Guideline for Cardiovascular Magnetic Resonance Imaging from the Korean Society of Cardiovascular Imaging—Part 1: Standardized Protocol

Yeseul Jo1*, JeongJae Kim2*, Chul Hwan Park3, Jae Wook Lee5, Jae Hye Hur6, Dong Hyun Yang6, Bae-Young Lee7, Dong Jin Im8, Su Jin Hong9, Eun Young Kim6, Eun-Ah Park10, Pan Ki Kim8, Hwan Seok Yong11

1 Department of Radiology, Incheon St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Incheon, Korea
2 Department of Radiology, Jeju National University Hospital, Jeju, Korea
3 Department of Radiology and Research Institute of Radiological Science, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Korea
4 Department of Radiology, Soochunhyang University Bucheon Hospital, Bucheon, Korea
5 Department of Radiology, Hanil General Hospital, Seoul, Korea
6 Department of Radiology and Research Institute of Radiology, Asan Medical Center, University of Ulsan College of Medicine, Seoul, Korea
7 Department of Radiology, Eunpyeong St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Seoul, Korea
8 Department of Radiology and Research Institute of Radiological Science, Severance Hospital, Yonsei University College of Medicine, Seoul, Korea
9 Department of Radiology, Hanyang University Guri Hospital, Hanyang University College of Medicine, Guri, Korea
10 Department of Radiology, Seoul National University Hospital, Seoul, Korea
11 Department of Radiology, Korea University Guro Hospital, Seoul, Korea

Cardiac magnetic resonance (CMR) imaging is widely used in many areas of cardiovascular disease assessment. This is a practical, standard CMR protocol for beginners that is designed to be easy to follow and implement. This protocol guideline is based on previously reported CMR guidelines and includes sequence terminology used by vendors, essential MR physics, imaging planes, field strength considerations, MRI-conditional devices, drugs for stress tests, various CMR modules, and disease/symptom-based protocols based on a survey of cardiologists and various appropriate-use criteria. It will be of considerable help in planning and implementing tests. In addressing CMR usage and creating this protocol guideline, we particularly tried to include useful tips to overcome various practical issues and improve CMR imaging. We hope that this document will continue to standardize and simplify a patient-based approach to clinical CMR and contribute to the promotion of public health.

Key words Heart · Cardiovascular · Magnetic resonance imaging · Protocol · Guideline.

INTRODUCTION

Given recent technical advances, cardiac magnetic resonance (CMR) imaging is widely used in many areas of cardiovascular disease assessment [1]. Currently, health insurance in Korea covers CMR for cardiomyopathy and complex congenital heart dis-
ease, though insurance coverage is expected to expand further in 2019, which will probably increase the number of tests compared with the past.

In 2010, the Asian Society of Cardiovascular Imaging published standardized protocols for CMR imaging [2] and in 2013 the Society for Cardiovascular Magnetic Resonance published an updated version of the standardized protocols [3]. Herein, we offer a practical standard CMR protocol for beginners designed to be easy to follow and implement. This protocol guideline is based on previously reported CMR guidelines [1-9] and includes sequence terminology used by vendors, essential MR physics [10-17], imaging planes [2,18], field strength considerations [19-25], MRI-conditional devices [10,20,26-33], drugs for stress tests [34], various CMR modules [16,35-46], and disease/symptom-based protocols [47-58] based on a survey of cardiologists, and various appropriate use criteria. It will be of considerable help in planning and implementing tests. We particularly tried to include useful tips to overcome various practical issues and improve CMR imaging.

By addressing CMR usage and creating this protocol guideline, we are working to continue the standardization and simplification of the patient-based approach to clinical CMR and contribute to the promotion of public health. As CMR imaging technology progresses, we will update this guideline at regular intervals.

This protocol guideline is a joint report of the Korean Society of Cardiovascular Imaging and the Korean Society of Radiology.

GENERAL CONSIDERATIONS

Appropriate criteria
CMR imaging is useful in the diagnosis, stratification, treatment planning, prognosis prediction, and therapeutic effect evaluation of various cardiac diseases [53,59,60]. However, appropriate criteria for disease, ethnicity, socioeconomic status, and the medical insurance system are essential to maximizing its clinical utility [1,61]. In 2014, guidelines for the appropriate use of CMR were published jointly by the Korean Society of Cardiology and the Korean Society of Radiology to guide physicians, imaging specialists, medical associates and patients, and improve the overall performance of the health system [1]. In 2017, expert consensus–based, multimodality appropriate-use criteria for noninvasive cardiac imaging were generated [7]. It is necessary to keep up with the latest appropriate criteria. Various clinical scenarios and optimal CMR protocols are provided at the end of this report.

Patient preparation
Adequate patient preparation before a CMR examination is a mandatory part of good CMR practice. Checklists include MR indication, contraindications, informed consent, fasting, food, and medications [2]. A detailed explanation of the exam and instructions on how to breathe should be provided to the patient. Patients should be comfortable during their MR examination. Obtaining an electrocardiogram (ECG) signal is essential to acquiring appropriate MR images [62]. Patient preparation checklists are provided in Appendix 1.

- General tips for patient preparation
  1) In cases of difficulty with breath holding, arrhythmia, or motion artifacts, consider a single-shot module or free breathing with real-time image acquisition.
  2) In cases of difficulties due to profound respiratory motion, consider an abdominal band to reduce artifacts.
  3) In cases of difficulties due to pericardial effusion and a weak ECG signal, consider peripheral pulse gating.
  4) In cases of difficulties due to ghost artifacts caused by pleural effusion and respiratory difficulties, consider postponing the CMR imaging until after pleural effusion drainage.

Sequence terminology
I. MR sequences at a glance
1. Spin-echo
   A. Use a 90° excitation pulse and a 180° re-focusing pulse (Fig. 1)
   B. Advantages
      1) Robust to off-resonance effects
      2) Flexible to obtain different contrasts using various time of echo (TE) and time of repetition (TR)
   C. Disadvantages
      1) Long acquisition time
      2) Limited temporal resolution
      3) Sensitive to motion and flow
   D. Fast spin-echo (FSE)
      1) Acquisition times shortened by using a multi-echo approach (Fig. 2)
      2) Turbo spin-echo (TSE), FSE, or rapid acquisition

Fig. 1. Spin echo sequence. TR: time of repetition, TE: time of echo, RF: radio frequency.
with relaxation enhancement

2. Gradient-echo (GRE)
   A. Use a low flip angle and gradient pulses
   B. Advantage: faster image acquisition than spin-echo sequences
   C. Disadvantage: low signal to noise ratio (SNR)
   D. Two strategies
      1) Spoiled GRE eliminates the remaining transverse magnetization at the end of the TR (Fig. 3)
         a) Strength: fast acquisition of T1 images after injection of contrast agent
         b) Weakness: saturation of signals when the TR is very short or the flow is very slow
      2) Balanced steady-state free precession (SSFP) refocuses and reuses the remaining transverse magnetization at the end of the TR (Fig. 4).
         a) Strengths
            • Signal strength mostly unaffected by blood flow
            • Rapid image acquisition with a high contrast to noise ratio (CNR)
            • Bright vessel and cardiac chamber without a contrast agent
         b) Weakness: sensitive to the off-resonance effect, causing dark rim artifacts
   E. Popular form of CMR due to short acquisition time (better temporal resolution)

3. Preparation pulses
   A. Inversion pulses
      1) Invert the longitudinal magnetization (Fig. 5A)
      2) After an inversion pulse, longitudinal magnetization starts to recover toward the equilibrium from the inverted point crossing the nulling point.
      3) Can be used to null the signal of selective objects, such as water, fat, blood, or the myocardium
   B. Saturation pulses
      1) Saturate the longitudinal magnetization to null a net magnetization (Fig. 5B)
      2) After a saturation pulse, longitudinal magnetization starts to recover toward the equilibrium.

4. Echo-planar imaging (EPI)
   A. Acquires multiple echoes per excitation
   B. Can be used with TSE or GRE

II. Cardiac MRI sequences (Table 1)
   1. Spin echo: morphology, anatomy, tumor, etc.
   2. Gradient echo: cine, perfusion, late gadolinium enhancement (LGE), MR coronary angiography (MRCA)

![Fig. 2. Fast spin echo sequence. RF: radio frequency.](image)

![Fig. 3. Spoiled gradient echo sequence. TR: time of repetition, TE: time of echo, RF: radio frequency.](image)

![Fig. 4. Balanced steady-state free precession. TR: time of repetition, TE: time of echo, RF: radio frequency.](image)

![Fig. 5. Preparation pulses. A: Inversion recovery pulse. B: Saturation recovery pulse.](image)
A. Spoiled gradient echo: perfusion, LGE, 3D MRCA with 3.0 tesla (T)
B. Balanced SSFP: 2D cine, 3D MRCA with 1.5T
3. Inversion recovery: LGE, T1 mapping (Modified look-locker inversion recovery, MOLLI)
4. Saturation pulse: first-pass perfusion, fat saturation pulses, T1 mapping (Saturation recovery single-shot acquisition, SASHA)

**IMAGING PLANE**

The heart has its own unique axis. CMR should be performed based on the exact planes that meet the purpose of imaging. Even though recent MR machines provide a support system for the CMR imaging plane, clinicians should be familiar with various image axes for accurate imaging interpretation.

**Basic planes**

1. Left ventricle (LV) 2-chamber view, LV 4-chamber view, LV short axis view
   1. Scout imaging or localizer imaging
      A. Multi-stack transaxial, coronal, and sagittal images should be obtained.
   2. Vertical long axis image (Supplementary Fig. 1 in the online-only Data Supplement)
      A. Obtained from the transaxial localizer
         1) Orthogonal to a transaxial scout image at the level of the mitral valve (MV) and tricuspid valve (TV)
         2) Aligned through the apex and center of the MV
   3. Horizontal long axis (Supplementary Fig. 2 in the online-only Data Supplement)
      A. Obtained from vertical long axis images
         1) Orthogonal to vertical long axis images and horizontal long axis image
         2) Perpendicular to the interventricular septum
         3) Covers the whole ventricle from the MV to the LV apex at the diastolic phase
   4. Short axis image (Supplementary Fig. 3 in the online-only Data Supplement)
      A. Obtained from vertical long axis images and horizontal long axis images
         1) Simultaneously orthogonal to vertical long axis images and horizontal long axis images
         2) Perpendicular to the interventricular septum
         3) Covers the whole ventricle from the MV to the LV apex at the diastolic phase
   5. Four-chamber view (Supplementary Fig. 4 in the online-only Data Supplement)
      A. Obtained from vertical long axis images and the short axis view
         1) Orthogonal to the vertical long axis images passing through the LV apex and center of the MV
         2) Aligned through the center of the LV chamber and lower corner of the right ventricle (RV) border on short axis images
   6. Two-chamber view (Supplementary Fig. 5 in the online-only Data Supplement)
      A. Obtained from the 4-chamber view and short axis images
      1) Orthogonal to the 4-chamber view, passing through the LV apex and center of the MV
      2) Passing through the mid-LV chamber in the short axis view, parallel to the ventricular septum

II. LV 3-chamber view and LV outflow tract (LVOT) long axis

1. LV 3-chamber view (Supplementary Fig. 6 in the online-only Data Supplement)
   A. Obtained from the basal short axis view
      1) Parallel to the long axis view
      2) Bisecting MV and apex
      3) Bisecting LVOT

<table>
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<tr>
<th>Table 1. Routine cardiac MRI sequence terminology (vendor)</th>
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<td><strong>Module</strong></td>
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<td>Flow imaging</td>
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2. LVOT long axis view (Supplementary Fig. 7 in the online-only Data Supplement)
   A. Obtained from a true axial scout image
      1. Slice through the aortic root toward the LV apex

III. RV
1. RV short axis (Supplementary Fig. 8 in the online-only Data Supplement)
   A. Obtained from the RV 2-chamber view and 4-chamber view
      1) Orthogonal to the RV 2-chamber view and 4-chamber view
      2) Perpendicular to the interventricular septum
      3) Covers the whole ventricle from the TV to the RV apex at the diastolic phase
2. Right ventricle outflow tract (RVOT) view (Supplementary Fig. 9 in the online-only Data Supplement)
   A. Obtained from an axial scout image
      1) Slice through the center of the main pulmonary artery (MPA) and the RV apex

Specific planes
I. MV view (Supplementary Fig. 10 in the online-only Data Supplement)
   1. Can be obtained from the 2-chamber view and 4-chamber view
      A. Plane is parallel to the MV in the middle of the MV.
II. TV (Supplementary Fig. 11 in the online-only Data Supplement)
   1. Can be obtained from the 2-chamber view and 4-chamber view
      A. Plane is parallel to the TV in the middle of the TV.
III. Aortic valve (AV) view (Supplementary Fig. 12 in the online-only Data Supplement)
   1. Can be obtained from the 3-chamber and LVOT views
      A. Plane is parallel to the AV just above the AV
IV. Pulmonic valve (PV) view
   1. Can be obtained from the two orthogonal RVOT views
      A. Plane is parallel to the PV just above the PV
V. MPA view (Supplementary Fig. 13 in the online-only Data Supplement)
   1. Can be obtained from two orthogonal views, which are parallel to the MPA
2. Plain is perpendicular to the MPA flow
VI. Right pulmonary artery (RPA) and left pulmonary artery (LPA) views (Supplementary Fig. 14 in the online-only Data Supplement)
   1. Plain is perpendicular to the RPA or LPA flow, 1–1.5 cm distal to the MPA bifurcation

SPECIAL CONSIDERATIONS AND PATIENT SAFETY

Field strength considerations
I. The popularity of 3.0T CMR
   1. 3.0T MR applications become increasingly used. Furthermore, many new MR-conditional devices can be used in 3.0T
   2. Advantages
      A. Increased SNR
      B. Increased spatial and/or temporal resolution
   3. Weaknesses
      A. Increase in inhomogeneities of the radio-frequency (RF) excitation field
      B. Increase in the effect of magnetic susceptibility artifacts
      C. Increase in the specific absorption rate (SAR)
II. Safety
   1. No definite safety guideline for performing 3.0T MRI in patients with a cardiac implantation electronic device (CIED)
   2. Careful 3.0T MRI is necessary, including pre-MRI reprogramming of the device monitoring, supervision, and follow-up
III. RF exposure
   1. SAR
      A. RF energy absorbed by the body
      B. Measured in watts per kilogram (W/kg)
      C. Depends on patient size and weight
   2. B1+RMS
      A. Root mean square (RMS) of the time-averaged B1+ magnetic field
      B. Not patient-dependent, but related to pulse sequences
      C. Can be used for implant heating
   3. Ways to reduce SAR and B1+RMS
      A. Higher degrees of parallel imaging
      B. Refocusing flip-angle modulation techniques
         1) Frequency-selective inversion-recovery
         2) Reduction of flip angle
IV. CMR at 3.0T influences the performance of several sequences
   CMR at 3.0T requires protocol optimization, careful shimming, and adjustment of the RF pulses to prevent artifacts.
   1. Improvements: First-pass perfusion, MR angiography, coronary imaging, myocardial tagging, MR spectroscopy, and fat saturation
   2. Equivalent to 1.5T: LGE, flow quantification, and black-blood imaging
   3. Considerable limitation: SSFP
   4. Main challenges: B0 inhomogeneities, B1 inhomogeneities, off-resonance band artifacts, susceptibility effects,
and chemical shift artifacts

**Devices**

I. CIED in MRI machines
1. Common clinical situation
2. Historically regarded as a contraindication but no longer an absolute contraindication to MRI
3. Adverse interactions
   A. Device failure, lead failure, heating, force, torque
   B. Magnetic susceptibility artifacts (Fig. 6)
4. MR-conditional CIED
   A. CMR is possible under the adequate workflow protocol.
   B. Consider the device, device insertion duration, scan region, battery power, MR system, and sequences
   C. Need cooperation between cardiologists and radiologists
   D. MR safety information on the websites
      3) MRI safety.com: http://www.mrisafety.com
5. MR-non-conditional CIED
   A. Not recommended

B. Can be performed at 1.5T under the supervision of a physician and radiologist, if benefits outweigh the overwhelming risks

6. MR-conditional CIED checklists are provided in Appendix 2

7. Recommendations to minimize artifacts from a CIED
   A. Sufficient distance (>6 cm) between the CIED pulse generator and the heart or CIED pulse generator in the right chest wall
   B. Spoiled GRE sequence with wide bandwidth rather than SSFP
   C. Change the center offset frequency using the SSFP sequence.
   D. Long-axis plane for the mid to apical LV and short-axis plane for the LV base

**Drugs**

I. Gadolinium-based MRI contrast agents
1. Shorten the relaxation times of nuclei within the body
2. Nephrogenic systemic fibrosis
   A. A rare and serious syndrome
   B. Fibrosis of skin, joints, eyes, and internal organs
   C. High-risk patients
      1) Chronic kidney disease stages 4 and 5 (glomerular filtration rate <30 mL/min/1.73 m²)

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![Fig. 6. Magnetic susceptibility artifact by cardiac implantable electronic device. Cine image (A) and late gadolinium enhancement image (B) show significant magnetic susceptibility artifact caused by the cardiac implantable electronic device.](image-url)
2) Acute renal failure or chronic liver disease

D. The gadolinium-containing contrast agents can be divided into three risk groups
   1) Safest: macrocyclic structure
      a) Gadoterate, gadobutrol, and gadoteridol
   2) Intermediate: an ionic linear structure
      a) Gadopentetate, gadobenate, gadoxetate, and gadofosveset
   3) Most risky: linear non-ionic structure
      a) Gadodiamide and gadoversetamide

3. Brain deposition
   A. Gadolinium can lodge in the deep nuclei of the brain, especially when injected repeatedly
   B. Macrocyclic agents might accumulate less than linear agents
   C. No reliable data about clinical effects or significance

4. The Korean Food and Drug Administration recommends the use of a gadolinium-based MRI contrast agent with a macrocyclic structure. In Korea, the supply of gadopentetate, gadodiamide, and gadoversetamide has been discontinued. In the EU, the use of gadolinium-based MRI contrast agents with a linear structure is prohibited.

II. Pharmacologic stressors and vasodilators
1. Dobutamine
   A. Inotrope
      1) Directly stimulates β1 receptors in the sympathetic nervous system
      2) Increases myocardial oxygen demand → promotes myocardial ischemia
      3) Increases heart rate, blood pressure, and contractility similar to exercise
      4) Half-life: approximately 2 minutes
      5) Typical maximum dose: 40 µg/kg/min
   B. Contraindications
      1) Unstable angina pectoris
      2) Severe systemic arterial hypertension (≥220/120 mm Hg)
      3) Severe aortic stenosis
      4) Obstructive hypertrophic cardiomyopathy with hemodynamic significance
      5) Uncontrolled cardiac arrhythmias
      6) Uncontrolled congestive heart failure
      7) Endocarditis
      8) Myocarditis or pericarditis
      9) Family history of sudden cardiac death
      10) Aortic dissection
      11) High-grade aortic aneurysm
      12) Mobile thrombus in LV or left atrium
   2. Adenosine, dipyridamole, and regadenoson
      A. Vasodilators
      1) Promote systemic arterial vasodilation to bring about a super-physiologic increase in vascular flow
      2) Emphasize the difference between normal coronary arteries (which can dilate) and a stenosed coronary artery (which is already maximally dilated)
      B. Adenosine
         1) Acts on the vascular smooth muscle surface to cause vasodilation
         2) Binds non-selectively to A1, A2A, A2B, and A3
            a) Activation of A2A → coronary vasodilation
            b) Activation of A1, A2B, and A3 → bronchospasm, atrioventricular block, etc. (unwanted side effects)
         3) Dose: 0.14 mg/kg/min
         4) Half-life: 10–30 seconds
         5) Competitive inhibitors of adenosine
            a) Aminophylline, theophylline, and other xanthine-containing foods, such as coffee, tea, cocoa products, and soft drinks
            b) Should be restricted for approximately 24 hours prior to the study
         6) Contraindications
            a) Hypersensitivity to adenosine
            b) Bronchoconstriction or bronchospastic disease
            c) 2nd or 3rd degree atrioventricular block
            d) Significant sinus bradycardia (resting heart rate <45 bpm)
            e) Systolic blood pressure less than 90 mm Hg
            f) Severe arterial hypertension
            g) Myocardial infarction within 3 days
            h) Disease requiring the regular use of inhalers for asthma, sinus arrhythmia, stenotic valvular disease, or carotid artery stenosis
      7) Antidote: intravenous (IV) aminophylline
   C. Dipyridamole
      1) Inhibits the cellular uptake and metabolism of adenosine → increases the interstitial adenosine concentration
   D. Regadenoson
      1) Higher selectively for A2A activation than adenosine
      2) Dose: 0.4 mg single injection
      3) Half-life: 2–3 minutes
      4) Precautions
         a) Restriction of products containing xanthine for 24–36 hours before the test
         b) No caffeine for at least 6 hours, but ideally 24 hours, before the test
         c) No tobacco for 4 hours before the test
   3. Please use checklists to ensure patient safety and image quality [2].
EXAM MODULES

Cine imaging
I. Purpose: to assess cardiac wall motion
II. Sequences
1. Balanced SSFP or spoiled GRE
2. Real time cine (patients with poor breath holding or arrhythmia)
III. Image parameters
1. ECG gating: retrospective rather than prospective
2. Slice thickness: 6–8 mm (no gap)
3. Temporal resolution: ≤45 ms between phases
4. Acquired time frames: 25–30 frames/R-R interval
5. Parallel imaging: used as available
IV. Tips
1. Uses retrospective gating rather than prospective triggering
   A. Acquisition of the entire cardiac cycle
   B. Can select the appropriate segment
   C. Arrhythmia rejection
2. Banding artifacts (Fig. 7)
   A. More severe on 3.0T MR than 1.5T due to B0 field inhomogeneity
   B. Solutions
      1) Shimming
         a) Volume shim centered on the left ventricle
         b) During shimming, minimize motion (e.g., breathe shallowly)
      2) Shortest TR
      3) The center frequency is aligned closely with the water resonance frequency
V. Dobutamine stress test
1. To evaluate the viability and contractile reserve
2. Avoid beta-blockers and nitrates
3. Infusion dose
   A. Start: 10 µg/kg/min
   B. Increase: 10 µg/kg/min every 3 min
   C. Infusion time: 5–10 min
   D. Target heart rate: 85% of (220 - age)
   E. Option: If heart rate response is poor, add 0.3 mg of atropine in fractional doses of up to 2 mg
   1) Contraindications for atropine
      a) Advanced heart block
      b) Glaucoma
      c) Pyloric stenosis
      d) Obstructive uropathy
      e) Myasthenia gravis
4. Caution: indications for stopping the test
   A. New wall motion abnormality or wall thickening abnormality
   B. Systolic blood pressure >240 mm Hg or diastolic blood pressure >120 mm Hg
   C. Systolic blood pressure decrease of 20 mm Hg or greater below baseline
   D. Severe chest pain or other intractable symptoms
   E. Complex cardiac arrhythmias or reaching peak heart rate

Perfusion imaging
I. Purpose: to evaluate myocardial perfusion (ischemia)
II. Sequences: saturation-recovery imaging with GRE-EPI hybrid, GRE, or SSFP readout (Fig. 8)

Fig. 7. Banding artifact. Cine image of 2-chamber right ventricle view shows severe banding artifact which hampers appropriate interpretation (A). After cardiac shimming and time of repetition adjustment, the image quality is improved without the banding artifact (B).
III. Image parameters
1. Slice thickness: 8–10 mm
2. In-plane resolution: <3 mm
3. Two-fold acceleration and readout temporal resolution: <100–125 ms (shorter if available)
4. Parallel imaging (if available)

IV. Scan protocol
1. Scout imaging: same as LV structure and function
2. Stress myocardial perfusion
   A. Slices: at least three short-axis slices per heartbeat at the LV base, mid, and apical levels
      1) To reduce motion artifacts, obtain the apical slice first and the basal slice last during the cardiac cycle
      2) If possible, add one slice to the 4-chamber or 2-chamber views
   B. Do a rehearsal scan without contrast or vasodilator injection (dry run) to check the image quality and correct the parameters
      1) At the end expiration
      2) 5–10 phases to check
   C. Vasodilator infusion: adenosine stress perfusion
      1) Place two intravenous (IV) catheters in each arm
         a) 20G IV catheter for contrast material injection
         b) 20–22G IV catheter for adenosine infusion
      2) Adenosine infusion
         a) 0.14 mg/kg/min
         b) 4–6 min continuous infusion
         c) When the gadolinium has passed through the LV myocardium, the adenosine infusion should be stopped after imaging 50–60 heartbeats
         d) Please check the drug section (adenosine, dipyridamole, and regadenoson)
      3) Antidote: aminophylline, 125 mg in 50 mL normal saline by IV infusion for 5–6 minutes
         a) Use if chest pain or shortness of breath occurs.
      D. Gadolinium contrast agent
         1) 0.05–0.1 mmol/kg, 3–7 mL/s during the last minute of adenosine infusion
         2) Saline flush: at least 30 mL (3–7 mL/s)
      E. Breath-hold: during the early phases of contrast infusion, before contrast reaches the LV cavity
      F. Readout for 40–60 heartbeats, in which time contrast will have passed through the LV myocardium
3. LV function mode between a stress test and resting test while waiting for contrast washout
4. Rest myocardial perfusion imaging
   A. After a washout period of at least 10 min for the gadolinium from the stress perfusion imaging to pass
   B. Same protocol for stress perfusion (except for vasodilator infusion)
5. LGE

V. Tips
1. Dark rim artifact (Fig. 9)
   A. Most common artifact with the perfusion module
   B. Commonly occurs at the subendocardial border
   C. Can be confused with a perfusion defect
   D. Related factors
      1) Limited spatial resolution
      2) Cardiac motion
      3) Partial volume artifact
      4) Higher concentration of the contrast agent
   E. Solutions
1) Low dose of contrast medium
2) High spatial resolution (in the phase encoding direction)
3) Thin slice thickness
4) High field strength
5) Fast imaging

2. Use the checklists for the adenosine stress test [2]

LGE imaging
I. Purpose: to evaluate myocardial viability
II. Sequences (Fig. 10)
1. Patients with sufficient respiratory support: 2D segmented inversion recovery GRE or SSFP, phase-sensitive inversion-recovery (PSIR), and 3D sequences
2. Patients with poor breath holding: single-shot imaging (SSFP readout)

III. Image parameters
1. Acquisition duration per R-R interval: below 200 ms
2. Slice thickness and slices at the identical location: same as for cine imaging (short- and long-axis views)

IV. Scan protocol
1. Axis: same as cine imaging
2. Contrast medium injection: 0.1–0.2 mmol/kg gadolinium
3. Wait at least 10 minutes after administration
4. Set inversion time to null normal myocardium using time of inversion (TI) map

V. Tips
1. If the inversion time is inaccurate, use the PSIR sequences.
2. If the image quality is poor due to motion artifacts or poor breath holding, use single shot LGE (Fig. 11)

3. Ghosting artifacts with long T1 tissue
   A. Pericardial effusion, cerebrospinal fluid, and the silicon bag can cause ghosting artifacts.
      1) This ghosting artifact is not a motion artifact.
      2) Solution: single shot LGE

Flow imaging
I. Purpose: to measure flow velocity and volume
1. Measure pulmonary blood flow (Qp)
2. Measure systemic blood flow (Qs)
3. Pulmonary-to-systemic flow ratio (Qp:Qs)
4. Calculate regurgitant fractions
5. Calculate the valve area
6. Calculate the aortopulmonary collateral flow

II. Sequences
1. Velocity-encoded cine gradient echo
   A. Magnitude images provide anatomic information
   B. Phase images provide velocity information

III. Image parameters
1. ECG gating: retrospective gating includes the entire diastolic portion of the cardiac cycle
2. Slice thickness: 5–8 mm
3. In-plane resolution: at least 1/10 of the vessel diameter, 1.3–2.0 mm
4. Velocity encoding sensitivity (VENC): adapted to the expected velocities
5. Acquired time frames: 25–30 frames/R-R interval
6. Average number of signals: 2–3

IV. Tips

Fig. 9. Dark rim artifact during perfusion magnetic resonance imaging. Subendocardial dark rims are seen at the basal septum on both stress (A) and rest (B) perfusion images.
1. Plane: perpendicular to the vessel and distal to valve leaflet tips of interest
   A. Deviations of more than 15° cause significant errors in the peak velocity and flow rate.
   2. VENC (Fig. 12)
   A. Adjust 10–20% higher than expected peak velocities
   B. A too-low velocity causes aliasing
   C. A too-high velocity causes noise and inaccurate measurements.
   D. Usual peak velocities
      1) Main pulmonary artery: 60–120 cm/s
      2) Right/left pulmonary artery: 60–120 cm/s
      3) Ascending aorta: 100–160 cm/s
   3. TE: as short as possible
   4. Spatial resolution
      A. Sufficient spatial resolution to prevent significant partial volume effects
      B. Recommendation: more than 3 pixels across the diameter or more than 8 pixels in the cross-section of the region of interest

---

**Fig. 10. LGE sequences.** Sequences of LGE with magnitude inversion recovery (A) and PSIR (B). LGE: late gadolinium enhancement, PSIR: phase sensitive inversion recovery, TD: trigger delay, TI: inversion time, FA: flip angle.
5. Temporal resolution
   A. Sufficient temporal resolution to prevent a smooth pulsatile flow curve and cause inaccuracies
   B. Recommendation: acquire a minimum of 20 non-interpolated images during the cardiac cycle

Morphology imaging
   I. Purpose: to delineate anatomic structures
   II. Sequences
      1. Spin-echo sequence: FSE or TSE techniques
         A. TSE black blood preparation pulses: two 180° RF inversion pulses followed by a delay before the spin echo pulse sequence

---

Fig. 11. Better image quality of single shot late gadolinium enhancement (LGE) in a patient with poor breath holding. LGE image with two-dimensional segmented inversion recovery gradient-echo (A) in a patient with poor breath holding shows poor image quality with significant motion artifact. Single shot LGE (B) shows much improved image quality with less motion artifact.

Fig. 12. Velocity encoding sensitivity (VENC) effect on phase-contrast flow imaging. Very low VENC factor (A, VENC factor=90 cm/s) causes aliasing on the phase contrast flow image of the ascending aorta. The usual peak of the ascending aorta is 100–160 cm/s (B, VENC factor=130 cm/s; C, VENC factor=160 cm/s). Very high VENC factor (D, VENC factor=190 cm/s) causes noise and inaccurate measurement.
B. Strength: high CNR
C. Weakness: sensitive to motion artifacts
2. Half-Fourier acquisition single-shot turbo spin-echo (HASTE)
3. Dark blood GRE: less sensitive to artifacts or motion

III. Image parameters
1. Slice thickness: 6–8 mm (no gap)
2. Black blood inversion preparation pulse: 20 mm
3. Echo train length: 15–20

IV. Tips
1. Breath-hold, pre-contrast segmented FSE or TSE imaging with double inversion recovery: sequence with good CNR preferred
2. If motion artifact is significant with FSE or TSE, try HASTE or dark blood GRE
3. Optimizing readout time by acquiring multiple images throughout the diastole is essential to minimizing dropout artifacts

Fig. 13. T1 mapping sequences. T1 mapping sequences with modified look-locker inversion recovery (MOLLI) (A) and saturation recovery single-shot acquisition (SASHA) (B).
A. T2 weighted image (T2WI) is prone to be inhomogeneous with readout time changes, which could hamper the appropriate interpretation
B. T2 map could be better than T2WI for evaluating myocardial edema

**Tissue characterization: T1 mapping**

I. Purpose: to evaluate the absolute T1 value of the myocardium

II. Sequences (Fig. 13)

1. Inversion recovery-based protocol
   A. MOLLI or shortened MOLLI
   B. Strength
   1) Good SNR, good image quality
   2) Better precision than SASHA
   C. Weakness
   1) Sensitive to heart rate

2. Saturation recovery-based protocol
   A. SASHA
   B. Strength
   1) Better accuracy than MOLLI
   2) Insensitive to heart rate
   C. Weakness
   1) High image noise

3. Combined: saturation pulse–prepared, heart-rate-independent inversion recovery (SAPPHIRE) sequence

III. Image parameters

1. Slice thickness: 6–8 mm
2. In-plane resolution: less than 2 mm
3. Acquisition time
   A. 9–17 heartbeats
   B. Various, depending on the used T1 mapping sequences

IV. Tips

1. Need site-specific normative values
   A. Normative mapping values can be affected by various factors, including field strength, vendor, sequence, contrast regime, and patient population (age/sex)
   1) Reported normal values for native T1 of normal myocardium
      a) 1.5T: 930–1052 ms
      b) 3.0T: 1052–1158 ms

2. Native T1 and extracellular volume (ECV) fraction: preferred to partition coefficient and post contrast T1

3. Contrast media injection
   A. Bolus-only protocol for ECV measurement
      1) Sufficient for most myocardial ECV applications
      2) A delay of at least 15 minutes is recommended for dynamic equilibrium

V. Scan protocol (Fig. 14)

1. Native T1 mapping is performed prior to contrast.
2. Post-contrast T1 mapping: perform >15 min after administration of contrast agent
3. Blood sampling is required for ECV assessment

**Tissue characterization: T2 mapping**

I. Purpose: to evaluate the absolute T2 value of the myocardium

II. Sequences

1. Single shot SSFP: T2-prepared single-shot SSFP sequence acquired with different T2 prep times

---

**Fig. 14.** Native T1 map and post T1 map. Native T1 map image (A) acquired prior to contrast injection provides pixel-wise absolute native T1 values. Post T1 map image (B) acquired after the administration of the contrast agent provides pixel-wise post T1 values. Using native T1 values and post T1 values of the myocardium and blood cavity and hematocrit value, the extracellular volume fraction of the myocardium could be calculated.
III. Image parameters
1. Slice thickness: 6–8 mm
2. In-plane resolution: less than 2 mm
3. Acquisition time: 7 R-R
IV. Tips
1. Obtain prior to contrast administration

Tissue characterization: T2* mapping
I. Purpose
1. To evaluate the absolute T2* value of the myocardium
2. To assess cardiac iron deposition in diseases such as thalassemia major
II. Sequences
1. Single shot SSFP
III. Image parameters
1. Slice thickness: 8–10 mm
2. In-plane resolution: less than 2 mm
IV. Tips
1. Obtain prior to contrast administration

Coronary angiography
I. Purpose: to evaluate coronary artery disease
II. Sequences
1. 1.5T
   A. SSFP MRCA sequences without injection of gadolinium-based contrast agent
   2. 3.0T
      A. Gradient-echo sequence with the administration of contrast medium
      B. SSFP MRCA—not appropriate due to severe banding artifacts
      C. T2 prep-MRCA without contrast enhancement
III. Advantages compared to coronary computed tomography angiography
1. No ionizing radiation
2. No iodine contrast agent
3. Excellent temporal resolution
4. Evaluation of heavily calcified plaques
IV. Image parameters
1. Slice thickness: 1–1.5 mm
2. In-plane resolution: 1.0 mm or less
3. Slices
   A. 50–80 slices to encompass vessels of interest
   B. Adjust trigger delay and acquisition window according to the coronary period
   C. Navigator placed over the right hemidiaphragm
V. Tips
1. Whole heart MRCA: respiratory gating and ECG gating
2. Vessel targeted MRCA: can reduce imaging time
3. Regular (slow) heartbeat: use mid-diastolic phase.

Table 2. Disease/symptom-based protocol, based on a questionnaire

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<th>Cine, RV</th>
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Each score given is the median. A: appropriate (7–9); U: unknown (4–6); I: inappropriate (1–3). LV: left ventricle, RV: right ventricle, LGE: late gadolinium enhancement, VENC: velocity encoding sensitivity
4. Arrhythmia or tachycardia: use the systolic phase.
5. Continuous infusion of contrast medium (3.0T): can improve SNR
VI. Scan protocol
1. LV structure and function module
2. Horizontal long axis images for the imaging period of the right coronary artery
3. MRCA sequence
4. Transaxial slices if desired

Disease/symptom-based protocol
Eighteen expert panel members, 9 cardiologists and 9 radiologists who were familiar with cardiac MRI, completed a questionnaire about the appropriate protocol for a variety of clinical situations (Table 2). To assess each clinical situation, they gave 9 points if a pulse sequence was necessary and 1 point if it was not necessary. If more than half of the panelists in one group voted in the same manner [A: appropriate (7–9); U: unknown (4–6); I: inappropiate (1–3)], it was deemed a consensus. Items without consensus in the first survey reappeared in the second survey, after which consensus was reached on all items. Each score given is the median (Table 2).

Supplementary Materials
The online-only Data Supplement is available with this article at https://doi.org/10.22468/cvia.2019.00108.

Conflicts of Interest
The authors have no potential conflicts of interest to disclose.

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REFERENCES


## Appendix 1. Checklists for patient preparation

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<th>Exam Date :</th>
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### Contraindications
- MR examination
- Stress study
- Contrast administration, if needed.

### Informed consent
- MR examination
- Contrast administration, if needed.

### Fasting before examination (not mandatory, but is often recommended)

### Stop the intake of foods and medications
- Dobutamine: β-blockers and nitrates.
- Adenosine/regadenoson: caffeine (coffee, tea, foods or beverages e.g. chocolate, caffeinated medications), theophylline, dipyridamole

### Breath instruction

### Earplugs or headset

### Optimal attachment of electrodes gating.

### Set the best comfortable position for the patient
- Lift arms over the patients’ head
- Side or crossed over the chest if the patient cannot tolerate
### Appendix 2. Checklists for MR-conditional CIED

<table>
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<th>ID</th>
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#### Pre-procedure

- **Type of CIED**
- **Conditionality of CIED**
  - Yes
  - No

- **Duration of CIED implantation**
  - Need more than 6 weeks implantation duration

- **Abandoned lead or fractured lead**

- **Informed consent**

- **Pre-MRI evaluation and reprogram**
  - Pacemaker dependency
  - If Yes → asynchronous pacing mode needed
  - If No → sensing only mode needed

#### During procedure

- **MR sequence and SAR**
  - SAR less than 2.0 W/kg

- **Monitoring devices**
  - ECG, pulse rate, blood pressure, oxymetry

#### Post-procedure

- **Post-MRI evaluation and reprogram**

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CIED: cardiac implantation electronic device, SAR: specific absorption rate, ECG: electrocardiogram