## 2. Tissue characterization of wall (histological)

- Major**
- Residual myocytes  $<60\%$  by morphometric analysis (or  $<50\%$  if estimated), with fibrous replacement of the RV free wall myocardium in  $\geq 1$  sample, with or without fatty replacement of tissue on endomyocardial biopsy
- Minor**
- Residual myocytes  $60\%$  to  $75\%$  by morphometric analysis (or  $50\%$  to  $65\%$  if estimated), with fibrous replacement of the RV free wall myocardium in  $\geq 1$  sample, with or without fatty replacement of tissue on endomyocardial biopsy



# Diagnostic Criteria

## 3. Repolarization abnormalities

- Major** • Inverted T waves in right precordial leads (V1, V2, and V3) or beyond in individuals >14 years of age (in the absence of complete right bundle-branch block QRS  $\geq 120$ ms)
- Minor** • Inverted T waves in leads V1 and V2 in individuals >14 years of age (in the absence of complete right bundle-branch block) or in V4, V5, or V6
- Inverted T waves in leads V1, V2, V3, and V4 in individuals >14 years of age in the presence of complete right bundle-branch block

## 4. Depolarization / conduction abnormalities

- Major** • Epsilon wave (reproducible low-amplitude signals between end of QRS complex to onset of the T wave) in the right precordial leads (V1 to V3)
- Minor** • Late potentials by SAECG in  $\geq 1$  of 3 parameters in the absence of a QRS duration of  $\geq 110$ ms on the standard ECG
- Filtered QRS duration (fQRS)  $\geq 114$ ms
- Duration of terminal QRS  $< 40\mu V$  (low-amplitude signal duration)  $\geq 38$ ms
- Root-mean-square voltage of terminal 40ms  $\leq 20\mu V$
- Terminal activation duration of QRS  $\geq 55$ ms measured from the nadir of the S wave to the end of the QRS, including R', in V1, V2, or V3, in the absence of complete right bundle-branch block

# Diagnostic Criteria

## 5. Arrhythmias

- Major** • Nonsustained or sustained ventricular tachycardia of left bundle-branch morphology with superior axis (negative or indeterminate QRS in leads II, III, and aVF and positive in lead aVL)
- Minor** • Nonsustained or sustained ventricular tachycardia of RV outflow configuration, left bundle-branch block morphology with inferior axis (positive QRS in leads II, III, and aVF and negative in lead aVL) or of unknown axis >500 ventricular extrasystoles per 24 hours (Holter)

## 6. Family history

- Major** • ARVC confirmed in a first-degree relative who meets current Task Force criteria
- ARVC confirmed pathologically at autopsy or surgery in a first-degree relative
  - Identification of a pathogenic mutation<sup>†</sup> categorized as associated or probably associated with ARVC in the patient under evaluation
- Minor** • History of ARVC in a first-degree relative in whom it is not possible or practical to determine whether the family member meets current Task Force criteria
- Premature sudden death (<35 years of age) due to suspected ARVC in a first-degree relative
  - ARVC confirmed pathologically or by current Task Force Criteria in second-degree relative

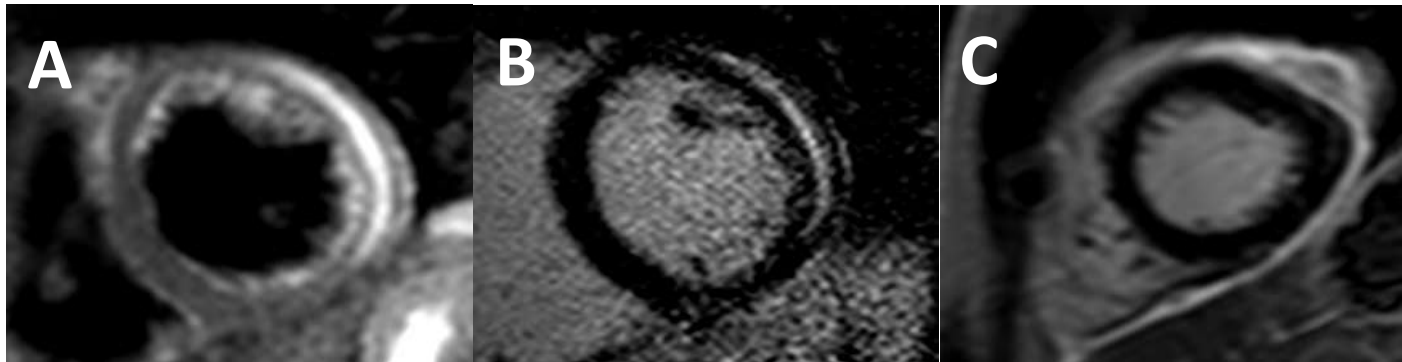
# Myocarditis / Pericarditis<sup>1/2</sup>

## Protocol

1. **Anatomy** module
2. **LV function** (RV function) module
3. **Edema** module
4. **LGE** module

## Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF
  - RV: EDV, ESV , SV, EF
  - **Regional wall motion abnormalities**
2. Presence and location of **edema**
3. Presence and location of **LGE**
4. **Pericardial effusion / enhancement**



*SA views show edema on T2w (A), mid-wall (B) and pericardial enhancement on LGE (C).*

**Index**

# Myocarditis / Pericarditis<sup>2/2</sup>

## Key Points

### 1. Diagnostic CMR criteria

**Myocardial inflammation ( $\geq 2$  of the following criteria)**

**Myocyte injury and / or scar (if focal lesion is present)**

- **Regional or global myocardial SI increase on T2w**
  - SI ratio of myocardium over skeletal muscle of  $\geq 2.0$
- **Global myocardial SI increase on EGE**
  - SI ratio of myocardium over skeletal muscle of  $\geq 4.0$   
or absolute myocardial enhancement of  $\geq 45\%$
- **At least 1 focal lesion with non-ischemic regional distribution (sub-epicardial layer or mid-wall)**
  - Infarction always involves sub-endocardial layer

### 2. Presence of **LV dysfunction** or **pericardial effusion** provides additional, supportive evidence

### 3. **Repeat scan** in 1-2 weeks after the first study, if

- **None of the criteria** are present plus **very recent onset of symptoms** plus **strong clinical evidence**
- **One of the criteria is present**

## Tips & Tricks

1. **Right ventricular dysfunction** seems to be the greatest predictor of mortality and cardiac transplantation

*Modified from reference 7)*

[Index](#)

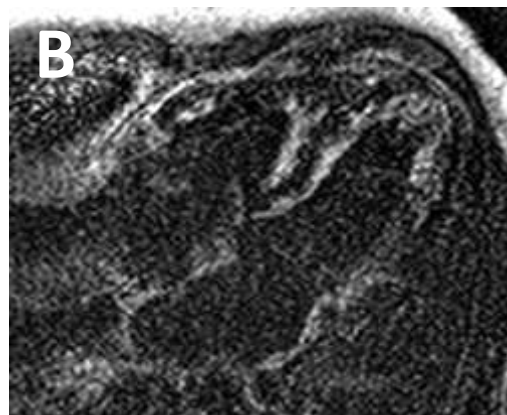
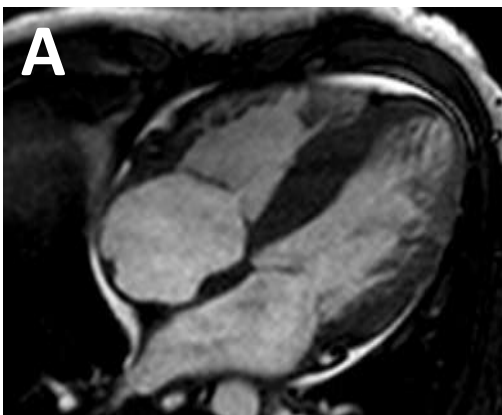
# Amyloidosis

## Protocol

1. **Anatomy** module
2. **LV function** (RV function) module
3. **Edema** module
4. **EGE / LGE** module

## Report

1. **Dimensions, mass** (corrected for BSA), and **function**
  - LV: EDV, ESV , SV, EF, longitudinal function, mass
  - RV: EDV, ESV, SV, EF, longitudinal function
  - Regional wall motion abnormalities
  - Thickness of interatrial septum
2. **Valve regurgitation**
3. **LGE** pattern
4. **Pericardial / pleural effusion**



*Cardiac amyloidosis: Hypertrophic LV on 4-ch (A) with diffuse sub-endocardial LGE (B)*

# Amyloidosis

## Key Points

1. **Restrictive LV pattern** (non-dilated ventricles, preserved LV function, restrictive filling pattern, enlarged LA / RA) and global LV hypertrophy
2. **LV hypertrophy**
3. Consider amyloidosis if myocardial nulling difficult to achieve on LGE images despite good technique
4. **Abnormal** myocardial and blood-pool gadolinium **kinetics**
  - Faster Gd washout from blood and myocardium
5. **Epicardial - endocardial gradient** on early imaging
6. **LGE pattern**:
  - Predominantly global sub-endocardial distribution
7. **Atrial septum hypertrophy of >6mm** (in <20% of cases)
8. **Pericardial** and **pleural effusion** are common
9. Cardiac involvement without hyperenhancement is rare

## Tips & Tricks

1. Consider T1 mapping techniques for the detection of global gadolinium uptake
2. CMR guidance for myocardial biopsy

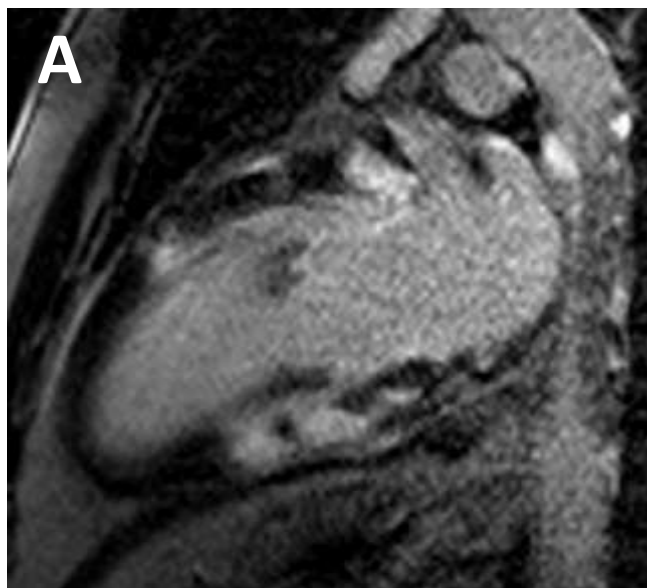
# Sarcoidosis

## Protocol

1. **Anatomy** module
2. **LV function** (RV function) module
3. **Edema** module
4. **LGE** module

## Report

1. **Dimensions, mass** (corrected for BSA), and **function**
  - LV: EDV, ESV , SV, EF, longitudinal function, mass
  - RV: EDV, ESV, SV, EF, longitudinal function
  - **Regional wall motion abnormalities**
2. **Myocardial granulomas** on LGE images
3. **Extra-cardiac findings**



# Sarcoidosis

## Key Points

1. **Restrictive LV pattern** (non-dilated ventricles, preserved LV function, restrictive filling pattern, enlarged LA / RA)
2. **Cardiac involvement:**
  - in about 25% of patients with systemic sarcoidosis
3. **Myocardial granulomas** on LGE images:
  - Intramural
  - Spotty
  - Predominantly basal lateral
  - Respond to immunosuppressive drugs
  - Enhancement not in CAD territory distribution
4. **LV dysfunction** is common
5. **Focal edema** indicates inflammation
  - may mimic hypertrophic cardiomyopathy
6. Usually accompanied with **extra-cardiac findings:**
  - Hilar lymphadenopathy
  - Involvement of any other organ system possible

## Tips & Tricks

1. High degree AV nodal blocks, AF and NSVT are common



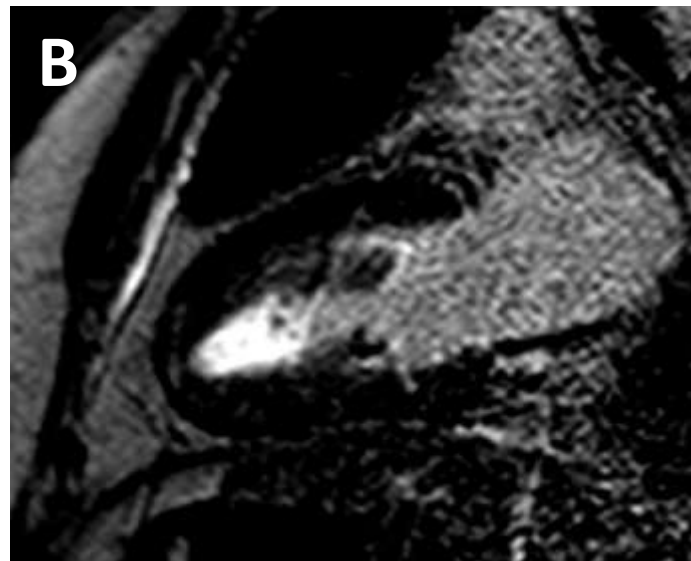
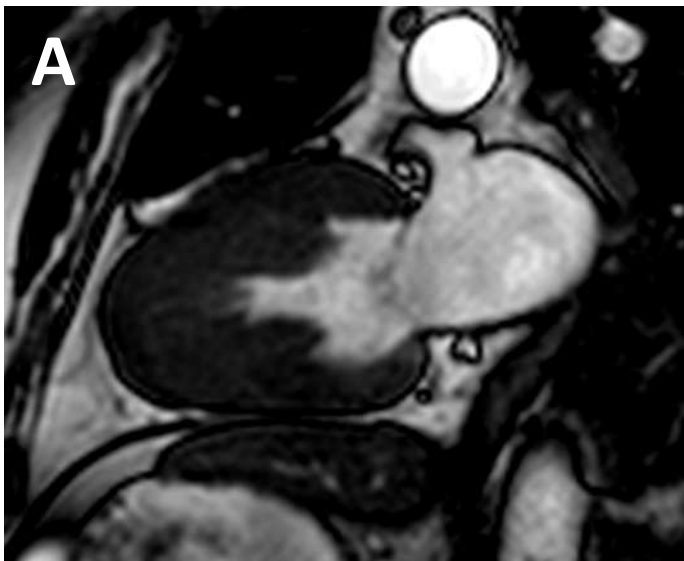
# Endomyocardial Fibrosis<sup>1/2</sup>

## Protocol

1. **Anatomy** module
2. **LV function** (RV function) module
3. **Edema** module
4. **EGE / LGE** module

## Report

1. **Dimensions, mass** (corrected for BSA), and **function**
  - LV: EDV, ESV , SV, EF, longitudinal function, mass
  - RV: EDV, ESV, SV, EF, longitudinal function
2. Presence and extent of **fibrosis**
3. Presence of **ventricular thrombus**



*Hypertrophied LV (A) with endocardial fibrosis on LGE (B)*

# Endomyocardial Fibrosis<sup>2/2</sup>

## Key Points

1. **Tropical or non-tropical** (Löffler's syndrome/ eosinophilic cardiomyopathy) eosinophilic endomyocardial fibrosis
2. **Usually increased eosinophil count**
3. **Restrictive LV pattern** (non-dilated ventricles, preserved LV function, restrictive filling pattern, enlarged LA / RA)
4. **Endocardial thickening and scarring**
5. **RV involvement** in about 50% of cases
6. Ventricular **thrombi** are common (EGE images)
7. **LGE** pattern
  - Circumferential sub-endocardial hyperenhancement
  - Rarely affects more than 50% of the wall thickness

## Tips & Tricks

1. Hypereosinophilia and cardiac involvement are also seen in other diseases, i.e. Churg–Strauss syndrome, etc.

# Iron Overload Cardiomyopathy

## Protocol

1. **Anatomy and LV function** (RV function) module
2. **T2★** module

## Report

1. **Dimensions, mass** (corrected for BSA), and **function**
  - LV: EDV, ESV, SV, EF, longitudinal function, mass
  - RV: EDV, ESV, SV, EF, longitudinal function
2. **T2★ values of heart and liver**

## Key Points

1. **Restrictive LV pattern** (non-dilated ventricles, preserved LV function, restrictive filling pattern, enlarged LA / RA)
2. **Diagnostic signs:**
  - LV dysfunction; LV hypertrophy
  - Focal signal loss in native T1- and T2-weighted images
  - Abnormally "dark" liver
2. **Diagnostic T2★ values:**
  - Septal myocardium <20ms; liver tissue ≤6.3ms
3. **Follow-up** of iron loading to guide **chelation therapy**
4. Single cardiac or liver involvement is possible

## Tips & Tricks

1. Assess T2★ values in the septum (less artefacts)

# Tako-Tsubo Cardiomyopathy

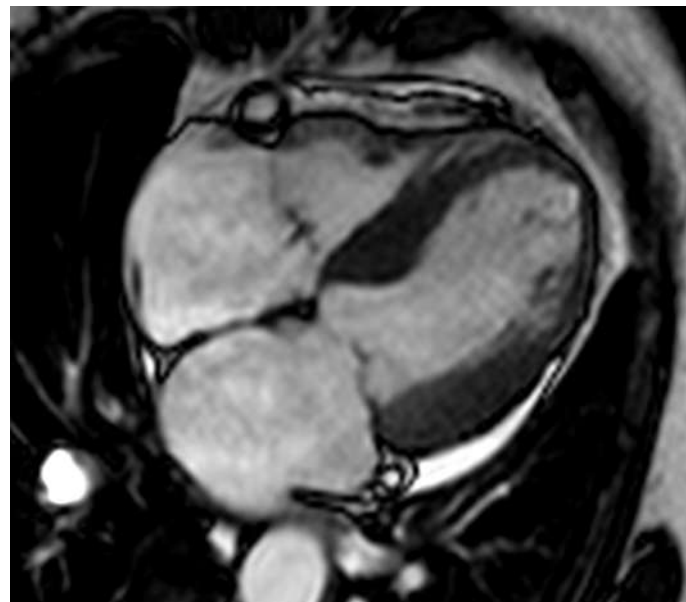
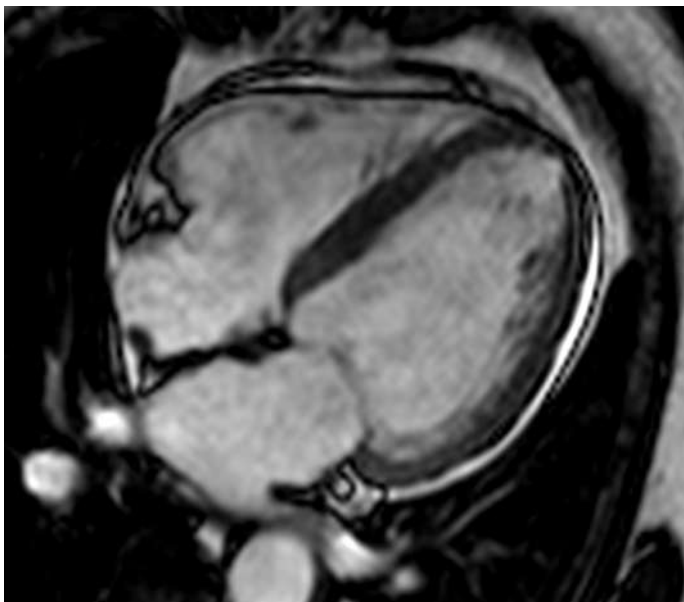
1/2

## Protocol

1. **Anatomy** module
2. **LV function** (RV function) module
3. **Edema** module
4. **LGE** module

## Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF
  - RV: EDV, ESV, SV, EF
  - Regional wall motion abnormalities
2. Presence of **edema**
3. Presence of **LGE**



*Typical Tako-Tsubo pattern of apical ballooning during systole*

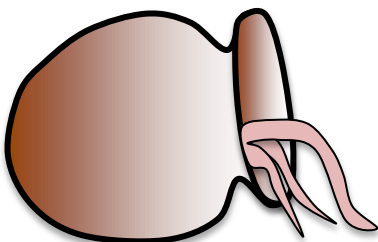
[Index](#)

# Tako-Tsubo Cardiomyopathy

2/2

## Key Points

1. **Transient acute left ventricular dysfunction** due to neurogenic myocardial stunning
2. Usually in **post-menopausal women** and in the setting of **acute emotional or physical stress**
3. Recovery takes place over a few days with full recovery over a few weeks
4. **Typical Tako-Tsubo pattern**
  - Apical akinesia / ballooning
  - Basal / mid-ventricular hyperkinesia
5. **Inverted Tako-Tsubo pattern**
  - Mid-ventricular and basal akinesia / ballooning
  - Apical hyperkinesia
6. Edema in the areas of wall motion abnormalities
7. Classically **NO** signs of LGE
  - Infarct-like hyperenhancement has been described in a few rare cases



[Index](#)

# Pericardial Effusion

## Protocol

1. **Anatomy** module including **T1 and T2 weighting**
2. **LV function** module
3. **Consider:**
  - Tumor module
  - Valve module
  - Real-time free-breathing cine (2 planes)
4. **LGE** module

## Report

1. **Pericardial thickness (normal <3mm)**
2. Presence and extent of **pericardial effusion**
3. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF
  - **Regional wall motion abnormalities**
  - Septal wall motion during normal respiration and breath holding
4. Presence or absence of **atrial or ventricular diastolic collapse**
5. **LGE** in RV, LV and pericardium

# Pericardial Effusion

## Key Points

- Pericardial tamponade is a clinical diagnosis**
  - Even a small and focal effusion can be haemodynamically significant
- Signs of tamponade:**
  - RA / LA collapse, RV / LV collapse
  - Septal shift towards LV during inspiration
- Typical causes of pericardial effusion:**
  - Global: uremic, infectious, myxedema, neoplastic
  - Regional: postoperative, trauma, purulent, cyst

## Tips & Tricks

- Pericardial effusion and pleural effusion are both seen as high signal in cine images, but differ on TSE sequences

| CMR appearance | T1 | Cine    | SI (b-SSFP) |
|----------------|----|---------|-------------|
| Transudate     | ↓  | simple  | ↑           |
| Exudate        | ↓↑ | complex | ↓↑          |
| Hemorrhage     | ↓↑ | complex | ↓↑          |
| Chylous        | ↑↑ | simple  | ↑           |

# Constrictive Pericarditis

## Protocol

1. **Anatomy** module including T1w and T2w
2. **LV / RV function** module
3. **RV function** module (axial and RVOT)
4. **Real-time dynamic respiratory cine**
5. **LGE** module

## Report

1. **Dimensions** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF
  - RV: EDV, ESV, SV, EF
2. Septal motion during normal and dynamic respiration
3. **Pericardial thickening  $\geq 3\text{mm}$**
4. Presence or absence of **RV diastolic collapse**
5. **LGE** enhancement in RV, LV and pericardium



# Constrictive Pericarditis

## Key Points

1. Pericardial **thickening, calcification, scarring** with **preserved LV function**, but **impaired diastolic filling**
2. Constrictive pericarditis is usually a **chronic disease**, but consider transient constriction in inflammation states
3. **Typical findings:**
  - Septal shift towards LV during inspiration
  - Dilated atria
  - Definitive diagnosis requires additional studies
4. Constriction can be **localized** but often leads to an **impairment of biventricular filling**
5. **Common causes:** post cardiac surgery / trauma, irradiation, inflammation, connective tissue disease, idiopathic

## Tips & Tricks

1. Pericardial constriction may be present even with a normal pericardial thickness or patchy thickening
2. Real-time dynamic respiratory sequence in several SA views and in a 4-ch view (paradoxical septal motion is often being limited to one part of the septum)
3. CMR cannot conclusively detect calcification

# Anomalous Coronary Arteries

1/2

## Protocol

### 1. Coronary Artery Imaging Module

## Report

### 1. Origin

- High / low / commissural
- From opposite coronary sinus
- Outside coronary sinuses
- Separate ostium for LAD and CX

### 2. Anomalous course

- Inter-arterial, retro-aortic, ...

### 3. Anomalies of intrinsic coronary arterial anatomy

- Ectasia, aneurysm, hypoplasia, ...
- Intramural coronary artery (muscular bridge)

### 4. Anomalies of coronary termination

### 5. Anomalous collateral vessels

[Index](#)

# Anomalous Coronary Arteries

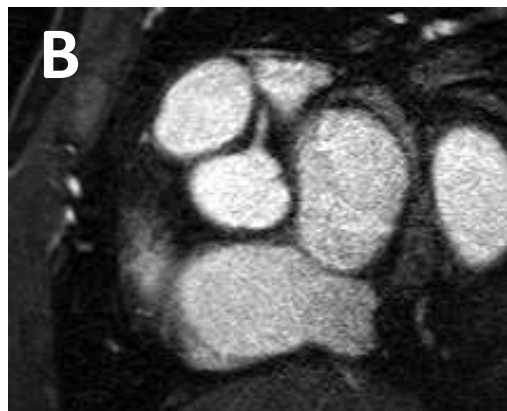
2/2

## Key Points

1. Spatial resolution can be less than that required to assess coronary lumen
2. **Malignant course:**
  - Inter-arterial course between aorta and RVOT, particular left coronary artery from right sinus
3. **Possible causes of ischemia:**
  - Inter-arterial dynamic compression
  - Slit-like origin
  - Myocardial bridging

## Tips & Tricks

1. Optimize image quality:
  - Use isotropic voxel sizes
  - Short acquisition window ( $< 150\text{ms}$ )
2. Consider dobutamine stress to demonstrate a regional wall motion abnormality (if inter-arterial course)



*Left coronary artery arising from the right coronary cusp with a retro-aortic course (A). Normal origin of the RCA (B)*

Index

# Aortic Disease

## Protocol

1. **Anatomy / LV function** module
2. **Phase contrast velocity encoded** module
3. **Sagittal oblique aorta** SSFP cines (candy cane view)
4. **Aortic valve** cine stack
5. **Angiography** module
6. **LGE** module, if relevant (arteritis)

## Report

1. **Dimensions: aortic root**
  - Annulus, Sinuses of Valsalva, ST junction**Dimensions: asc/desc Ao**
  - Asc Ao at level of PA
  - Aortic arch, usually btw. left carotid and subclavian a.
  - Desc Ao at level of PA and diaphragm
2. **Aorta position** (left or right) and **tortuosity**
3. **Atherosclerosis, aneurysm, dissection, inflammation**
4. **Aortic flow**
5. **Associated aortic valvular stenosis or regurgitation**

# Aortic Disease

## Key Points

1. Method of choice for **non-acute aortic diseases**
2. **Standardize protocol:**
  - Measure in **end-diastole** from **cine imaging**, if possible
  - Use **same slice thickness** (<7mm)
  - **Aortic root** (from 2 orthogonal LVOT cines or AV stack)
  - **Asc / desc Ao** (from sagittal oblique aorta cines or alternatively from MRA, if necessary)

## Tips & Tricks

1. Always perform **arterial and venous MRA**
2. **Be aware of following caveats:**
  - LVOT / oblique views are not planed through the centre of the aorta
  - MRA is usually ungated and averages pulsating aortic dimensions (i.e. not end-diastole)
  - Different “windowing” of MRA
  - Angeled view of aorta, if taken from transaxial stack
  - Inclusion of aortic wall, if taken from BB images

# Valvular Heart Disease

## Protocol

1. **Anatomy / LV function / RV function** module
2. **Optimized cine views:**
  - **Slice thickness 5mm**
  - **Two orthogonal** cine stacks through the valve
  - **One cine stack parallel to the annulus**
3. **Phase contrast velocity encoded** module

## Report

1. **Dimensions, mass** (corrected for BSA) and **function**
  - LV: EDV, ESV , SV, EF, mass
  - RV: EDV, ESV, SV, EF
2. **Valve morphology:** leaflets, annulus, chordae
3. Valve **stenosis**
  - Mean / peak valvular gradients
  - Minimum valve area
4. Valve **regurgitation**
  - Regurgitation volume and fraction
  - Estimated orifice area

# Valvular Heart Disease

## Key Points

1. CMR is a reasonable alternative if poor echocardiographic image quality (lower spatial and temporal resolution)
2. **Comprehensive valve assessment:**
  - LV / RV dimensions, mass, fibrosis, and function
  - Forward and regurgitant flow / fraction
  - Mean / peak velocity
  - Jet detection, direction and origin
  - Valve area by direct planimetry
3. **VENC** settings (see “Flow velocity encoding” section)

## Pulse sequence

## Indication

|                        |   |
|------------------------|---|
| SSFP cine              | <ul style="list-style-type: none"><li>• Anatomy and motion</li><li>• LV / RV volumes and function</li></ul> |
| Gradient echo cine     | <ul style="list-style-type: none"><li>• Valve leaflet motion</li><li>• Turbulent flow</li></ul>             |
| Flow velocity encoding | <ul style="list-style-type: none"><li>• Forward / regurgitant volume</li></ul>                              |

# Valvular Heart Disease

## Calculation of regurgitant volume in SINGLE valve disease

|                         |   |
|-------------------------|---|
| Aortic regurgitation    | <ul style="list-style-type: none"> <li>• Regurgitation volume/fraction from phase contrast VENC above aortic valve</li> <li>• Alternatively <math>LV\ SV - RV\ SV</math></li> </ul> |
| Mitral regurgitation    | <ul style="list-style-type: none"> <li>• SV from phase contrast VENC above aortic valve – <math>LV\ SV</math></li> <li>• Alternatively <math>LV\ SV - RV\ SV</math></li> </ul>      |
| Pulmonary regurgitation | <ul style="list-style-type: none"> <li>• Regurgitation volume/fraction from phase contrast VENC above pulmonary valve</li> <li>• <math>RV\ SV - LV\ SV</math></li> </ul>            |
| Tricuspid regurgitation | <ul style="list-style-type: none"> <li>• SV from phase contrast VENC above pulmonary valve – <math>LV\ RV</math></li> <li>• Alternatively <math>RV\ SV - LV\ SV</math></li> </ul>   |

## Limitations

1. **Degree of stenosis or regurgitation – cines imaging**
  - Visual assessment from cine images alone is NOT recommended due to a signal void in turbulent flow
2. **Valve area – planimetry**
  - Correct imaging planes at the tip of the leaflets are fundamental
  - Note that a perfect 2D image plane of a 3D structure is impossible



# Valvular Heart Disease

## Limitations

3. **Flow velocity encoding– forward flow / peak velocity**
  - VENC tends to underestimate velocities due to
    - Partial volume averaging
    - Slice orientation NOT perpendicular to the flow
4. **Flow velocity encoding– regurgitation volume / fraction**
  - Consider volume shift through moving aorta or PA during cardiac cycle
  - Consider regular back-flow into the coronary arteries

## Tips & Tricks

1. Reduce slice thickness to <6mm
2. Consider overlapping of slices
3. Patchy mid-wall fibrosis in conjunction with LV hypertrophy is a prognostic sign in aortic stenosis
4. Aortic regurgitation fraction of >33% predicts symptom development and the need for valve replacement
5. A pulmonary regurgitation fraction of >40% predicts symptom development and the need for valve replacement

# Cardiac Masses

## Protocol

1. **High resolution anatomy** module
2. **Cine imaging in all standard and targeted planes**
3. In 2 optimized orthogonal planes
  - **T1w black blood** images with **fat suppression**
  - **T1w black blood** images **pre and post contrast**
  - **T2w**
  - **First pass myocardial perfusion imaging**
  - **EGE and LGE**

## Report

1. **Location** and 3 dimensional **size**
2. Relation to peri-/ myocardium, valves and chamber
3. **Signal intensity** on T1, T1 fat sat, T2 and STIR images
  - Homogenous or heterogeneous
  - Hyper-/ iso- / hypointense to myocardium or chest wall
4. **Margins:** smooth, irregular, infiltrating, pediculated
5. Specify **motion** with myocardium / pericardium
6. Presence and location of **LGE**
7. Presence of **effusion (pericardial or pleural)**

# Cardiac Masses

## Key Points

1. **Cardiac metastatic lesions are up to 1000 times more common than primary tumors**
2. **Common sources of metastatic lesions**
  - Melanoma, thyroid cancer, breast cancer, renal carcinoma, soft tissue carcinoma, lung cancer, esophageal cancer, hepatocellular carcinoma
3. **Common benign primary tumors (70%)**
  - Myxoma, lipoma, fibroelastoma, fibroma, rhabdomyoma, hemangioma
4. **Common malignant primary tumors (30%)**
  - Angiosarcoma, rhabdomyosarcoma, mesothelioma, fibrosarcoma, lymphoma
5. Consider **pseudotumors**:
  - normal heart structures, thrombus, cyst or vegetation

## Tips & Tricks

1. Very small and highly mobile masses (e.g. vegetation, fibroelastoma) might be missed with CMR
2. CMR allows tissue characterisation, but cannot provide histopathologic information.

# Cardiac Masses

## Tissues Characteristics

| Cardiac Mass                    | T1w*                    | T2w*                    | LGE                        |
|---------------------------------|-------------------------|-------------------------|----------------------------|
| <b>Pseudotumors</b>             |                         |                         |                            |
| <b>Thrombus</b>                 | Low<br>(high if recent) | Low<br>(high if recent) | No uptake†                 |
| <b>Pericardial cyst</b>         | Low                     | High                    | No uptake                  |
| <b>Benign</b>                   |                         |                         |                            |
| <b>Myxoma</b>                   | Isointense              | High                    | Heterogeneous              |
| <b>Lipoma</b>                   | High‡                   | High‡                   | No uptake                  |
| <b>Fibroma</b>                  | Isointense              | Low                     | Hyperenhanced              |
| <b>Rhabdomyoma</b>              | Isointense              | Isointense/high         | No/min. uptake             |
| <b>Malignant</b>                |                         |                         |                            |
| <b>Angiosarcoma</b>             | Heterogenous            | Heterogenous            | Heterogeneous              |
| <b>Rhabdo-myosarcoma</b>        | Isointense              | Hyperintense            | Homogeneous                |
| <b>Undifferentiated sarcoma</b> | Isointense              | Hyperintense            | Heterogeneous/V<br>ariable |
| <b>Lymphoma</b>                 | Isointense              | Isointense              | No/min. uptake             |
| <b>Metastasis §</b>             | Low                     | High                    | Heterogeneous              |

Modified from reference 7). \* T1w and T2w imaging signal is given relative to myocardium; † best seen on early gadolinium enhancement imaging (no uptake) 2 minutes after contrast (Figure 1); ‡ similar to surrounding fat signal and characterized by marked suppression with fat-saturation pre-pulse. § the exception is metastatic melanoma which has a high T1w and a low T2w signal.

[Index](#)

# Common MR Terminology

| Sequence Type                                  | GE                | Philips           | Siemens        |
|--|-------------------|-------------------|----------------|
| Fast Spin Echo                                 | FSE (Fast SE)     | TSE (Turbo SE)    | Turbo SE       |
| Gradient recalled echo                         | GRE               | FFE               | GRE            |
| Spoiled gradient echo                          | SPGR / MPSPGR     | T1 FFE            | FLASH          |
| Balanced gradient echo                         | FIESTA            | bFFE / bTFE       | TrueFISP       |
| Gradient echo – echo planar                    | GRE EPI           | FFE-EPI / TFE-EPI | EPIFI          |
| Contrast enhanced MRA                          |                   | Bolus Trak        | Care Bolus     |
| k-space lines                                  | Views per segment | Turbofactor       | No of segments |
| Parallel imaging: Image-based reconstruction   | ASSET             | SENSE             | mSENSE         |
| Parallel imaging: k-space-based reconstruction | ARC               |                   | GRAPPA         |

# Abbreviations

|               |   |             |  |              |                              |
|---------------|---|-------------|--|--------------|------------------------------|
| <b>2-ch</b>   | 2-chamber view                                  | <b>FOV</b>  | Field of view                                  | <b>ROI</b>   | Region of interest           |
| <b>3-ch</b>   | 3-chamber view                                  | <b>Gd</b>   | gadolinium                                     | <b>R-L</b>   | Right - left                 |
| <b>4-ch</b>   | 4-chamber view                                  | <b>GFR</b>  | Glomerular filtration rate                     | <b>RV</b>    | Right ventricle              |
| <b>AF</b>     | Atrial fibrillation                             | <b>HCM</b>  | Hypertrophic cardiomyopathy                    | <b>SA</b>    | Short axis                   |
| <b>Ao</b>     | Aorta   | <b>HLA</b>  | Horizontal long axis                           | <b>SAECG</b> | Signal averaged ECG          |
| <b>ARVC</b>   | Arrhythmogenic right ventricular cardiomyopathy | <b>HR</b>   | Heart rate                                     | <b>SAM</b>   | Systolic anterior motion     |
| <b>Asc</b>    | Ascending                                       | <b>LAD</b>  | Left anterior descending artery                | <b>SD</b>    | Standard deviation           |
| <b>AV</b>     | Aortic valve                                    | <b>LGE</b>  | Late gadolinium enhancement                    | <b>SI</b>    | Signal intensity             |
| <b>BSA</b>    | Body surface area                               | <b>LV</b>   | Left ventricle                                 | <b>SSFP</b>  | Steady-state free precession |
| <b>b-SSFP</b> | Balanced steady-state free precession           | <b>LVNC</b> | Left ventricular non compaction cardiomyopathy | <b>STIR</b>  | Short TI inversion recovery  |
| <b>CMR</b>    | Cardiac magnetic resonance                      | <b>LVOT</b> | Left ventricular outflow tract                 | <b>SV</b>    | Stroke volume                |
| <b>CX</b>     | Circumflex artery                               | <b>NC/C</b> | Non-compacted / compacted                      | <b>T1w</b>   | T1-weighted                  |
| <b>DCM</b>    | Dilated cardiomyopathy                          | <b>NSVT</b> | Nonsustained ventricular tachycardia           | <b>T2w</b>   | T2-weighted                  |
| <b>Desc</b>   | Descending                                      | <b>MR</b>   | Mitral regurgitation                           | <b>T2★</b>   | T2 star                      |
| <b>EDV</b>    | End-diastolic volume                            | <b>MRA</b>  | Magnetic resonance angiography                 | <b>TI</b>    | Time from inversion          |
| <b>EGE</b>    | Early gadolinium enhancement                    | <b>MVO</b>  | Microvascular obstruction                      | <b>VENC</b>  | Velocity Encoding            |
| <b>EF</b>     | Ejection fraction                               | <b>PA</b>   | Pulmonary artery                               | <b>VES</b>   | Ventricular extra systole    |
| <b>EOA</b>    | Effective orifice area                          | <b>fQRS</b> | Filtered QRS                                   | <b>VLA</b>   | Vertical long axis           |
| <b>EPI</b>    | Echo planar-imaging                             | <b>RA</b>   | Right atrium                                   | <b>WMSI</b>  | Wall motion score index      |
| <b>F-H</b>    | Foot- head                                      | <b>RCA</b>  | Right coronary artery                          |              |                              |

[Index](#)

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**Index**