Myocardial Perfusion and Viability

Rapid magnetic resonance imaging of the heart during the first pass of a bolus-injected contrast agent can be used to assess myocardial perfusion (Manning et al., 1991; Rossum et al., 1990; Wilke et al., 1994; Wilke et al., 1993). In this context, the term perfusion refers to transport of the contrast agent into myocardial tissue by blood flow, distribution in the tissue, and washout. Following the course of enhancement after injection of an extracellular MR contrast agent such as Gd-DTPA (gadolinium diethylenetriamine pentaacetic acid) provides a means to determine myocardial blood flow. The rate of contrast enhancement depends on the rate of transport of the contrast agent through a tissue region, indicating sensitivity to the level of tissue blood flow. Assessment of perfusion over the entire heart with MRI is generally accomplished by 2-dimensional imaging of multiple slices. Cardiac motion appears frozen if the acquisition time for each image is short on the time scale of a heart beat, and if the image acquisition is synchronized to the heart rhythm.

Compared with other organs, the heart has a relatively high resting blood flow and blood volume on the order of ~1 ml/min per gram of tissue and 0.1 ml per gram of tissue, respectively. The wash-in of an injected contrast agent takes, under normal conditions, only a couple of heart beats. This determines the required temporal resolution for dynamic first pass studies. Multislice coverage of the heart and sequential imaging with a temporal resolution of ~1 image per heart beat for each slice location can be met with rapid T_1-weighted, gradient echo imaging techniques. T_1-weighted imaging is the method of choice for imaging of perfusion in the heart. Contrast agent bolus dosages typically used for T_1-weighted myocardial perfusion imaging of the heart give rise to a several-fold signal intensity increase over the precontrast level of signal intensity. T_2^*-weighted imaging is by definition sensitive to magnetic susceptibility changes produced by the introduction of paramagnetic contrast agents. T_2^*-weighted imaging is more prone to susceptibility-induced artifacts–the arrival of the contrast agent in the ventricular cavity gives rise to a marked drop of T_2^*-weighted signal intensity that extends into myocardial tissue.

Extracellular contrast agents such as Gd-DTPA, are commonly used for MRI perfusion studies. Extracellular contrast agents cross the cell membrane only after severe myocardial injury and the loss of myocardial viability has occurred (Judd et al., 1995; Kim et al., 1996; Lima et al., 1995; Tong et al., 1993a,b). The distribution volume of an extracellular contrast agent is larger in injured tissue than in normal tissue. Given sufficient time, an extracellular contrast agent reaches an approximate equilibrium distribution where the contrast enhancement of tissue relative to the contrast enhancement in the ventricular blood pool is proportional to the distribution volume (Pereira et al., 1996; 1999). Loss of viability and leakage of the contrast agent into the cell results in T_1-weighted signal hyperenhancement.

Both first pass perfusion studies and imaging of delayed hyperenhancement can be combined in one patient exam. The MRI protocols for myocardial perfusion and viability assessment are presented together in this unit due to the complimentary information that is obtained with both protocols. Also, the imaging techniques used for both protocols are closely related. Basic Protocol 1 should be used in patients with symptoms of coronary artery disease or ischemic cardiomyopathies. Basic Protocol 1 assesses the functional severity of coronary artery lesions. Basic Protocol 1 takes ~30 min, including the time for patient preparation and study set-up. If imaging of perfusion during pharmacological stress is included, the duration is increased to ~45 min. Basic Protocol 2 should be used, in addition to Basic Protocol 1, when a patient presents with symptoms of myocardial

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infarction or post-coronary revascularization to determine the presence and extent of nonviable myocardium. Basic Protocol 2 adds an additional 20 min for the completion of the examination.

BASIC PROTOCOL 1

IMAGING MYOCARDIAL PERFUSION DURING FIRST-PASS CONTRAST-ENHANCEMENT

By its very nature, the short repetition times and high bandwidths of fast imaging techniques used for myocardial perfusion imaging can create a challenge for achieving an acceptable signal-to-noise ratio (SNR) that allows reliable interpretation of the images. It is, therefore, generally only possible to obtain acceptable SNRs at field strengths of ≥1.0 T. The only exception occurs with echo-planar imaging sequences, which may work better at lower field strengths due to the inherent reduction of T_2^* artifacts at lower field strengths. Single-shot echo-planar imaging (EPI) techniques applied to the heart are more prone to image artifacts than multi-shot EPI techniques or segmented gradient-echo/EPI sequences. The latter can be used for cardiac perfusion imaging to improve the speed of image acquisition, without incurring a significant penalty in image quality.

Fast T_1-weighted imaging sequences, such as spoiled gradient-echo imaging with T_R's as short as 2 msec and a magnetization preparation for T_1-weighting, are applied to image the contrast-enhancement during the first pass of the injected contrast agent. Once the limits of gradient system performance have been reached with gradient-echo imaging, multi-shots between conventional gradient echo and echo-planar imaging provide an additional boost in image acquisition speed. Instead of reading out a single gradient echo after each slice-selective radio-frequency excitation pulse, segmented pulse sequences create a train of typically 3 to 5 gradient echoes after each radio-frequency excitation pulse. Reading out the closely spaced gradient echoes without the need to (re)apply a slice selective radio-frequency pulse before each gradient echo boosts the rate of image acquisition.

The image intensity obtained with an inversion-recovery (IR) or saturation-recovery-prepared fast gradient echo sequence is strongly T_1-weighted. With an IR preparation the signal intensity depends not only on the inversion time after the preparation but also on the state of the magnetization before the inversion pulse is applied. During rapid serial imaging with electrocardiograph-triggered (ECG-triggered) IR-prepared gradient echo sequences, therefore, the signal intensity depends on the heart rate. A saturation recovery magnetization preparation consists of a non-slice selective 90° radio frequency pulse, followed by a gradient crusher pulse to dephase the transverse magnetization (Tsekos et al., 1995). Driving the magnetization into a well-defined state, with all magnetization components nulled or dephased, allows one to obtain a T_1-weighted gradient-echo signal that is independent of the duration of an any previous relaxation recovery delay. The saturation recovery preparation prevents modulation of the image intensity, when the ECG-triggered image acquisition rate varies due to fluctuations in heart rate. Saturation-recovery prepared gradient echo imaging is therefore preferred over the inversion-recovery preparation when heart rate variations, or an unreliable ECG trigger are of concern (Tsekos et al., 1995). Furthermore, multi-slice imaging is more easily implemented with a saturation-recovery preparation than with an IR magnetization preparation (Wilke et al., 1997).

Rapid contrast agent administration is crucial for assessing myocardial perfusion with contrast agents as this improves the sensitivity for detecting changes of myocardial blood flow (Kroll et al., 1996). The goal is to assure that the primary bottleneck to the rate of contrast enhancement is the rate of transport of contrast agent through myocardial tissue, and not the rate at which the contrast agent is injected. The regional image intensity

Table A11.3.1 Equipment Parameters for First Pass Perfusion Imaging

Coil type	Quadrature phase-array torso coil.
Gradient coil strength	24 mT/m (or higher if the system permits)
Cardiac gating	Yes, fiber-optic systems are preferred for studies performed during pharmacologic stress or vasodilation
Peripheral gating	For safety only
Respiratory gating	No
Respirator	If required by patient
Oxygen	If required by patient
Breath-holding	Optional
Motion cushions	Can be used for patient comfort
Use of contrast agents	Extracellular or intravascular contrast agent administered with power injector through intravenous (i.v.) needle in antecubital vein
Power injector	Important for rapid and reproducible administration of contrast agent
Infusion pump	Required for pharmacological stress or vasodilation
Monitoring equipment	Heart rate, oxygen saturation, and blood pressure should be monitored with MRI-compatible equipment. EKG rhythm strip monitoring should be available if pharmacologic stress or vasodilation is planned.

contrast enhancement should ideally be proportional to the contrast agent concentration. Such an approximate linear relationship between regional signal intensity and contrast agent concentration is only observed at lower contrast agent dosages–typically, <0.05 mmol/kg of Gd-DTPA for fast, IR-prepared gradient-echo sequences ($T_R \leq 3$ msec; $T_E \leq 2$ msec; Jerosch-Herold et al., 1998). A more marked contrast enhancement can be obtained with higher contrast agent dosages, but then the kinetics of the contrast agent, and the correlation of contrast enhancement with tissue blood flow can not be assessed in a strict quantitative manner. The choice of contrast agent dosage is therefore in part dictated by the quantitative requirements for a perfusion study.

Table A11.3.1 lists the required equipment for first-pass perfusion imaging.

NOTE: Adenosine or dipyridamole is not FDA (Food and Drug Administration)-approved for use with MRI. Gd-DTPA is not FDA-approved for cardiac imaging. While any physician can use any drug already FDA-approved for another reason off-label, the protocol described herein suggests the off-label use of two drugs simultaneously. This protocol has been developed for research only.

Materials

Normal saline (0.9% NaCl), sterile
Extravascular GD-DTPA contrast agent (e.g., Magnevist or Omniscan)
16-G i.v. needle and injection line
Disposable syringes for power injector

Set up patient and equipment

1. The same precautions as with any other MRI exam should be followed when preparing a patient for an MRI examination of myocardial perfusion. Check for possible counter-indications and for ferromagnetic implants. For patients with heart

disease, check heart rate, blood pressure, and other vital signs while the patient undergoes the MRI examination. Emergency equipment such as a defibrillator, and emergency medications for treating cardiac arrests (e.g., epinephrine) should be nearby. If measurement of perfusion during vasodilation is being contemplated, a cardiac nurse or a cardiologist should be present to monitor the patient during the examination, and be prepared to initiate emergency procedures if an adverse event occurs.

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

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.

2. If the procedure is a research protocol, have the patient sign any necessary consent form.
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 and image artifacts.
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 earphones or headphones are used to protect the ears from the loud sounds produced by the gradients, the patient will be asked to wear these, but will be able to communicate with you at any time during the imaging.
   b. The patient will be given a safety squeeze-bulb or similar equipment to request assistance at any time (demonstrate how this works).
   c. For good results, the patient should not talk, and should avoid or minimize swallowing or other movement, during each scan–i.e., as long as the banging sounds continue. Between scans, talking and swallowing are allowed in most cases, but should be avoided when comparative positional studies are being performed; the patient will be informed when this is the case.
   d. Nevertheless, the patient may call out at any time if he or she feels it necessary.
6. An intravenous (i.v.) line should be started before the examination for administration of the contrast agent. Myocardial perfusion studies require either a central or peripheral injection of contrast agent, preferably with a power injector at a rate of 5 to 10 ml/sec. A venous catheter line advanced through the antecubital vein to the superior vena cava, or a 16-G needle in an antecubital vein, will allow injection of the contrast agent as a compact bolus. Use a dual-port connector with the needle to allow injection of contrast agent and infusion of pharmacological agent, such as adenosine.
7. If a power injector is used, the contrast agent and saline should be loaded under sterile conditions into the proper (disposable) syringes of the power injector. Great care should be taken to expel all air bubbles from the reservoirs and catheter lines. Luer fittings should be examined to ensure that they are secure and tight. Injection dosage and rate should be set appropriately. Newer power injector systems have touch-sensitive liquid crystal display (LCD) screens to set the injection parameters. Contrast agent injections should generally be followed without delay by an injection of physiologic saline solution to assure that the entire contrast agent dosage is injected

into the vein. A constant saline drip before and after bolus administration is recommended to keep i.v. injection lines open.

For older power injector models that cannot be brought near the magnet, the contrast agent is preloaded through an i.v. catheter and a long i.v. line is connected to a remotely positioned power injector.

8. Position the patient supinely on the scanning table. Provide him/her with a cushion under the legs for comfort.

9. Place the ECG electrodes around the heart with ≤4 in. of separation between them. This results in an improved quality of the ECG signal and more reliable triggering of the pulse sequence. Align the ECG wires parallel to the magnetic-flux lines of the static magnetic field. Conductive cables should not cross inside the bore, and they should also be kept away from the sides of the bore. These precautions are necessary to minimize the risk of burns due to radio-frequency power deposition.

   ECG triggering is often a source of problems in cardiac MRI examinations due to degradation of the ECG signal by superimposed voltages that are generated by blood flow through the great vessels while the patient is positioned in a strong magnetic field. Special MR-compatible physiologic recorders, which can be interfaced with the MRI scanner, often use customized ECG electrodes and proprietary filtering techniques to reduce artifacts in the ECG.

   The ECG electrodes may be placed on the chest or back. Placing them on the chest is best for monitoring, but in this position the ECG signal is more susceptible to artifacts from breathing motion, as well as image artifacts from the leads affecting the right ventricle. The dry rub method improves electrode contact to the skin and reduces contact resistance. If the baseline of the ECG moves up and down with respiration, then the ECG leads need to be moved up higher on the chest. Asking the patient to avoid strong breathing motion can help. Reducing the distance between the ECG leads can reduce interference from switching of the gradient coils.

   The quality of the ECG signal is normally just sufficient for counting the heart rate and triggering the MR image acquisition with the R wave of the QRS complex, but not good enough to diagnose the on-set of ischemia from changes in the ST segment. (Q, R, S, and T are the standard nomenclature for distinctive features on the ECG trace that correspond to well defined events during the cardiac cycle. The reader is referred to introductory physiology textbooks for further details.) It is therefore important to supplement the ECG signal with measurements of the arterial oxygen saturation and blood pressure, especially if the patient will be undergoing a stress protocol or pharmacological vasodilation in the magnet. If pharmacologic stress or vasodilation is planned, fiber optic leads that reduce the signal artifact caused by patient motion and radiofrequency interference is preferred. A rhythm strip should be run between each sequence acquisition during adenosine, dipyridamole, or dobutamine administration. While ischemic changes cannot be monitored, the strips can be monitored for heart block or arrhythmias.

10. Wrap blood pressure cuff around the arm to monitor blood pressure. MRI compatible monitoring systems use a pump that inflates and deflates the blood pressure cuff at predefined time intervals or when the technologist manually initiates a blood pressure measurement. Place a fiber optic sensor on the patient's finger to measure the arterial oxygen saturation. Take note of the baseline heart rate, systemic blood pressure, and oxygen saturation.

11. Use a dedicated cardiac coil for these studies to maximize the achievable SNR. Center the coil at the level of the heart, or over the patient's heart, if a relatively small surface coil is used.

    In many cases phase-array coils with anterior and posterior elements fitted under the patient and over the patient's chest work best for this purpose.

Table A11.3.2 Primary Clinical Imaging Parameters for Sequence 1 (Pilot Scan)

Patient position	Supine
Scan type	Fast gradient echo with dark blood preparation
Imaging plane (orientation)	Transverse, pseudo-long axis, double oblique short axis
Central slice or volume center	Laser light centered on coil center (at heart)
Echo time (T_E)	2.3 msec
Repeat time (T_R)	5 msec
Flip angle (FA)	10°
Fields of view (FOV_x, FOV_y)	400 mm, 400 mm
Resolution (Δx, Δy)	1.56 mm, 3.13 mm
Number of data points collected (N_x, N_y)	256, 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	10 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Slice location	Not applicable
Saturation pulses	Not applicable
Scan time	~600 msec

12. Instruct the patient on the procedure for breath-holding during the MRI examination. First pass studies can be performed with the patient breathing normally, although the absence of breathing motion facilitates interpretation of the images.
13. Provide the patient with headphones or earplugs. The intercom equipment should be used during the MRI study to guide the patient and assure his/her cooperation. Alert the patient before an i.v. injection or infusion, particularly in cases where the infusion of a pharmacological agent induces hemodynamic changes. Tell the patient to signal any discomfort or the onset of pain. Communication with the patient is important for the success and safety of the study!
14. Position the patient in the magnet such that the heart is in the center of the magnet.
15. Check that a strong ECG R-wave is received before proceeding. Otherwise the ECG leads have to be reconfigured to produce a more prominent R-wave peak.

Sequence 1: Scout imaging of the heart

16. Acquire a transverse scout with a fast gradient echo sequence, preferably with dark blood preparation for better visualization of ventricular cavities. Typical sequence parameters for such a pulse sequence are listed in Table A11.3.2.
17. *Oblique pseudo-long axis scout:* Prescribe on the previous image a slice through the middle of the left ventricle and acquire an image for this view as localizer.
18. *Horizontal long axis scout:* Prescribe on previous scout, a slice parallel to the septum, centered in the LV cavity, positioned from the LV apex, through the mid portion of the mitral valve. Acquire image. An example of the images obtained by following steps 16 to 18 is shown in Figure A11.3.1.

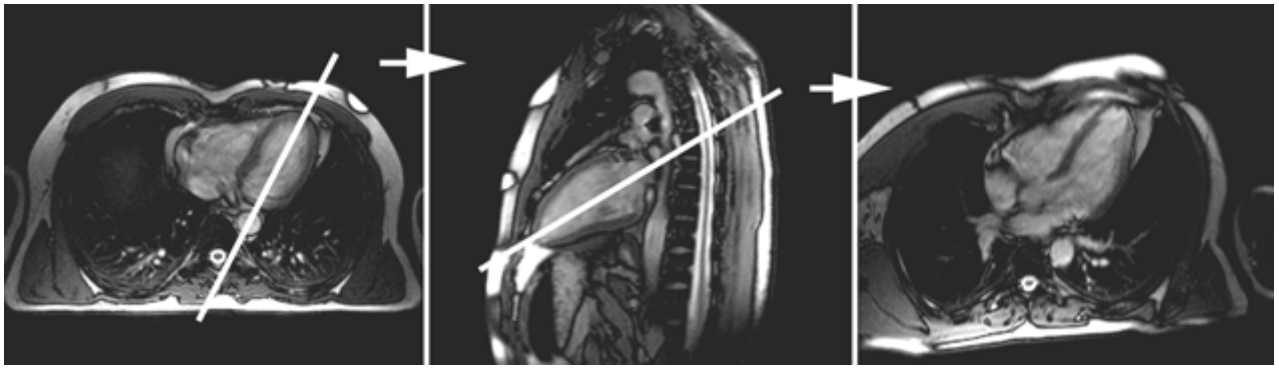

Figure A11.3.1 Scout images for transverse (step 16), pseudo-vertical long axis (step 17), and pseudo-horizontal long axis (step 18) in left-to-right order. The images were acquired with a fast steady-state free-precession (SSFP) scout imaging technique ("true FISP"), which was used because of the excellent definition of anatomical structures that is achieved with this technique. The use of SSFP imaging is currently limited to MRI systems with high-performance gradient systems. The thick white lines denote the image plane orientation for the next scout image to the right.

19. Acquire one mid-ventricular short axis view as second localizer. This second localizer is used in setting up sequences 2 and 3 to determine the smallest possible field of view dimensions that do not cause wrap-around that obscures the view of the heart.

Sequence 2: Magnetization-prepared, T_1-weighted FLASH (fast low angle shot) perfusion imaging

20. Call up the rapid, multi-slice T_1-weighted spoiled gradient-echo imaging as described in Table A11.3.3. Either a saturation-recovery or an inversion-recovery preparation can be used, although the former appears to be more advantageous for multi-slice, arrhythmia-insensitive imaging (Tsekos et al., 1995; Wilke et al., 1997). Table A11.3.4 gives the parameters for an inversion-recovery (IR) prepared echo-planar sequence, that can be used as an alternative to the sequence in Table A11.3.3 for myocardial perfusion imaging. Figure A11.3.2 shows a diagram of the pulse sequence protocol.

    IR-prepared segmented echo-planar pulse sequences represent a useful alternative on some scanners for first pass perfusion imaging (Ding et al., 1998; Fischer and Lorenz, 1997; Reeder et al., 1999). Instead of reading out all image data after a single radio-frequency (RF) pulse as is done in single-shot EPI, in multi-shot sequences RF pulses are applied repeatedly to produce short echo trains. The echo train length after each radio-frequency pulse is 4 to 6 echoes, and the optimal T_R is on the order of 10 to 15 msec at 1.5 T (Epstein and Arai, 2000). The pulse sequence is optimized for high temporal resolution (~6 to 7 slices per 2 R-to-R intervals). A slice-selective inversion-recovery magnetization preparation is applied for each slice. For multi-slice acquisitions, the slice-selective IR preparation for a given slice can be applied right before the EPI readout for a preceding slice to maximize the efficiency in image acquisition while maintaining a sufficiently long inversion time to optimize the T_1-weighting. For example, the IR preparation pulse for slice 2 is applied just before the EPI readout of slice 1. This construction constrains the choice of T_I but in practice the duration of the EPI read-out matches well the optimal T_I values. Call up the rapid, multi-slice, T_1-weighted, multi-shot echo-planar imaging sequence as described in Table A11.3.3.

21. Preset the contrast agent injection dosage at ~0.04 to 0.1 mmol/kg times patient body weight in kilograms divided by the concentration of Gd-DTPA when T_R/T_E/FA of the saturation-recovery prepared spoiled gradient echo sequence are on the order of 2.4 msec/1.2 msec/18°, respectively. Injection rate depends on the size of the i.v. needle or catheter but should be on the order of 5 ml/sec for a compact bolus.

    It is useful to remember that the injection rate specified on the control panel of the injector is often a nominal injection rate that is not reached if the catheter size is too small.

Table A11.3.3 Primary Clinical Imaging Parameters for Sequence 2 (First Pass Perfusion, T_1-weighted FLASH Variant)

Patient position	Supine
Scan type	Rapid serial, multislice 2-D gradient echo imaging with magnetization preparation for T_1-weighting
Imaging plane (orientation)	Double oblique short axis view
Central slice or volume center	Centered over the heart
Echo time (T_E)	1.2 msec, or as short as possible (usually <2 msec)
Repeat time (T_R)	2.4 msec or short as possible (usually <3 msec)
Inversion time (T_I)	10 msec for saturation recovery preparation and 100–150 msec for inversion recovery preparation
Flip angle (FA)	15°–18°
Fields of view (FOV_x, FOV_y)	320 mm, 320r mm, with r = 6/8 (rectangular field of view)
Resolution (Δx, Δy)	2.50 mm, 2.76 mm
Number of data points collected (N_x, N_y)	128, 118r, with r = 6/8 (rectangular field of view)
Display matrix (D_x, D_y)	128, 128
Slice thickness (Δz)	10 mm
Number of slices	2–6, or as many as needed to cover the heart from base to apex
Slice gap	0.3–0.5 of slice thickness
Number of acquisitions (N_{acq})	1
Number of repetitions	40 (number of serial images for first pass study)
Swap read and phase encoding	Only if this reduces aliasing artifacts and allows reduction of FOV
Slice location	User define short axis locations between base and apex
Saturation pulses	No
Slice series	Interleaved
ECG gating	Yes
Scan time	~40 R-to-R intervals

22. Adjust the number of phase encoding steps (N_y) to a value between 80 and 120 such that the combination of phase encoding steps and the number of slices result in an image acquisition time that matches the heart rate. Maintain an in-plane spatial resolution of <3 mm.

For a heart rate of 60 beats/min (R-to-R interval of 1000 msec) the repetition time (T_R) times the number of phase encoding steps (N_y) plus the time for the magnetization preparation (T_I) determine the time required to image one slice (T_{ACQ}): $T_{ACQ} = N_y^* T_R + T_I$. This time ($T_{ACQ}$) multiplied by the number of slices should be less than the R-to-R interval to maintain a temporal resolution of 1 image per heart beat for each slice location. The idle time at the end of the R-to-R interval should be ≥40 msec to anticipate possible small increases in heart rate during the image acquisition that could cause intermittent changes in rate of image acquisition.

Table A11.3.4 Primary Clinical Imaging Parameters for Sequence 2 (First Pass Perfusion, Multishot EPI variant)

Patient position	Supine
Scan type	Rapid, IR-prepared, segmented (multi-shot) EPI sequence
Imaging plane (orientation)	Double oblique short axis view
Central slice or volume center	Centered over the heart
Echo time (T_E)	As short as possible (usually <2 msec)
Echo train length (ETL)	4–6
Repeat time (T_R)	As short as possible (usually <15 msec)
Inversion time (T_I)	100–200 msec
ECG trigger delay	Minimum
Flip angle (FA)	20°
Fields of view (FOV_x, FOV_y)	360 mm, 360r mm, with r = 3/4 (rectangular field of view)
Resolution (Δx, Δy)	2.80 mm, 2.80 mm
Number of data points collected (N_x, N_y)	128, 128r, with r = 3/4 (rectangular field of view)
Display matrix (D_x, D_y)	128, 128
Slice thickness (Δz)	8 mm
Number of slices	3–6, or as many as needed to cover the heart from base to apex
Slice gap	0.25 of slice thickness
Number of acquisitions (N_{acq})	1
Number of repetitions	~40
Swap read and phase encoding	Only if this reduces aliasing artifacts and allows reduction of FOV
Slice location	User define short axis locations between base and apex
Saturation pulses	No
Slice series	Interleaved
ECG gating	Yes
Scan time	~40 R-to-R intervals

23. Use the scout images acquired earlier to prescribe the slices for the perfusion study. Except for the visualization of apical perfusion defects, double oblique slices that give a short axis view of the heart are recommended for this study. For multi-slice acquisitions, set the gap between slices to 30% to -50% of the chosen slice thickness.

    An arbitrary gap thickness may be chosen if maintenance of adequate temporal resolution (1 image per 1 to 2 heart beats) allows only imaging of 2 to 3 slices. The choice of slice locations is often guided by findings from wall-motion studies that are performed beforehand. Slice positions are then chosen based on the location of wall-motion defects.

24. Minimize the fields of view without causing aliasing ("wrap-around") artifacts. Use the double oblique short-axis localizer (see sequence 1) for this purpose. Choose the read-out direction parallel to the chest wall as this reduces the possibility of aliasing and other artifacts. See Figure A11.3.3 showing perfusion images for three slice locations.

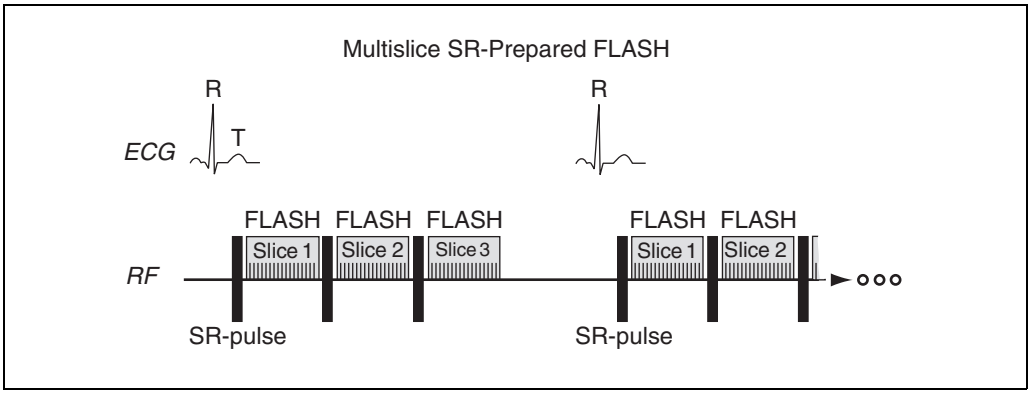

Figure A11.3.2 Schematic sequence diagram of multislice perfusion imaging sequence with nonslice-selective saturation-recovery (SR) preparation before each FLASH readout. The delay between the SR preparation and the FLASH readout can be kept as short as 10 msec and still provides good T_1-weighting of the signal intensity. By comparison, an inversion recovery preparation requires a relaxation delay (T_I) of ~100 msec. A slice-selective magnetization-preparation would lead to modulation of the signal intensity from spins flowing into the magnetization-prepared volume. A nonslice-selective preparation pulse eliminates this flow-dependent modulation of the signal intensity.

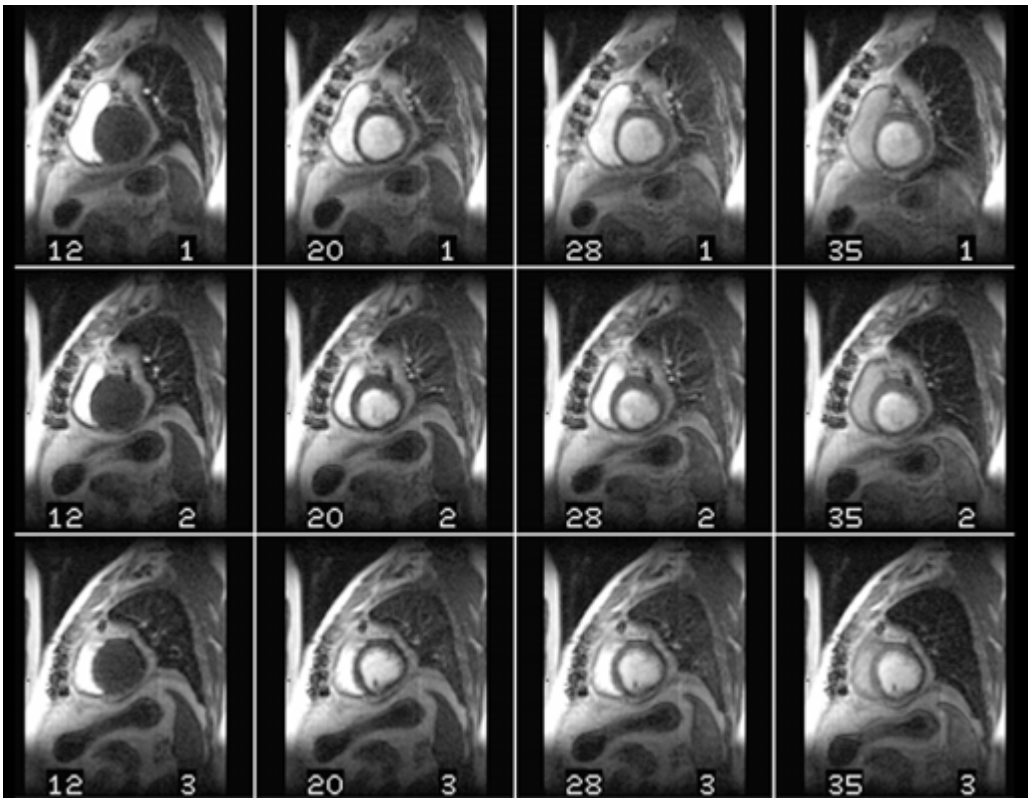

Figure A11.3.3 Selected frames from a multislice first pass perfusion study acquired in a 53 year old male patient with a scarred infarct in the inferior wall. The images are arranged in separate rows for each slice position, and in each row the images show the sequential appearance of the contrast agent bolus in the right ventricle, the left ventricle, and enhancement of myocardial tissue. Images were acquired while the patient held his breath. The images in this example have not been cropped and they illustrate how the rectangular field of view is adjusted to avoid wrap-around in the phase encoding direction, which can otherwise obstruct the view of the heart.

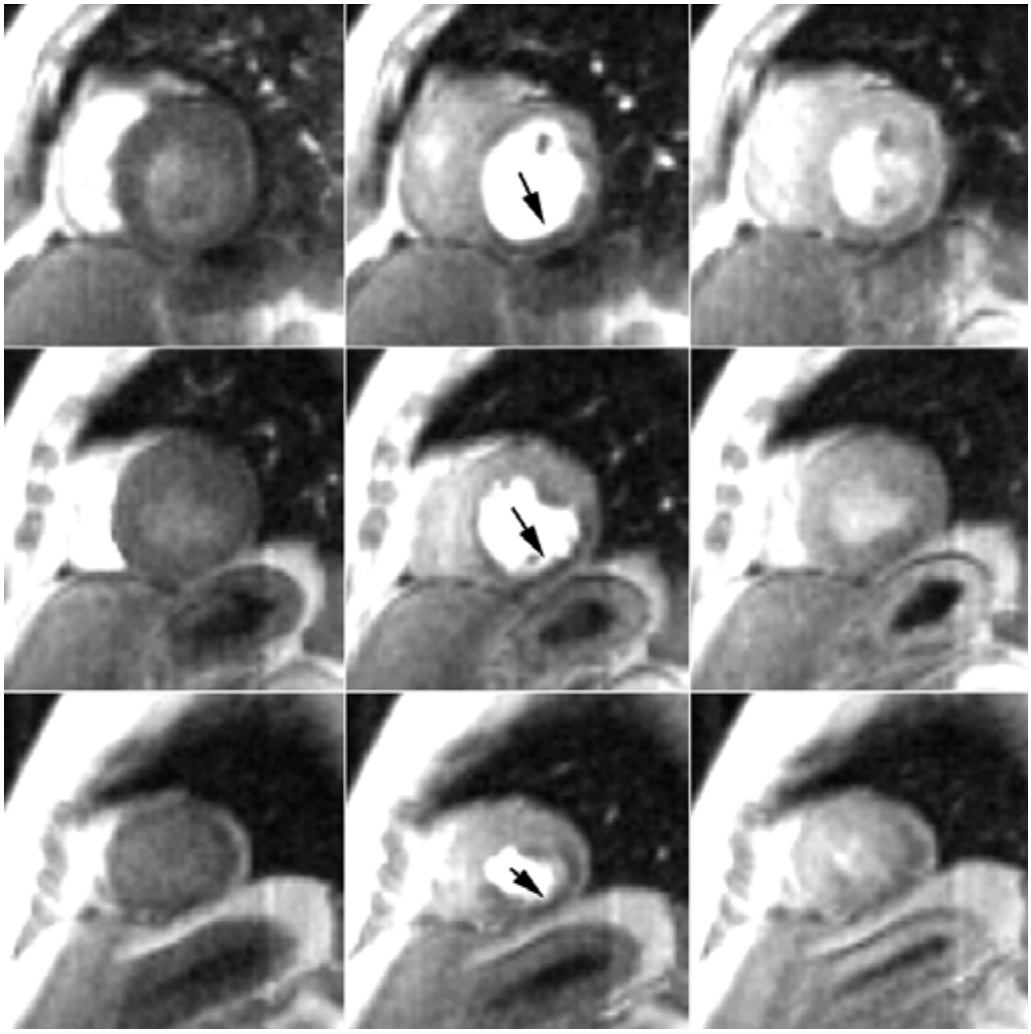

Figure A11.3.4 Magnified multislice perfusion images in a patient with an inferior perfusion defect. The perfusion defect results in a reduced and slowed contrast enhancement after the first pass through the left ventricle. Patient had shown a fixed defect in the inferior wall segment on single plot on emission computed tomography (SPECT).

25. Start the pharmacological stress protocol before the contrast injection if this is part of the study. Note that adenosine requires 3 min to reach steady state. Slowly increment the dosage of the pharmacological agent, such as dipyridamole or adenosine if induction of hyperemia is desired. Monitor the patient's blood pressure and heart rate. Run a rhythm strip between each dose increase and between each sequence acquisition. Observe for an atrial block or any other abnormalities in heart-rhythm. Discontinue the infusion immediately in case problems develop. Have aminophylline ready in case dipyridamole was used, and it becomes necessary to relieve or reverse its effects.

    The first pass measurement during pharmacological stress can be repeated at 10 to 15 min after a previous first pass study, for example, a baseline "rest" study. The first pass studies can be repeated up to 3 times with a dosage of 0.03 to 0.05 mmol/kg of Gd-DTPA and with the sequence parameters shown in Table A11.3.2.

    The effect of potent coronary vasodilators such as adenosine or dipyridamole is adequate for perfusion imaging when the heart rate increases by 10 bpm and diastolic blood pressure decreases by 10 mm Hg. The patients often feel some chest pressure and slight discomfort during vasodilation with adenosine or dipyridamole. Patients on beta-blockers will not show a significant rise in heart rate during i.v. adenosine or dipyridamole.

26. The power-injector should be armed, i.e., readied for injection.

27. If breath-holding is used, the patient should be asked to take a deep breath and hold his/her breath.

    This pulse sequence does not necessarily require breath-holding to avoid breathing motion artifacts in the image. It is nevertheless recommended that the patient holds his/her breath as long as possible so that the position of the heart appears fixed in consecutive images.

28. Begin the scan as soon as the patient starts to hold his/her breath. Listen for regular sounds from the gradients that indicate regular triggering of the pulse sequence by the ECG. The contrast agent injection should be started after acquisition of 3 to 4 "baseline" images.

Process data and view for sequence 2

29. View the acquired series of sequential images in cine mode to determine that the contrast agent bolus was successfully injected. It is important to ascertain that a sufficient number of images were acquired to track the passage of the contrast agent through the first pass at least to the beginning of recirculation in the left ventricular cavity. This initial visual assessment should be performed immediately after image acquisition. Absence of any contrast enhancement due to a problem with the contrast agent injection or other malfunctions should be corrected and the study repeated no earlier than 5 min after the previous contrast injection.

    The initial visual assessment already provides an impression about any spatial heterogeneities and temporal delays in myocardial contrast enhancement. This may indicate regional impairments in myocardial blood flow, but potential pitfalls in interpretation like a drop-off in signal intensity due to an inhomogeneous surface coil profile need to be kept in mind. Figure A11.3.4 shows an example from a "rest" study in a patient with a fixed perfusion defect in the inferior wall. Pharmacological vasodilation is necessary to detect mild to moderate perfusion defects.

BASIC PROTOCOL 2

IMAGING MYOCARDIAL VIABILITY

With imaging of hyperenhancement, the requirements for very short image acquisition times can be somewhat relaxed to improve the signal-to-noise ratio (SNR) and the spatial resolution. Nevertheless the avoidance of image artifacts from cardiac motion still requires that the image acquisition be performed only during a relatively small fraction of the cardiac cycle, and preferably during the most quiescent diastolic period of the cardiac cycle. The most successful techniques employed for imaging of delayed (hyper-) enhancement in injured and/or infarcted myocardium have resorted to the segmented acquisition of the *k*-space data, but are otherwise very similar to the imaging techniques employed for first pass imaging. The goal is to maximize the T_1-weighted contrast, with minimum interference from T_2* effects and cardiac motion.

T_1-weighted imaging is applied ~10 to 20 min after injection of the contrast agent to identify severely injured, nonviable myocardial segments (Tong et al., 1993a). For delayed enhancement studies, one is interested in the imaging differences of distribution volume of the contrast agent. By the time the contrast agent distribution is in a semi-equilibrium, the duration of the contrast agent injection has no noticeable effect, unless prolonged over minutes. Hand injections of the contrast agent are therefore acceptable. Image sequences that employ segmented acquisitions of *k*-space data require breath-holding for the duration of each image acquisition to achieve optimal image quality.

Timing for imaging of hyperenhancement is an important aspect of this study. The time to reach 90% of equilibrium concentration depends on the distribution volume, but

generally does not >15 min (Tong et al., 1993a). Larger infarcts can show a core zone that initially lacks enhancement even at ≥5 min after contrast agent injection. This phenomenon, linked to microvascular obstruction, was shown to carry a graver prognosis for the patient, than if the core no-enhancement zone was absent (Rochitte et al., 1998; Wu et al., 1998b). Microvascular obstruction creates a severe bottleneck for the delivery of contrast into the affected zone, but given sufficient time a central no-enhancement zone will also display hyperenhancement compared to remote zones (Wu et al., 1998a). The observation of hypoenhancement and hyperenhancement will depend on the delay between contrast agent injection and acquisition of the images. A hypoenhancement zone with a surrounding hyperenhanced rim indicates that contrast agent has not yet reached the core zone. A dark core zone can not simply be interpreted as a zone with reduced distribution volume. The measurement should be repeated after an additional delay.

In cases where relatively low dosages of contrast agent are used for the first pass study, one would follow the first pass study with a second and higher dosage injection of contrast agent to image the late-enhancement. Typical dosages used for imaging of viability are on the order of 0.1 to 0.2 mmol/kg of Gd-DTPA. For example, with a bolus dosage of 0.05 mmol/kg of Gd-DTPA for a first pass study an additional dosage of 0.15 mmol/kg of Gd-DTPA contrast agent should be injected for imaging of viability. The time delay after injection of the contrast agent and before imaging of the delayed hyperenhancement should be used for optimizing the T_1-contrast through adjustment of the image parameters, primarily the inversion time T_I.

Set up patient and equipment

1. The same precautions as with any other MRI exam should be followed when preparing a patient for an MRI examination of myocardial viability (see Basic Protocol 1). This includes checking for possible counter-indications and for ferromagnetic implants. For patients with suspected acute myocardial infarction, heart rate, blood pressure, and other vital signs should be checked while the patient undergoes the MRI examination. Emergency equipment such as a defribillator, and emergency medications for treating cardiac arrests (e.g., epinephrine) should be nearby.
2. An i.v. injection line for administration of contrast agent should be started before the examination.
3. Position the patient supinely on the scanning table. Provide him/her with a cushion under the legs for comfort.
4. Place the ECG electrodes around the heart with ≤4 in. of separation between each one. This results in an improved quality of the ECG signal and more reliable triggering of the pulse sequence. Align the ECG wires parallel to the magnetic flux lines of the static magnetic field. Do not cross the conductive cables inside the bore, and also keep away from the sides of the bore.

   These precautions are necessary to minimize the risk of burns due to radio-frequency power deposition.

   ECG triggering is often a source of problems in cardiac MRI examinations due to degradation of the ECG signal by superimposed voltages that are generated by blood flow through the great vessels while the patient is positioned in a strong magnetic field. Special MR-compatible physiologic recorders, which can be interfaced with the MRI scanner, often use customized ECG electrodes and proprietary filtering techniques to reduce artifacts in the ECG.

   The ECG electrodes may be placed on the chest or back. Placing them on the chest is best for monitoring, but in this position the ECG signal is more susceptible to artifacts from

breathing motion, as well as artifacts from the leads affecting the right ventricle. The dry rub method improves electrode contact to the skin and reduces contact resistance. If the baseline of the ECG moves up and down with respiration, then the ECG leads need to be moved up higher on the chest. Asking the patient to avoid strong breathing motion might help. Reducing the distance between the ECG leads might reduce interference from switching of the gradient coils.

5. Use a dedicated cardiac coil for these studies to maximize the achievable signal-to-noise ratio. Center the coil at the level of the heart, or over the patient's heart, if a relatively small surface coil is used.

   In many cases phase-array coils with anterior and posterior elements fitted under the patient and over the patient's chest work best for this purpose.

6. Instruct the patient on the procedure for breath-holding during the MRI examination. Breath-holding durations are relatively short (i.e., ~10 sec) for T_1-weighted imaging of viability with segmented *k*-space acquisition, as described below.

7. Provide the patient with headphones or earplugs. Tell the patient how to communicate to the persons performing the exam while he/she lies in the magnet. The intercom equipment should be used during the MRI study to guide the patient and assure his/her cooperation.

8. Position the patient in the magnet such that the heart is in the center of the magnet.

9. Check that you receive a strong *R*-wave before proceeding. Otherwise the ECG leads have to be reconfigured to produce a more prominent *R*-wave peak.

10. Run the scout sequence as listed in sequence 1 of Basic Protocol 1.

Sequence 3: T_I-weighted gradient-echo imaging with segmented acquisition

11. Call up the protocol with a pulse sequence for rapid, T_1-weighted imaging as described in Table A11.3.5. The parameters in Table A11.3.5 are for an ECG-triggered FLASH sequence with segmented acquisition of *k*-space lines (33 lines per segment) and a non-slice selective inversion recovery (IR) magnetization preparation (Simonetti et al., 2000). Figure A11.3.5 shows a pulse sequence diagram that illustrates the acquisition technique and acquisition parameters.

    The IR magnetization preparation should be repeated before each k-space acquisition. For the parameters listed in Table A11.3.5, and a contrast agent dosage of 0.2 mmol/kg, one should use an inversion time (T_I) of 150 msec as starting value. T_I refers to the delay between the inversion pulse and the acquisition of the first phase-encoded line of a segment, as illustrated in Fig. A11.3.5. The definition of T_I can vary between different sequences and is also manufacturer-dependent. It may, for example, also refer to the time between the inversion pulse and the acquisition of the central k-space line of each segment. T_I needs to be adjusted by the user to null the signal from presumably normal myocardium, and to maximize the differential contrast enhancement of injured and non-viable myocardium. The protocol produces best results if the patient holds his breath during image acquisition.

12. A delay of at least 2 heartbeats should follow the acquisition of each *k*-space segment to allow for relaxation of the magnetization before the next inversion-recovery preparation is applied. Without a delay the observable contrast enhancement is reduced.

    As with all breath-hold sequences, the adjustment of the total number of phase encoding steps, the relaxation delay after acquisition of a k-space segment and the number of averages should result in a total acquisition time that is within a comfortable breath-hold duration.

Table A11.3.5 Primary Clinical Imaging Parameters for Sequence 3 (Distribution Volume Assessment)

Patient position	Supine
Scan type	Rapid segmented 2-D gradient echo with magnetization preparation for T_1-weighting
Imaging plane (orientation)	Double oblique short axis view
Central slice or volume center	Centered over the heart
Echo time (T_E)	<3.5 msec, or as short as possible
Number of lines per segment	23–30
Repeat time (T_R)	<8 msec, or as short as possible
Inversion time (T_I)	~150–250 msec
Delay time (T_D)	Adjust to T_D to obtain diastolic images
Flip angle (FA)	15°
Fields of view (FOV_x, FOV_y)	350 mm, 350*r* mm, with r = 3/4 (rectangular field of view)
Resolution (Δx, Δy)	1.37 mm, 1.59 mm
Number of data points collected (N_x, N_y)	256, 220*r*, with r = 3/4 (rectangular field of view) (segmented acquisition of phase encoding steps if possible)
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6 mm
Number of slices	1; repeated breath-holds for acquisition of contiguous slices from base to apex
Slice gap	0.0–0.5 of slice thickness
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	Only if this reduces aliasing artifacts and allows reduction of FOV
Slice location	User define short axis locations between base and apex
Saturation pulses	No
Slice series	Interleaved
ECG gating	Yes
Scan time	6–12 heart beats

13. If the patient can not hold his/her breath, the number of acquisitions (or number of excitations – NEX) needs to be set to a value of ≥3 to average out respiratory motion. The number of averages can be <3 if respiratory gating can be used.

14. Use the scout images acquired earlier to prescribe the slice positions for imaging of delayed hyperenhancement.

    Imaging the entire heart with contiguous slices in the short-axis orientation assures that the extent of infarcts or severe injury can be accurately assessed.

15. Inject the contrast agent and take note of time. Wait now ≥1 min before starting to optimize the inversion time (T_I). This requires acquiring images for a series of different T_I values, and determining the T_I that will result in nulling of signal from normal myocardium. T_I can be set 5% to 10% higher than the optimal value to

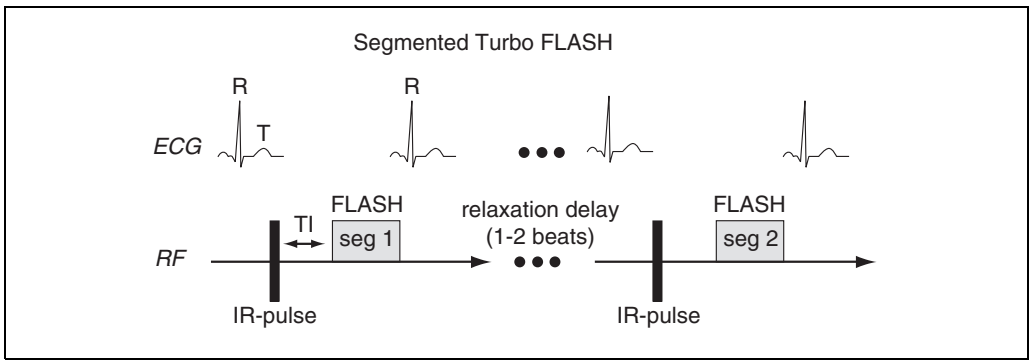

Figure A11.3.5 Timing diagram for segmented, ECG-gated gradient echo sequence with inversion recovery preparation for imaging of delayed enhancement. The inversion-recovery preparation is repeated before acquisition of each segment of phase-encoding lines, and a sufficient delay on the order of 2 to 3 heartbeats needs to be placed between the inversion pulse and the previous segment acquisition. The inversion time (T_I) is adjusted 1 to 2 min after injection of the contrast agent to null the signal in normal myocardium.

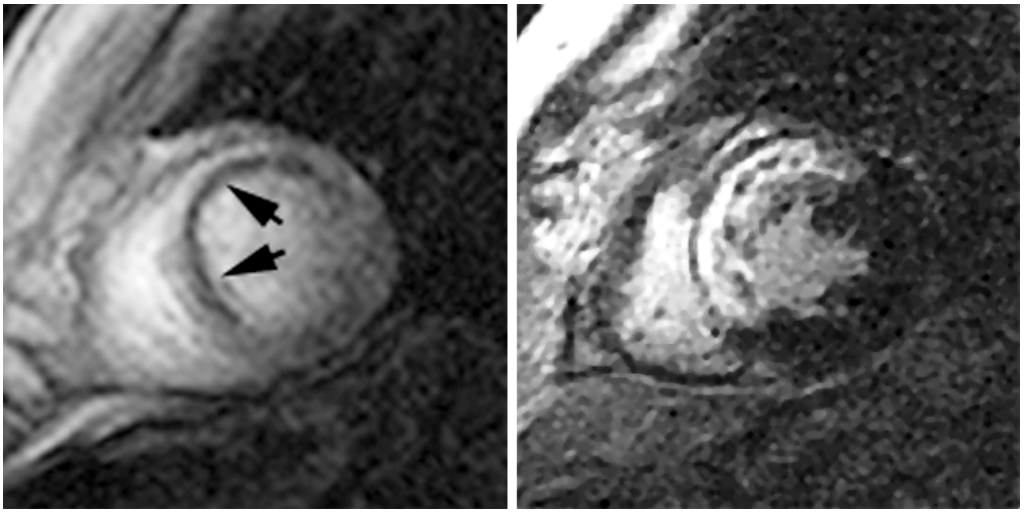

Figure A11.3.6 Images of early (left) and delayed (right) contrast enhancement in a 65 year old male patient 4 days after his first acute large anterior myocardial infarction (creatine kinase >7000). In the images of the early enhancement a dark region in the antero-septal region indicates the presence of a no-reflow zone. The image acquired with a 10 min delay shows hyperenhancement in the same area and clearly delineates the extent of the infarction. The images were acquired with an ECG-gated fast gradient echo sequence with an inversion recovery preparation for maximum T_1-weighting. Blood signal supression was used for better delineation of the endocardial border, and images were acquired at end-diastole. Images courtesy of Drs. João Lima and Bernhard Gerber, Johns Hopkins Medical Institution, Baltimore.

anticipate the slow, but steady decrease of contrast agent concentration (the half-time for Gd-DTPA is ~30 min).

16. Acquire images for slices in the short axis orientation from base to apex using a 6-mm slice thickness and no gap, or a small gap of <0.2 of slice thickness. Ask the patient to hold his/her breath for each image acquisition as the sequence for the slice positions from base to apex is repeated.

For the detection of microvascular obstruction it is necessary to perform the acquisition of images <5 to 10 min after the injection of contrast agent (Rochitte et al., 1998; Rogers et al., 1999). The hypoenhancement characeteristic of microvascular obstruction will only persist for a limited period after which the contrast between non-infarcted tissue and the zone with microvascular obstruction disappears. Consistent hyperenhancement through-

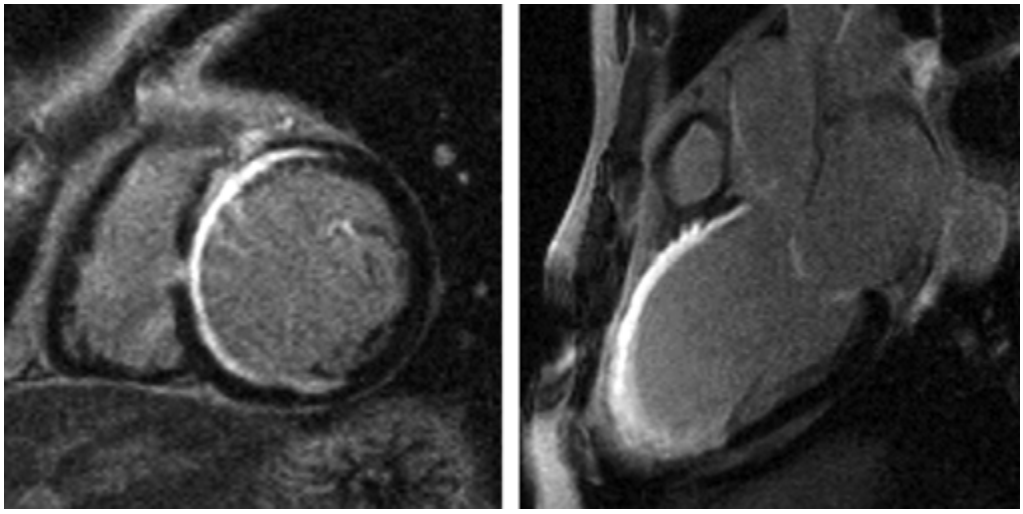

Figure A11.3.7 Images of delayed contrast enhancement obtained in a 49-year-old male with a history of two myocardial infarctions—one myocardial infarction (MI) four years before MRI followed by percutaneous transluminal coronary angioplasty (PTCA) and stent to his right coronary artery (RCA). The images shown in the figure were acquired 2.5 months after a second, anterior wall MI and subsequent coronary artery bypass graft (CABG) surgery. Gadolinium DTPA of 40 ml was used and imaging was performed ~30 min after contrast injection with a segmented turbo FLASH sequence as shown in Fig. A11.3.5. Images provided by Dr. R. White, Cleveland Clinic Foundation.

out the entire infarct zone has been reported in studies where contrast enhancement was measured 20 to 30 min after injection of the contrast agent (Kim et al., 1999). Figure A11.3.6 shows images during early (<1 to 2 min post-injection) and delayed enhancement (~10 min post-injection) acquired in a patient with myocardial infarct in the anterior wall. Figure A11.3.7 shows images in another patient acquired ~30 min after contrast agent injection with the sequence and parameter settings described in Table A11.3.5.

Gadopentetate dimeglumine (Gd-DTPA) has been the predominantly used contrast agent for studies of myocardial viability. Hyperenhancement of injured and non-viable myocardial tissue reflects an increased volume of distribution compared to normal myocardium. With protein-binding contrast agents the hyperenhancement in injured and/or non-viable myocardium may not only reflect an increase of the distribution volume but also a change of the contrast agent relaxivity with binding to proteins released after myocardial injury.

Process data and view for sequence 3

17. View images of delayed contrast enhancement with an identical window-setting for all slices. A simultaneous display of images for all slices is recommended for a visual assessment of the extent of contrast hyperenhancement.

18. Software with simple planimetric measurement tools is useful to quantify the extent of myocardial regions with contrast hyperenhancement. Determine the signal intensity in the region with hyperenhancement and in a remote region. Measure the relative area of hyperenhancement in each slice.

COMMENTARY

Background Information

Coronary artery diseases remain the most common cause of death for Americans. It is estimated that this year 1,100,000 Americans will suffer a new or recurrent myocardial infarction. Over 40% of people who experience a myocardial infarction in a given year will die from it. It is estimated that the economic cost of coronary artery disease in the United States was $118.2 billion in 1999. While nuclear medicine and echocardiography tests remain the primary imaging modalities for assessing the presence of myocardial ischemia and viability, each test suffers from limitations of spatial resolution and artifacts. First-pass MRI perfusion imaging is emerging as a very capable

alternative for non-invasive assessment. The excellent spatial resolution of MRI allows for the detection of subendocardial ischemia. This is not possible with other tests and explains, in part, why some studies reported better sensitivity and specificity with MRI than other non-invasive imaging tests.

While the first pass of gadolinium contrast agent is useful for the detection of ischemia, late enhancement of the myocardium identifies injured myocardium, infarct, and scar. It can be used to effectively assess viable myocardium. Late enhancement combined with the detection of wall motion abnormalities by MR cine appears to be highly effective in establishing a cardiac cause for chest pain in an emergency-room setting.

Critical Parameters and Troubleshooting

First pass image quality is limited by signal-to-noise ratio. Thus, it is advantageous to use a phase-array torso coil. As the sensitivity profile of these coils is less at the lateral wall of the left ventricle than the interventricular septum or anterior wall, signal in the lateral wall needs to be normalized not to mistake it for ischemia. This can be corrected by acquiring calibration images with the surface coil or the body coil as receive elements, respectively. Calibration images should be acquired for the same slice locations and fields of view as used for the perfusion study. Comparison of the signal intensity in the two calibration images for identical region of interest (ROI) locations allows accurate determination of the scaling factors that normalize the signal intensity curves to a common standard. Susceptibility changes with the passage of contrast through the heart can produce apparent subendocardial perfusion defects that are artifactual. These appear predominantly in the read direction and are more severe with longer T_E. These artifacts tend not to persist as long as true ischemic changes and can be accounted for with experience.

Better SNR is achievable at higher doses of gadolinium-based contrast agent. However, the high concentration of contrast media in the blood will result in saturation of signal and eliminates the potential for quantitative analysis. The authors find that 0.03 to 0.05 mmol/kg of Gd-DTPA provides adequate SNR with minimal saturation effects. It is possible to repeat the injection if necessary to either increase the coverage of the left ventricle or to obtain a stress set of images in addition to the baseline. Antecubital injections at 5 to 8 ml/sec provide a satisfactory bolus in most patients.

Adequate coverage of the left ventricle for first pass imaging requires at least three 1-cm slices in the short axis. The number of slices that can be obtained in a sequence depends on both the minimum T_R and the heart rate. Likewise, the spatial resolution (number of phase encoding steps) is inversely related to the temporal resolution. Thus, for fast heart rates, it may be necessary to obtain an image of every other heart beat in order to obtain adequate spatial resolution.

Optimal detection of myocardial ischemia depends on achieving maximal hyperemia. This may be accomplished with either adenosine or dipyramidole. It is vital to monitor the blood pressure to avoid hypotension. Additionally, it is important to remain in close communication with the patient to assess chest pain or dyspnea. If any of these conditions present, the drug is immediately discontinued and appropriate therapy is given.

A higher dose of contrast agent is commonly used for studies of enhancement. Good results have been obtained with 0.1 mmol/kg of Gd-DTPA. It is recommended to image 3 to 15 min after injection.

Anticipated Results

Visual inspection of first pass perfusion images can identify ischemic zones in many patients. As indicated above, it is important to assure that a dark zone is not an artifact by verifying that it persists for more than a few seconds. Even greater sensitivity may be achieved by the use of quantitative methods that model the tissue perfusion.

Delayed enhancement of infarcted myocardium appears to be robust and a number of groups have excellent results with this simple test. There does remain some controversy as to whether all hyperenhanced myocardium is in fact non-viable (Rogers et al., 1999). Nevertheless, in the appropriate setting, this is a very useful test.

Data processing and viewing of perfusion images

Region of interest analysis is very useful to generate time courses for the signal intensity that facilitate the interpretation of regional contrast enhancement (Wilke et al., 1993). Changes in signal intensity from image to image are assumed to reflect changes in contrast agent residue concentration but this interpreta-

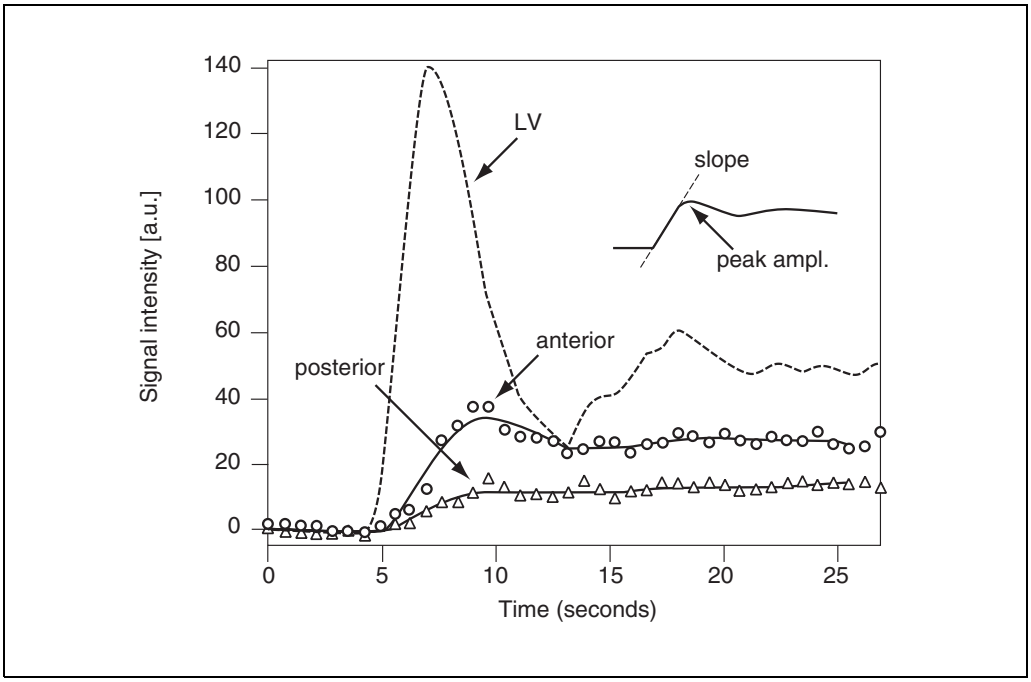

Figure A11.3.8 Signal intensity curves from regions of interest (ROI) in a series of perfusion images, that is also shown in Fig. A11.3.4. The signal intensity curves correspond to the basal slice position. The dashed line represents the signal changes in for an ROI in the center of the left ventricular (LV) cavity. The signal curves with open circles and triangles were obtained for transmural ROI's in the anterior and posterior segments, respectively. Signal curves were scaled to correct for inhomogeneity of sensitivity profile of the receiver coil. Relevant parameters for assessing perfusion in a semiquantitative manner are the up-slope during contrast agent wash-in, and the peak amplitude. The definition of these two parameters is illustrated in the inset of this figure. Perfusion in the inferior/posterior wall segment was abnormally low in this patient.

tion applies rigorously only under special conditions (Burstein et al., 1991). The resulting curves of signal intensity versus time can be compared for different myocardial ROI's to compare the kinetics of contrast agent wash-in (Jerosch-Herold et al., 1999; Kroll et al., 1996).

The initial increase in signal intensity during wash-in of the contrast agent represents the portion of the signal curves that is most sensitive to changes in myocardial blood flow (Jerosch-Herold et al., 1998; Kroll et al., 1996). Several semi-quantitative parameters may be used to characterize the contrast agent up-take. Examples are the up-slope of the signal curve during the contrast agent wash-in, which is indicative of the rate of contrast agent up-take, and the peak amplitude during the first pass that provides a relative measure of the peak concentration of contrast agent in a tissue region. With a compact bolus, as can be achieved by central injection of the contrast agent, the maximum amplitude of the tissue curves is indicative of the level of tissue perfusion, i.e., blood flow. This correlation of the peak amplitude with blood flow becomes weaker as the bolus duration is increased, and the up-slope correlates more closely with relative changes of tissue blood flow when the bolus is intravenously injected (Bassingthwaigthe et al., 1993).

Calculation of semi-quantitative parameters needs, in general, to be performed "off-line" on a personal computer or workstation with appropriate analytical software to analyze the signal curve characteristics. Semi-quantitative perfusion parameters such as the up-slope of the signal intensity curve are best determined from a smooth approximation to the measured data. This requires the use of some sort of model that is fit to the measured data. Figure A11.3.8 shows an example where a model of the impulse response was used for convolution with the measured "input" function in the left ventricle to calculate a tissue curve. The model parameters were adjusted to the measured data by using a least squares fitting algorithm.

A simple approach to obtaining a smooth approximation to the measured data consists of performing a nonlinear least squares fit of a gamma-variate function to the first pass of the measured data. From the fit of the gamma-variate function to the measured data, only the portion of the signal curve before appearance

of the recirculation can be used. The recirculation of tracer often can not be clearly identified in tissue curves and the reappearance of contrast agent in the left ventricle should then be used as a "cut-off" criterion. Many graphing and data analysis programs for personal computers offer the option of fitting the data to a user-defined function, such as a gamma-variate function, with a non-linear least squares algorithm. A rigorous analysis of the curves with tracer kinetic models is possible if the MRI protocol is set up such that the signal intensity can provide an accurate measure of the contrast agent concentration in blood and tissue regions. Tracer kinetic modeling generally requires the use of an arterial input function. The signal time course for an ROI in the left ventricle is often chosen as an approximation for this purpose. For further details on modeling of myocardial perfusion the reader is referred to the literature (Jerosch-Herold and Wilke, 1997; Jerosch-Herold et al., 1999; Kroll et al., 1996; Wilke and Jerosch-Herold, 1998).

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Internet Resources

http://www.heartmri.com

This web site is addressed at users of GE scanners and provides specifics on sequences and techniques for imaging of myocardial perfusion and viability.

http://www.drad.umn.edu/cvmr/home/html

The authors' web site has a document in Adobe Acrobat format with specific instructions on how to perform myocardial perfusion studies on a Siemens Vision scanner.

http://nsr.bioeng.washington.edu

This is a useful site for readers interested in state-of-the-art tracer kinetic analysis that has been applied for analysis of MRI perfusion data. The National Simulation Resource is an NIH-funded resource.

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