Coronary MRA

Magnetic resonance imaging (MRI) is an attractive screening technique for coronary artery disease because it is noninvasive, does not require ionizing radiation or iodinated contrast media, can provide hemodynamic information in addition to vascular morphology, can provide three-dimensional structural data, and may be significantly less expensive than conventional angiography. Three steady-state free precession (SSFP) coronary MRA techniques are presented here: a free-breathing navigator-gated whole-heart technique (Weber et al., 2003), a free-breathing navigator-gated targeted technique, and a breath-hold method (Deshpande et al., 2001). The parameters given here are derived from experience at 1.5 T and may need to be altered depending on the field strength and the equipment manufacturer.

STRATEGIC PLANNING

A number of factors determine what the appropriate imaging protocol should be, whether breath-hold or free-breathing, whole-heart or targeted. Although this choice will also largely be determined by experience, we outline some common questions to consider before choosing a protocol (see Table A11.5.1).

Table A11.5.1 Questions to Consider Before Choosing an MRA Protocol

Condition	Free-breathing whole heart protocol (Basic Protocol)	Free-breathing targeted protocol (Alternate Protocol 1)	Breath-holding protocol (Alternate Protocol 2)
Patient cannot tolerate ~20-24 sec breath-holds	√	√	
Patient can hold still over long scans, ~10 min	√		
Patient unable to hold still over long scans, ~10 min		√	√
Irregular heartbeat			√

RESPIRATORY-GATED WHOLE-HEART IMAGING USING A STEADY-STATE FREE PRECESSION SEQUENCE

BASIC PROTOCOL

Coronary MRA may be performed as a navigator-gated free breathing protocol or a breath-hold protocol. There are advantages and disadvantages to each approach. While breath-hold imaging uses many short scans, a free breathing approach uses one or two long scans to acquire the same data. Breath-hold imaging may not be well tolerated by patients with severe heart disease, and the free-breathing protocol is therefore presented here as the Basic Protocol. Free breathing with motion correction using navigator echoes relieves the constraint on imaging time. Higher spatial resolution can be achieved using this approach as compared to the breath-hold protocol, but at the expense of imaging time. The entire protocol takes about 1 hr. With experience, this time may be cut down to approximately 30 to 35 min.

Table A11.5.2 lists the hardware necessary to perform the procedure, along with appropriate parameters. The available gradient strength will depend on the scanner, and the

Contributed by Vibhas S. Deshpande and Debiao Li
Current Protocols in Magnetic Resonance Imaging (2008) A11.5.1-A11.5.22

Table A11.5.2 Equipment Parameters for Coronary MRA

Coil type	Cardiac phased array surface coil
Gradient coil strength	40 mTm (at least greater than or equal to 30 mTm)
Cardiac gating	Yes
Peripheral gating	For safety only
Respiratory gating	No external equipment is required but a sequence is used in the Basic Protocol and Alternate Protocol 1
Respirator	If required by patient
Oxygen	If required by patient
Use of contrast agents	No

echo times given in other tables below may vary accordingly (the lower the gradient strength, the longer the echo time for a particular scan).

NOTE: Be sure that technologists and nurses have immediate access to any emergency equipment that may be relevant to a given study, or that may be needed for a particular patient, such as crash carts or oxygen.

Set up patient and equipment

1. Interview (screen) the patient to ensure that he or she has no contraindications such as cardiac pacemakers or other implants containing ferromagnetic materials that may be problematic for patient safety or good image acquisition. Also be sure to find out if the patient has any health conditions that may require the presence of special emergency equipment during the scanning procedure, or necessitate any other precautions.

   Generally, standard screening forms (APPENDIX 1) are used for all patients scanned in a magnetic resonance system.

   The presence of any ferromagnetic metals may be a health hazard to the patient when he or she is inside the magnet, and will also affect the imaging. If in doubt as to the exact composition of the items, it is best to exclude patients with any metal implants; see Shellock (2001) for discussion of what implants may be safely scanned using magnetic resonance.

   Patients may be accompanied into the magnet room by a friend or family member, who can sit in the room during the scan and comfort the patient as needed. This companion must be screened as well to ensure the absence of loose metal objects on the body or clothing, as well as other items as described above.

2. If the procedure is a research protocol, have the patient sign any necessary consent forms.

3. Have the patient remove all jewelry and change into a gown to eliminate any metal that might be found in clothing.

4. Have the patient wash off any mascara and other makeup to avoid local tissue heating.

5. Inform the patient about what will occur during the procedure, what he or she will experience while in the magnet, and how to behave, including the following:

   a. If earplugs, earphones or headphones are used to protect the ears from the loud sounds produced by the gradients, the patient will be asked to wear one of these devices, but will be able to communicate with you at any time during the imaging.

b. The patient may be given a safety squeeze-bulb or similar equipment to request assistance at any time (demonstrate how this works).

c. Nevertheless, the patient may call out at any time if he or she feels it necessary.

d. In the interest of safety, inform the patient not to cross his/her arms or legs during a scan.

6. Have the patient mount onto the table. Either before or right after the patient lies down, set up the ECG triggering and any other monitoring equipment that is to be used.

7. If needed, place a pillow or other support under the knees to make the patient more comfortable.

8. Place a cardiac phased array coil over the patient on the chest, with the coil centered on a line joining the nipples and slightly offset to the left side of the chest. Use the centering light to position the patient with the horizontal line coinciding with the center of the coil.

   Once this step has been performed, so long as the patient does not move on the table, the table itself can be moved and then returned to the same position as before without jeopardizing the positioning of one scan relative to another.

9. If the patient is unable to hold still, provide an appropriate sedative.

Sequence 1: Rapid three-plane positioning pilot scan

10. To acquire the scout scans in three dimensions, run the system's pilot (or scout) scan using the imaging sequence and parameters given in Table A11.5.3. Please

Table A11.5.3 Primary Clinical Imaging Parameters for Sequence 1 (3-Plane Scout Scan)

Patient position	Supine
Scan type	Single-shot 2-D SSFP (different manufacturers may have different standard protocols)
Imaging plane (orientation)	Sagittal, coronal, and transverse (triple plane orthogonal scouts)
Central slice or volume center	Laser light centered on heart
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Repeat time (T_R)	As short as possible (e.g., 3 msec)
Delay time (T_D)	Data acquisition in diastole (e.g., 300 msec)
Flip angle (FA)	70°
Fields of view (FOV_x, FOV_y)	400 mm, 400 mm
Resolution (Δx, Δy)	3.12 mm, 3.12 mm
Number of data points collected (N_x, N_y)	128, 128
Slice thickness (Δz)	8 mm
Number of slices	3 per orientation
Slice gap	32 mm (400%)
Number of acquisitions (N_{acq})	1
ECG gating	Yes
Scan time	9 cardiac cycles

refer to manufacturer specifications for standard default settings, and swap as necessary.

This sequence usually consists of three orthogonal planes to allow localization. The images are also used later to determine where to place the following localization scans.

Sequence 2: Scout scan for setting up the respiratory-gating scan

11. Repeat the above scout scan only in the transverse plane. Prescribe the slice group based on the coronal scout images (acquired from step 10) such that the region of the dome of the liver and its surroundings are covered. Run the sequence according to parameters given in Table A11.5.4.

Sequence 3: Localizer for 4-chamber view

12. Acquire a 4-chamber orientation according to an illustration of the steps shown in Figure A11.5.1 and listed below.

The reader is also encouraged to see Figures A11.4.1 and A11.4.2 in UNIT A11.4.

13. Use a single-slice 2D SSFP localizer scan (similar to the sequence in step 11, but with one single slice) to get a 2-chamber view. Set up the parameters for this scan according to Table A11.5.4, with the exception that the number of slices is changed to 1, the orientation of the slice is oblique coronal, and the scan time is one heartbeat. To position this scan, bring up a transverse scout image (obtained from step 11) of the heart that shows a cross-section of the left ventricle. Prescribe the intended slice along the long axis of the left ventricle. Start the scan.

14. Repeat the sequence to get a 4-chamber view. Bring up the resulting image from the previous scan (step 13) and prescribe the intended slice along the long axis of the left ventricle. Start the scan.

Table A11.5.4 Primary Clinical Imaging Parameters for Sequence 2 (Transverse Scout Scan)

Patient position	Supine
Scan type	Single-shot non-triggered 2D SSFP (different manufacturers may have different standard protocols)
Imaging plane (orientation)	Transverse
Central slice or volume center	Dome of the liver
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Repeat time (T_R)	As short as possible (e.g., 3 msec)
Delay time (T_D)	NA (not triggered)
Flip angle (FA)	70°
Fields of view (FOV_x, FOV_y)	400 mm, 400 mm
Resolution (Δx, Δy)	3.12 mm, 3.12 mm
Number of data points collected (N_x, N_y)	128, 128
Slice thickness (Δz)	8 mm
Number of slices	10
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
ECG gating	Not needed for this sequence
Scan time	~5 sec

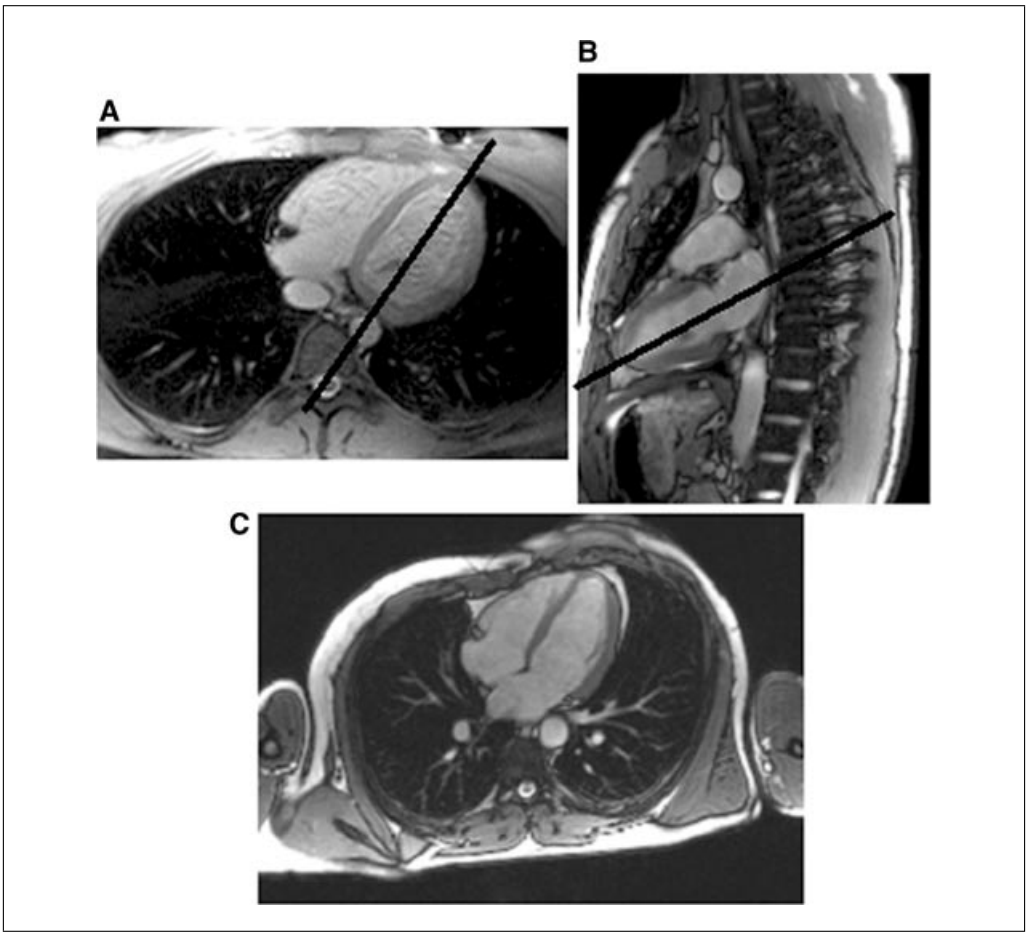

Figure A11.5.1 Prescribing a 4-chamber view orientation. (**A**) On a transverse scout scan through the heart, an oblique coronal slice is prescribed along the long axis of the left ventricle to get a 2-chamber view as shown in (**B**). A slice prescribed along the long axis of the left ventricle on the 2-chamber view gives the 4-chamber view as shown in (**C**).

Sequence 4: Cine scan to estimate quiescent period of the cardiac cycle

15. Bring up a 2D SSFP cine sequence on the console. Set up the parameters as given in Table A11.5.5.

    Note that this protocol must be run as a free-breathing scan, not breath-hold. Use an alternate free-breathing cine scan if one is recommended by your manufacturer. Temporal resolution should be on the order of 20 msec.

16. Copy the 4-chamber orientation from step 14, and start the scan.

Data processing and viewing for Sequence 4

17. Load the images into the appropriate cine viewing software provided by the vendor. If this is not available, simply scrolling the images back and forth is sufficient.

18. View the cross section of the coronary arteries in the atrioventricular groove (A-V groove) in the acquired images.

    When viewed in cine mode, the motion of the artery in a cardiac cycle can be visualized. The optimal mid-diastolic period of the cardiac cycle, when the artery is relatively stationary, can be chosen on the basis of these data. Write down the start and end times after the R-wave, during which the artery remains relatively stationary. The time at which a particular image is acquired after the R-wave is usually indicated as a time stamp on the image.

Table A11.5.5 Primary Clinical Imaging Parameters for Sequence 4 (2D Free-Breathing Cine)

Patient position	Supine
Scan type	2-D SSFP cine sequence
Imaging plane (orientation)	4-chamber orientation
Central slice or volume center	Middle of the heart
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	7
Repeat time (T_R)	As short as possible (e.g., 3 msec); temporal resolution is ~20 msec
Delay time (T_D)	0 msec
Flip angle (FA)	70°
Fields of view (FOV_x, FOV_y)	300 mm, 200 mm
Resolution (Δx, Δy)	1.17 mm, 1.16 mm
Number of data points collected (N_x, N_y)	256, 172/g, with $g = 2$ (acceleration factor in parallel imaging)[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	3
Read direction	Usually left-right
Number of cardiac phases	If available, use retrogating, i.e., use 40 reconstructed cardiac phases. Otherwise, set the number of cardiac phases to the maximum number that is allowed.
ECG gating	Yes
Scan time	42 heartbeats

[a]The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is $172/2 + 12 = 98$.

Sequence 5: Setting up the navigator pulses for respiratory gating

For respiratory-gated imaging, navigator echoes are collected along the cranial-caudal direction at the dome of the diaphragm to track respiratory motion, and data are acquired only in the end expiratory position of the diaphragm. The boundary between liver (high signal) and lung (low signal) is detected to track the motion of the diaphragm during breathing. The position shifts of the diaphragm are converted to coronary artery motion using a correction factor of 0.6 (Wang et al., 1995). Two different approaches may be used to acquire a navigator echo—in the first approach, two intersecting slices are excited—one with a 90° pulse and the other one with an 180° pulse. The two slices are oriented on the transverse navigator scout scan images (Sequence 2) such that the navigator is positioned at the dome of the right hemidiaphragm. A schematic is shown in Figure A11.5.2. The intersection of these two slices then describes the column of tissue excited by the navigator pulses as shown on the coronal image (Fig. A11.5.2B). The resulting

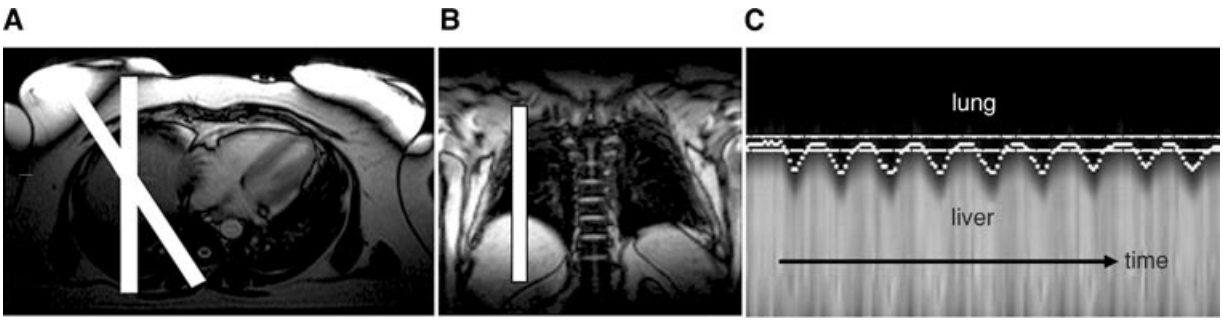

Figure A11.5.2 (**A**) An image illustrating placement of slices for acquisition of the navigator echo to estimate respiratory motion. (**B**) A coronal view showing the column of tissue excited by the navigator echo. (**C**) Resulting temporal display of multiple navigator echoes showing diaphragmatic motion. The boundary between the liver (high signal in the lower portion of the image) and lung (low signal in the upper portion of the image) is marked with thick lines and the range of motion accepted for image reconstruction is indicated by dotted lines.

Table A11.5.6 Primary Clinical Imaging Parameters for Sequence 5 (Navigator Echo Setup)

Patient position	Supine
Scan type	Navigator-echo setup
Imaging plane (orientation)	Not applicable (one column is excited)
Central slice or volume center	Right hemidiaphragm
Echo time (T_E)	Default (e.g., 20 msec)
Repeat time (T_R)	100 msec
Flip angle (FA)	Default (90°, 180°, for the navigator described in this unit, 30° for a 2D navigator pulse.)
Fields of view (FOV_x, FOV_y)	Default (e.g., $FOV_x = 256$ mm)
Resolution (Δx, Δy)	Default (e.g., $\Delta x = 1$ mm)
Number of data points collected (N_x, N_y)	Default (e.g., $N_x = 256$)
Slice thickness (Δz)	Default (e.g., 10 mm)
Number of slices	Not applicable
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Number of repetitions	150
Scan time	15 sec

temporal display using multiple navigator echoes showing diaphragmatic motion is also shown in Figure A11.5.2C. In the other method, a 2D excitation may be used to excite a column of tissue and a gradient echo used to acquire the navigator profile.

19. Bring up a 3D segmented SSFP scan protocol. Usually, the navigator-echo is setup as a part of this protocol. Switch ON the scout mode if available. Start the navigator-echo sequence according to Table A11.5.6.

    In scout mode, the sequence acquires and displays only the navigator-echo signal; no imaging data are required. For the first run of this scout scan, the default position of the search window position may be used.

Table A11.5.7 Primary Clinical Imaging Parameters for Sequence 6 (Whole-Heart High-Resolution Scan)[a]

Patient position	Supine
Scan type	3D navigator-gated segmented SSFP
Imaging plane (orientation)	Transverse
Central slice or volume center	Place slab such that the whole heart is covered
Echo time (T_E)	As short as possible (e.g., 1.3 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	21-41 (depending on heart rate)
Repeat time (T_R)	As short as possible (e.g., 3.4 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 600 msec)
Flip angle (FA)	As high as possible (e.g., 90°)
Fields of view (FOV_x, FOV_y)	300 mm, 220 mm
Resolution (Δx, Δy)	0.94 mm, 0.95 mm
Number of data points collected (N_x, N_y)	320, $232/g$, with $g = 2$ (acceleration factor in parallel imaging)[b]
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm (interpolated to 1.5 mm)
Number of slices	60 (interpolated to 120)
Slab thickness	180 mm[c]
Number of slabs	1
Slice gap	NA
Number of acquisitions (N_{acq})	1
Magnetization transfer	T_2-preparation, 40 msec
Fat suppression	Yes
ECG gating	Yes
Scan time	~12 min, assuming a heart rate of 60 beats per minute, 32 lines per segment, and 30% navigator efficiency. If the navigator efficiency is 100%, the scan time will be 3-6 min with 21-41 lines per segment.

[a]The respiratory gating is turned on when acquiring this sequence. The center of respiratory gating window should be at the expiratory position of the diaphragm. The gating window is set to be ± 2 mm. If possible, set the motion correction factor to be 0.6.

[b]The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is $232/2 + 12 = 128$.

[c]An extra 10% (18-mm) slice oversampling is used. The oversampled slices are not visible and are not included in the number of slices.

20. Repeat the navigator-echo sequence after changing the center of the search window to the estimated expiration position of the diaphragm, based on the scout images acquired from step 19.

    The positioning of the navigator echo may be changed if the navigator signal does not display a sharp boundary between the lung and the liver interface.

21. Repeat the scout scan (i.e., navigator-echo sequence) as many times as necessary until the expiration position can be estimated with reasonable accuracy.

Sequence 6: 3D navigator-gated free breathing segmented SSFP whole heart high-resolution scan

22. Bring the sequence for a navigator-gated 3D segmented SSFP scan up onto the console. Set the imaging parameters as shown in Table A11.5.7.

    The numbers of lines per segment are chosen such that the data acquisition time per heartbeat (lines per segment × TR) is less than or equal to the quiescent period of the heartbeat (measured in step 18 of this protocol).

23. Copy the navigation positions obtained from the previous navigator echo scout scan (Sequence 5, step 21).

24. Set the navigator gating window to ±2 mm from the expiratory diaphragmatic position (data are accepted only if the diaphragm position lies within this 4-mm window). Set the correction factor relating the diaphragm motion to the coronary artery motion to 0.6 (this may not be an editable parameter on some systems, depending on manufacturer).

25. Switch ON motion adaptive gating (this option may not be available depending on manufacturer).

    With this option enabled, the navigator gating window will adapt automatically if the breathing changes during the scan and the diaphragm position drifts. Adaptive gating ensures that data are always acquired at end expiration and thus reduces motion artifacts.

26. The imaging slab is axial, over the whole heart, from the apex to about 1 cm above where the origin of the left main coronary artery is expected to be.

27. Use the T_2 magnetization preparation to enhance the blood-myocardial contrast.

28. Start the sequence. At the beginning of acquisition, confirm that the expiration position of the diaphragm is close to the window preset for data acquisition. If not, stop the scan, alter the center of the gating window, and repeat the step.

    This step is valid even if motion adaptive gating is used.

RESPIRATORY-GATED TARGETED IMAGING USING A STEADY-STATE FREE PRECESSION SEQUENCE

ALTERNATE PROTOCOL 1

For Alternate Protocol 1, the high-resolution whole-heart coronary MRA scan in the Basic Protocol (Sequence 6) is substituted by two high-resolution scans with thinner slabs, one for the left coronary artery system—the left main (LM) and left anterior descending (LAD) arteries, and the other for the right coronary artery (RCA). The purpose is to reduce the imaging time of Sequence 6 in order to minimize potential motion artifacts and blurring in uncooperative patients where there may be gross motion over the duration of a whole heart scan, or if there are moderate variations in the patient's heartbeat. The entire Alternate Protocol 1 will take ~1 hr to perform. With experience, this time may be cut down to ~30 to 35 min.

Set up patient and equipment

1. Set up the patient as in the Basic Protocol. Perform steps 1 to 21 of the Basic Protocol.

Table A11.5.8 Primary Clinical Imaging Parameters for Sequence 7 (3D High-Resolution Scan)[a]

Patient position	Supine
Scan type	3D navigator-gated segmented SSFP
Imaging plane (orientation)	Oblique transverse
Central slice or volume center	Origin of LM coronary artery
Echo time (T_E)	As short as possible (e.g., 1.3 msec)
Receiver bandwidth (RBW)	810 Hz/pixel
Number of lines per segment	21-41 (depending on R-to-R interval)
Repeat time (T_R)	As short as possible (e.g., 3.2 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 600 msec)
Flip angle (FA)	As high as possible (e.g., 90°)
Fields of view (FOV_x, FOV_y)	300 mm, 220 mm (or as small as appropriate without significant aliasing)
Resolution (Δx, Δy)	0.94 mm, 0.95 mm
Number of data points collected (N_x, N_y)	320, 232/g, with $g = 2$ (acceleration factor in parallel imaging)[b]
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	3 mm (interpolated to 1.5 mm)
Number of slices	20 (interpolated to 40)
Slab thickness	60 mm[c]
Number of slabs	1
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Magnetization transfer	T_2-preparation, 40 msec
Fat suppression	Yes
ECG gating	Yes
Scan time	~4 min, assuming a heart rate of 60 beats per minute, 32 lines per segments, and a 30% navigator efficiency. If the navigator efficiency is 100%, the scan time will be 1-2 min with 21-41 lines per segment.

[a] The respiratory gating is turned on when acquiring this sequence. The center of respiratory gating window should be at the expiratory position of the diaphragm. The gating window is set to be ±2 mm. If possible, set the motion correction factor to be 0.6.

[b] The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is $232/2 + 12 = 128$.

[c] An extra 10% (6-mm) slice oversampling is used. The oversampled slices are not visible and are not included in the number of slices.

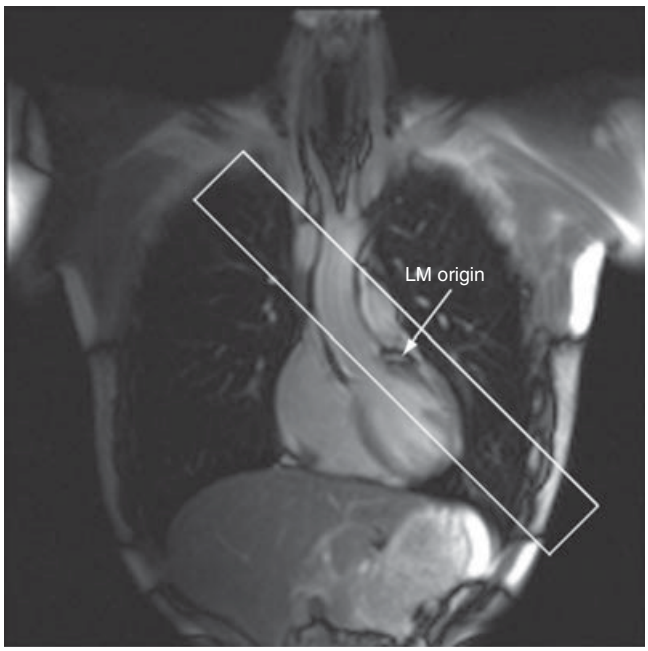

Figure A11.5.3 An image illustrating placement of the slab for the high-resolution targeted free-breathing LAD scan (Alternate Protocol 1). A 3D slab is placed along the left ventricle with the center of the slab at the origin of the left main coronary artery.

Sequence 7: 3D navigator-gated free-breathing segmented SSFP high-resolution scan for the LM and LAD

2. Bring the sequence for a 3D navigator-gated segmented SSFP scan up onto the console. Set the imaging parameters as shown in Table A11.5.8.

   The numbers of lines per segment are chosen such that the data acquisition time per heartbeat (lines per segment × TR) is less than or equal to the quiescent period of the heartbeat (measured in step 18 of the Basic Protocol).

3. Use the T_2 magnetization preparation to enhance the blood-myocardial contrast.

4. Prescribe the transverse 3D slab on the coronal scout image from Sequence 1 such that the center of the slab is at the approximate origin of the LM artery. Rotate the slab clockwise so that it covers the expected course of the LAD along the wall of the left ventricle.

   Refer to Figure A11.5.3 for an example of the slab orientation.

5. Copy the navigator positions obtained from the navigator echo scout scan (Basic Protocol, Sequence 5, step 21).

6. Set the navigator gating window to ±2 mm from the expiratory diaphragmatic position (data are accepted only if the diaphragm position lies within this window). Set the correction factor relating the diaphragm motion to the coronary artery motion to 0.6.

7. Switch ON motion adaptive gating (this option may not be available, depending on manufacturer). Start the sequence.

   With this option enabled, the navigator gating window will adapt automatically if the breathing changes during the scan and the diaphragm position drifts. Adaptive gating ensures that data are always acquired at end expiration, and thus reduces motion artifacts.

Table A11.5.9 Primary Clinical Imaging Parameters for Sequence 8 (Free-Breathing 2D RCA Localizer)[a]

Patient position	Supine
Scan type	2D navigator-gated segmented SSFP
Imaging plane (orientation)	Transverse
Central slice or volume center	Mid-ventricle
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	41
Repeat time (T_R)	As short as possible (e.g., 3 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 600 msec)
Flip angle (FA)	As high as possible (e.g., 90°)
Fields of view (FOV_x, FOV_y)	300 mm, 200 mm
Resolution (Δx, Δy)	1.17 mm, 1.43 mm
Number of data points collected (N_x, N_y)	256, 140/g, with $g = 2$ (acceleration factor in parallel imaging)[b]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3 mm
Number of slices	8
Slice gap	3 mm (100%)
Number of acquisitions (N_{acq})	1
Slice locations	Base of heart to apex
Magnetization transfer	T_2-preparation, 40 msec
Fat suppression	Yes
ECG gating	Yes
Scan time	~48 heartbeats, assuming a heart rate of 60 beats per minute and a 30% navigator efficiency. If the navigator efficiency is 100%, the scan time will be 16 heartbeats.

[a]The respiratory gating is turned on when acquiring this sequence. The center of respiratory gating window should be at the expiratory position of the diaphragm. The gating window is set to be ±2 mm. If possible, set the motion correction factor to be 0.6.

[b]The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is $140/2 + 12 = 82$.

8. If not using motion adaptive gating, confirm that the expiration position of the diaphragm falls within the window that has been preset for data acquisition during the scan. If not, stop the scan, alter the center of the gating window, and repeat the step.

Sequence 8: 2D Navigator-gated free breathing segmented SSFP RCA localizer (2D RCA localizer)

9. Bring the sequence for a 2D navigator-gated segmented SSFP scan up onto the console. Set the imaging parameters as shown in Table A11.5.9.

10. Copy the navigator positions obtained from the navigator echo scout scan (Basic Protocol 1, Sequence 5, step 21).

11. Use the coronal scout images acquired from the Basic Protocol, Sequence 1, step 10 for slice positioning. Prescribe transverse 2D slices on the coronal scout image such that cross sections of the RCA are acquired from the base of the heart to the apex, with gaps in between the slices.

12. Repeat steps 6 to 8 of this protocol.

Sequence 9: 3D high-resolution segmented SSFP scan for the RCA

13. Use a 3-point planning tool to prescribe the optimal scan plane. Bring three transverse images obtained from Sequence 8, step 11 of this protocol on the screen, one showing a proximal section of the artery, one the middle segment, and a third showing the distal portion.

    Step 11 of Sequence 8 is a localizer and only leads to 2D cross sections of the RCA, with large gaps in between slices. In Sequence 9, we use the cross sections from Sequence 8 to prescribe an optimal scan plane for a 3D scan, such that the entire RCA is visualized in the same plane.

14. Choose the 3-point tool on the system and select the proximal, mid, and distal points on the images displayed on the screen. Based on the selection, the system will automatically prescribe the scanning plane that is defined by the three points.

    An illustration of the 3-point planning method for the RCA and the resulting image is shown in Figure A11.5.4.

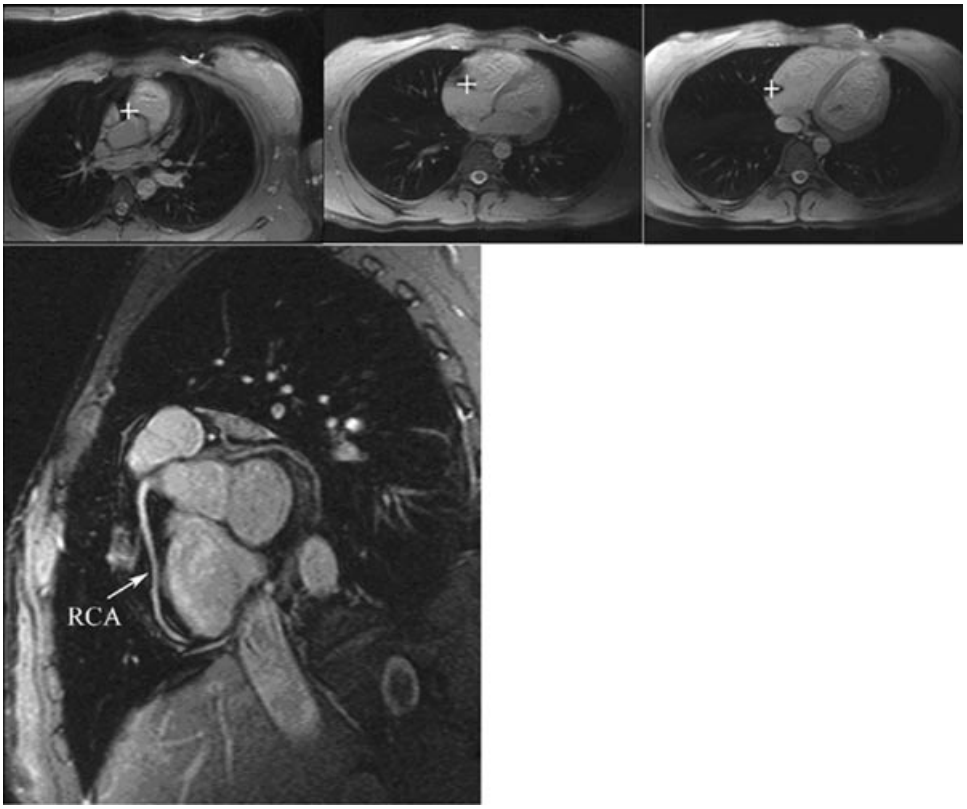

Figure A11.5.4 Images from a localizer scan showing the 3-point localization process and the resultant high-resolution 3D image of the RCA. Three images are chosen from the localizer scan, one showing the proximal portion of the RCA, one the middle portion, and one the distal section. When these three points are selected for slice planning, the system automatically determines a scan plane. The result of the high-resolution scan using the above-prescribed scan plane is shown in the bottom panel.

15. Use the slice orientation prescribed from step 14 of this protocol and run the 3D high-resolution scan (used in Sequence 7) for the RCA according to Table A11.5.8.

Sequence 10: 3D high-resolution segmented SSFP scan for the left circumflex artery (LCx)

16. Repeat the 3D high-resolution scan according to Table A11.5.8 (used in Sequence 7) except that the imaging plane (orientation) will be determined from images acquired from Sequences 7 and 8, using a 3-point planning procedure (step 14 of this protocol) to cover the LCx.

ALTERNATE PROTOCOL 2

BREATH-HOLD IMAGING USING A STEADY-STATE FREE PRECESSION SEQUENCE

In situations where scan time must be significantly reduced, a breath-held volume-targeted approach with thin-slab acquisitions can be used instead of the thick-slab free-breathing approach (Wielopolski et al., 1998). In principle, it is similar to Alternate Protocol 1, where small targeted volumes are scanned to cover different regions of the coronary arteries, but the slabs are even thinner and images are acquired in breath-held scans. A number of targeted scans may be performed to cover the entire coronary artery tree. Typically, two volumes are acquired, one volume for the left main (LM) and left anterior descending (LAD) arteries, and the other volume for the right coronary artery (RCA). Since the volume in each scan is quite small, finding the optimal scanning planes (localization) of the coronary arteries is of paramount importance.

Table A11.5.10 Primary Clinical Imaging Parameters for Sequence 12 (Coronal Scout Scan)

Patient position	Supine
Scan type	Single-shot 2D SSFP (different manufacturers may have different standard protocols)
Imaging plane (orientation)	Coronal
Central slice or volume center	Origin of the LM from the ascending aorta
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Repeat time (T_R)	As short as possible (e.g., 3 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 300 msec)
Flip angle (FA)	70°
Fields of view (FOV_x, FOV_y)	400 mm, 400 mm
Resolution (Δx, Δy)	3.12 mm, 3.12 mm
Number of data points collected (N_x, N_y)	128, 128
Slice thickness (Δz)	8 mm
Number of slices	6
Slice gap	4 mm (50%)
Number of acquisitions (N_{acq})	1
ECG gating	Yes
Scan time	6 heartbeats

Table A11.5.11 Primary Clinical Imaging Parameters for Sequence 13 (Breath-Hold 3D LAD Localizer)

Patient position	Supine
Scan type	3D segmented SSFP
Imaging plane (orientation)	Oblique, transverse to sagittal
Central slice or volume center	Centered on the origin of the left main artery from the aorta
Echo time (T_E)	As short as possible (e.g., 1.3 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	41
Repeat time (T_R)	As short as possible (e.g., 2.8 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 600 msec)
Flip angle (FA)	As high as possible (e.g., 90°)
Fields of view (FOV_x, FOV_y)	300 mm, 200 mm (or as small as appropriate without significant aliasing)
Resolution (Δx, Δy)	1.17 mm, 1.43 mm
Number of data points collected (N_x, N_y)	256, 140/g, with $g = 2$ (acceleration factor in parallel imaging)[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	4 mm (interpolated to 2 mm)
Number of slices	10 (interpolated to 20)
Slab thickness	40 mm
Number of slabs	1
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Read direction	Left-right
Fat suppression	Yes
ECG gating	Yes
Scan time	20 heartbeats

[a]The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is $140/2 + 12 = 82$.

The entire Alternate Protocol 2 takes ~1 hr. With experience in localizing the coronary arteries and increased familiarity with changing imaging parameters to suit the individual patients, this time may be reduced to about 30 min.

Set up patient and equipment

1. Set up the patient as in the Basic Protocol. Perform steps 1 to 9 of the Basic Protocol.

Sequence 11: Rapid three-plane positioning pilot scan

2. Set up a rapid three-plane positioning pilot scan (Sequence 1) under breath-holding. Give the patient breathing instructions such as "Breathe in …. Pause …. Breathe out …. Pause …. Breathe in and hold." Start the scan after the instructions. After the scan is completed, the patient may resume breathing normally.

Table A11.5.12 Primary Clinical Imaging Parameters for Sequence 15 (2-D Cine)

Patient position	Supine
Scan type	2D SSFP Cine Sequence
Imaging plane (orientation)	4-chamber view
Central slice or volume center	On the coronary artery
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	7
Repeat time (T_R)	As short as possible (e.g., 3 msec); the temporal resolution is ~20 msec
Delay time (T_D)	0 msec
Flip angle (FA)	70°
Fields of view (FOV_x, FOV_y)	300 mm, 300 mm
Resolution (Δx, Δy)	1.17 mm, 2.68 mm
Number of data points collected (N_x, N_y)	256, 112
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Read direction	Anterior-posterior
Number of cardiac phases	If available, use retrogating, i.e., use 40 reconstructed cardiac phases. Otherwise, set the number of cardiac phases to the maximum number that is allowed.
ECG gating	Yes
Scan time	~16 heartbeats

Sequence 12: 2D SSFP single-shot coronal localizer (optional)

3. View the coronal images acquired by Sequence 11. Only if the plane where the approximate origin of the LM is expected was not visualized, repeat the scout scan (Sequence 11), this time only in the coronal plane.

   The parameters for this scan are specified in Table A11.5.10. The slice group is positioned on the transverse images acquired using Sequence 11 such that the region of and around the expected origin of the LM from the ascending aorta is covered.

4. Repeat the breath-holding instructions in step 2 of this protocol and start the scan according to Table A11.5.10.

Sequence 13: 3D low-resolution segmented SSFP scan for localization of the LAD

5. Bring up the sequence for a 3D segmented SSFP scan onto the console. Set the imaging parameters as shown in Table A11.5.11.

6. Use the scout images obtained from Sequence 11 for slab positioning. Place a transverse 3D slab on the coronal scout image (Sequence 11 or Sequence 12) such that the center of the slab is at the approximate origin of the LM artery. Rotate the slab clockwise so that it covers the expected course of the left coronary artery along the wall of the left ventricle. Refer to Figure A11.5.3 for a schematic of the slab orientation.

Table A11.5.13 Primary Clinical Imaging Parameters for Sequence 16 (3-D High-Resolution Scan)

Patient position	Supine
Scan type	3D segmented SSFP
Imaging plane (orientation)	Determined from a 3-point planning tool
Central slice or volume center	Origin of LM coronary artery
Echo time (T_E)	As short as possible (e.g., 1.3 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	21-41 (depending on the R-to-R interval)
Repeat time (T_R)	As short as possible (e.g., 3.1 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 600 msec)
Flip angle (FA)	As high as possible (e.g., 90°)
Fields of view (FOV_x, FOV_y)	300 mm, 220 mm (or as small as appropriate without significant aliasing)
Resolution (Δx, Δy)	1.17 mm, 0.72-1.53 mm
Number of data points collected (N_x, N_y)	256, 144/g-304/g, with $g = 2$ (acceleration factor in parallel imaging)[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3 mm (interpolated to 1.5 mm)
Number of slices	6 (interpolated to 12)
Slab thickness	18 mm
Number of slabs	1
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Fat suppression	Yes
ECG gating	Yes
Scan time	24 heartbeats

[a]The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is between 144/2 + 12 = 84 and 304/2 + 12 = 164. The choice of actual total number of lines should be proportional to the choice of number of lines per segment listed above, such that the ratio of the two is about 4.

7. Repeat breath-holding instructions in step 2 of this protocol and begin the scan.

Sequence 14: Localizer for 4-chamber view

8. Acquire a 4-chamber orientation based on the illustration shown in Figure A11.5.1.

The reader is also encouraged to see Figures A11.4.1 and A11.4.2 in UNIT A11.4.

9. Use a single-slice 2D SSFP localizer sequence (similar to the sequence in Sequence 12, but with single slice only) to get a 2-chamber view. Set up the parameters for this scan according to Table A11.5.10, with the exception that the number of slices is changed to 1, the orientation of the slice is oblique coronal, and

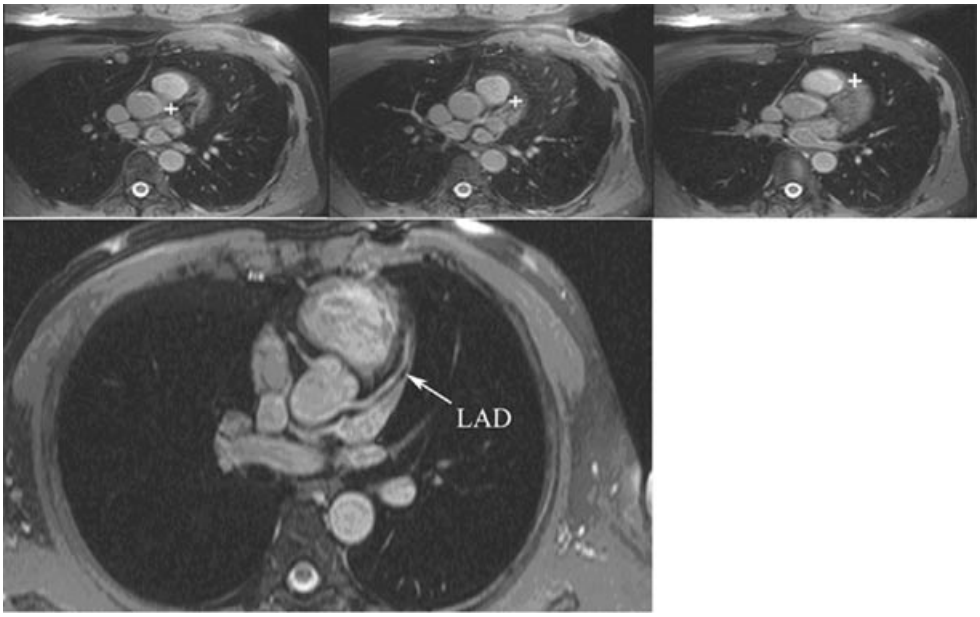

Figure A11.5.5 Images from a localizer scan showing the 3-point planning process and the resulting image of the LAD. Three images are chosen from the localizer scan, one showing the proximal portion of the LAD, one the middle portion, and one the distal section. When these three points are selected for slice planning, the system automatically determines a scan plane. The resulting image using this 3-point method to prescribe the scan plane is shown in the bottom panel.

the scan time is one heartbeat. To position this scan, bring up a transverse image of the heart that shows a cross-section of the left ventricle (step 2 of this protocol). Prescribe the intended slice along the long axis of the left ventricle. Repeat breath-holding instructions in step 2 of this protocol and start the scan.

10. Repeat the sequence in step 9 and alter the orientation to get a 4-chamber view. Bring up the resulting image from the previous scan (step 9 of this protocol) and prescribe the intended slice along the long axis of the left ventricle. Repeat breath-holding instructions in step 2 of this protocol and start the scan.

Sequence 15: Cine scan to estimate mid-diastolic period of the cardiac cycle

11. Bring up a SSFP cine scan on the console. Set up the parameters as given in Table A11.5.12.

12. Copy the 4-chamber orientation obtained from step 10 of this protocol.

13. Repeat the breath-hold instructions in step 2 of this protocol and begin the scan.

Data processing and viewing for Sequence 15

14. Load the images into the appropriate cine viewing software provided by the vendor. If this is not available, simply scrolling the images back and forth is sufficient.

15. View the cross-section of the coronary arteries in the atrioventricular groove in the acquired images.

    When viewed in cine mode, the motion of the artery in a cardiac cycle can be visualized. The optimal mid-diastolic period of the cardiac cycle when the artery is relatively stationary can be chosen as the basis of this data. Write down the start time and end time after the R-wave during which the artery remains relatively stationary. The time at which a particular image is acquired after the R-wave is usually indicated as a time stamp on the image.

Table A11.5.14 Primary Clinical Imaging Parameters for Sequence 17 (2-D RCA Localizer)

Patient position	Supine
Scan type	2D segmented SSFP
Imaging plane (orientation)	Transverse
Central slice or volume center	Mid-ventricle
Echo time (T_E)	As short as possible (e.g., 1.5 msec)
Receiver bandwidth (RBW)	980 Hz/pixel
Number of lines per segment	41
Repeat time (T_R)	As short as possible (e.g., 3 msec)
Delay time (T_D)	Data acquisition in mid-diastole (e.g., 600 msec)
Flip angle (FA)	As high as possible (e.g., 90°)
Fields of view (FOV_x, FOV_y)	300 mm, 220 mm (or as small as appropriate without significant aliasing)
Resolution (Δx, Δy)	1.17 mm, 1.57 mm
Number of data points collected (N_x, N_y)	256, 140/g, with $g = 2$ (acceleration factor in parallel imaging)[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3 mm
Number of slices	8
Slice gap	3 mm (100%, or as appropriate to acquire cross sections from the base of the heart to the apex)
Number of acquisitions (N_{acq})	1
Read direction	Left to right
Slice locations	Base of heart to apex
Fat suppression	Yes
ECG gating	Yes
Scan time	16 heartbeats

[a]The use of acceleration factor in parallel imaging does not affect the image resolution. Parallel acquisition also includes acquisition of extra "reference lines" (typically 12) to estimate a coil sensitivity map that is used to reconstruct the data in the *k*-space. In this sequence, the actual total number of lines along the phase-encoding direction, including the reference lines, is $140/2 + 12 = 82$.

Sequence 16: 3D high-resolution segmented SSFP scan

16. Bring up the sequence for a 3D scan onto the console. Set the imaging parameters as shown in Table A11.5.13.

    The numbers of lines per segment are chosen such that the data acquisition time per heartbeat (lines per segment × TR) is less than or equal to the quiescent period of the heartbeat (measured in step 15 of this protocol).

17. Use the 3D SSFP scout images obtained from Sequence 13 to prescribe the LAD. Use a 3-point tool as described in step 14 of Alternate Protocol 1, and illustrated in Figure A11.5.5.

18. Repeat the breathing instructions in step 2 of this protocol and begin the scan.

Sequence 17: 2D low-resolution segmented SSFP scan for localization of the RCA

19. Bring up the sequence for a 2D segmented SSFP scan onto the console. Set the imaging parameters as shown in Table A11.5.14.

20. Use the coronal scout image acquired from either Sequence 11 or Sequence 12 for prescribing the orientation of the slices in this sequence. Prescribe transverse 2D slices on the coronal scout image such that cross-sections are acquired at regions covered from the base of the heart to the apex.

21. Repeat the breath-holding instructions in step 2 of this protocol and begin the scan.

Sequence 18: 3D high-resolution segmented SSFP scan for the RCA

22. To define the scan orientation for the RCA, bring up three images that depict the proximal, mid, and distal portions of the RCA on the screen. The proximal portion of the RCA may be visible either on the 2D images acquired from Sequence 17 or on the 3D images obtained from Sequence 13. The cross-section of the mid-portion of the RCA and the distal RCA will be visible in the atrioventricular groove on the 2D images from Sequence 17. Repeat the 3-point localization process as described in step 14 of Alternate Protocol 1.

    An illustration of RCA localization is shown in Figure A11.5.4.

23. With the image orientation defined from the above step, set up the 3D high-resolution scan according to Table A11.5.13 (Sequence 16) for the RCA. Repeat the breath-holding instructions in step 2 of this protocol, and begin the scan.

COMMENTARY

Background Information

Coronary artery disease (CAD) is the leading cause of death in the United States (AHA, 1999). CAD is typically the result of atherosclerosis, which is a buildup of plaque in the blood vessels feeding the heart. As the plaque grows in size, the lumen of the coronary artery narrows, reducing and sometimes completely cutting off the supply of oxygen and nutrients to the myocardium. Prolonged deficiency of oxygen can lead to myocardial infarction. Myocardial infarction can even occur in the case of smaller blockages, where a rupture of the plaque may cause thrombosis in the coronary artery and occlude the coronary lumen. Early diagnosis of coronary artery stenoses and their characterization is important for health care management in patients.

Cardiac catheterization with contrast-enhanced X-ray angiography is currently the gold standard for diagnosis of CAD. The major advantage of diagnostic X-ray angiography is its ability to acquire high-resolution images with adequate SNR. However, X-ray angiography does suffer from certain drawbacks. The procedure is invasive, and in rare instances can lead to complications such as cardiac arrhythmias, embolism due to blood clot formation at the tip of the catheters, hemorrhage, stroke, or heart attack. Exposure of the patient and physician to ionizing radiation during catheter guidance and imaging procedures is also a concern. Furthermore, the iodinated contrast agent used in the procedure is nephrotoxic. These limitations discourage the use of X-ray angiography as a first step for the detection of coronary heart disease unless the symptoms and other tests such as a blood enzyme test or stress test are strongly suggestive of CAD. In addition, X-ray angiography cannot provide any information on the functional significance of CAD. Although semiquantitative methods exist for estimating the flow restrictions based on the X-ray images, the functional significance cannot be directly evaluated.

Magnetic resonance imaging is a noninvasive modality that offers exciting new possibilities for diagnostic imaging. MRI can acquire true three-dimensional information in any arbitrary tomographic plane in the body, which is ideally suited for the complicated anatomy of the coronary arteries. There is no known harmful effect of the magnetic field used in MRI, which allows for repeatability of the studies. Additionally, MRI can potentially provide functional information to complement the diagnosis of coronary artery stenosis, such as coronary artery blood flow reserve (Koskenvuo et al., 2001; Ibrahim et al., 2002), myocardial perfusion (Wilke et al., 1999),

myocardial function (Gerber et al., 2002), and viability imaging (Kim et al., 1999; Mahrholdt et al., 2002). This can aid the physician in deciding whether or not, and to what extent, an intervention will benefit the patient. With such potential benefits, MRI can be an attractive tool for diagnosis of cardiovascular disease.

The major challenges for coronary MRA are the presence of cardiac motion and respiratory motion. To minimize the effects of cardiac motion, data are usually collected during mid-diastole, when the heart is relatively stationary. This is done by acquiring the electrocardiographic (ECG) signal of the patient and collecting data after a certain delay from the R-wave. To eliminate respiratory motion, two approaches have been used. One is a breath-hold approach in which data are acquired during suspended breathing at inspiration. Breath-holding is a fast method of acquiring three-dimensional data and provides complete respiratory motion suppression in cooperative subjects. The major disadvantage of breath-holding imaging is the limited imaging time that is available, which in turn limits the signal-to-noise ratio (SNR) and/or spatial resolution and/or coverage. The other method of minimizing respiratory motion is to use navigator echoes to estimate the diaphragm position and correct the data for the change in position of the coronary arteries. Such techniques allow for acquisition of images with higher spatial resolution, but with a substantially longer imaging time. Although achievable SNR and resolution offered by free breathing techniques might be higher than what is obtained via the breath-holding techniques, the image quality depends on the gating window and the accuracy of detecting the diaphragm position. If the scan time is too long, there is often a tendency for the breathing pattern to drift, which may reduce scan efficiency and increase imaging time (Taylor et al., 1997). It is therefore important to use techniques such as motion adaptive gating to reduce the dependence of image quality on breathing consistency.

Critical Parameters and Troubleshooting

High spatial resolution with adequate SNR is critical to detect stenoses in small blood vessels such as the coronary arteries. Improving resolution often involves increasing imaging time—either by means of an increased acquisition window in a cardiac cycle or by increasing the total scan time. However, there is a limit to the improvement in spatial resolution that may be achieved by increasing these parameters. Motion artifacts will degrade the effective image resolution if the acquisition window or scan time is too long. Ghosting or blurring may also corrupt the images if the above parameters are increased beyond a certain limit. The optimal parameters must be estimated on a patient-by-patient basis, depending on the heart rate and the breath-holding ability of the subject or the variability in the breathing pattern for respiratory gated imaging.

Spatial resolution may also be restricted by the limit on the gradients and slew rates due to peripheral nerve stimulation. The actual application of the sequences presented in this unit may require some modifications if the peripheral nerve stimulation limit is exceeded. Usually, the gradient slew rates and amplitudes have to be compromised to reduce the stimulation levels. A concomitant effect of reducing gradient amplitudes and slew rates is the increase of T_E and T_R, which in turn will affect the readout bandwidth and reduce the permissible number of lines acquired per cardiac cycle, consequently increasing the imaging time. Another factor that affects imaging time is the navigator efficiency. In the free-breathing approach, data are acquired in each heartbeat, and the diaphragm position is recorded at the time of data acquisition. If the diaphragm position was within the preset navigator window, then the data are accepted; otherwise the data are rejected and are measured again in the next heartbeat. Navigator efficiency describes the percentage of data that were accepted over all the data that were measured. Typically, this number ranges between 25% and 50%.

A source of artifacts in a steady-state free precession imaging is the sensitivity to field inhomogeneities. One of the main sources for the resonance frequency offsets is B_0 field inhomogeneity. Another source is the incorrect adjustment of the synthesizer frequency. Careful shimming can minimize these effects. However, shimming can be challenging in the heart due to heart and respiratory motion, blood flow, chemical shift, and susceptibility variations at air-tissue interfaces. Recent work has shown that adjusting the imaging frequency can substantially reduce image artifacts in coronary MRA using SSFP (Deshpande et al., 2003). If artifacts such as ghosting, banding, substantial signal variations in the heart, or loss of fat suppression are visible in the images, changing the imaging frequency may reduce the artifacts in many cases. The frequency scout scans as described in Deshpande

et al. (2003) may be added to the sequences described in this unit to optimize the imaging frequency if necessary.

Anticipated Results

The clinical goals of coronary artery imaging may be to detect anomalous origins of coronary arteries, or narrowing due to atherosclerotic disease. The coronary arteries can be delineated well using MRA, due to separation of the blood, myocardial, and fat tissues, making the detection of anomalous coronary arteries quite robust. Stenoses are detected as a narrowing of the blood vessel or as areas of reduced signal in case of diffused disease. However, the spatial resolution of MRA techniques is limited; hence, the diagnosis is restricted to only the major coronary arteries and not their branches. Quantification of stenoses is also a problem due to limited spatial resolution. Many previous studies in patients have shown that coronary MRA has a high negative predictive value. In order to achieve positive predictive value, coronary MRA still needs improvement before it can challenge X-ray angiography clinically.

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Internet Resource

http://www.mrisafety.com

Covers a number of important patient management issues related to MR imaging, including recommended safety procedures, a list of metallic implants that have been tested for MR compatibility, and a list of other sources on MR safety.

Key Reference

Shellock, 2001. See above.

Covers a number of important patient management issues related to MR imaging, including recommended safety procedures, a list of metallic implants that have been tested for MR compatibility, and a list of other sources on MR safety.

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