Contrast-Enhanced Renal MRA

Magnetic resonance angiography (MRA) scans can be run at a range of field strengths with varying degrees of success. The success of the technique in imaging arteries is based on several factors and will be discussed in Critical Parameters and Troubleshooting. Although the pulse sequence parameters are defined with respect to 1.5 T scanners, the actual parameters differ according to available gradient strength. Therefore, T_R, T_E, and bandwidths are adjusted for maximum vascular signal. The advantage in using higher gradients is to obtain images with higher temporal resolution, a useful tool in time-resolved imaging studies. The entire protocol consists of four different pulse sequences. Sequence 2 is used to survey kidneys for additional morphologic information that is not obtained from MRA sequences. The total scan time should be less than or equal to about 30 min.

Imaging hardware necessary for performing renal MRA is listed in Table A28.1.1.

Available gradient strength will depend on the scanner, and accordingly, the echo times, repeat times, and bandwidths may be varied.

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.

Materials

Normal saline (0.9% NaCl), sterile

Extravascular contrast agent (e.g., Magnevist, Omniscan, or Prohance), volume estimated using patient weight (usual amount is based on a single dose, 0.1 mmol/kg)

Disposable contrast-agent syringes and i.v. line

Power injector

Set up patient and equipment

1. Interview and screen the patient to ensure that he or she has no contraindications to an MR examination. Contraindications include a cardiac pacemaker or defibrillator, intracerebral aneurysm clip, or ferromagnetic materials in or near vital structures, including the eyes. Also be sure to find out if the patient has any health condition that may require the presence of emergency equipment such as cardiac monitor or oxygen. Since a contrast agent will be injected, obtain an allergy history.

Table A28.1.1 Equipment and Parameters for Renal Artery MRA

Coil type	Phased-array or torso-array coil with at least 4 channels
Gradient coil strength	25 mT/m for Vision (40 mT/m for Sonata)
Cardiac gating	No
Peripheral gating	No
Oxygen	Yes, if patient finds it difficult to hold his/her breath for >15 sec, then administer 2 liters via a nasal cannula
Power injector	Yes
Contrast agents	Yes (e.g., Magnevist, Omniscan, or Prohance)

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Generally, standard screening forms (see 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 a 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 consent form as required by the hospital research administration.
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 and headphones are used to protect the ears from the loud sound produced by the gradients, the patient will be asked to wear 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. For good results, the patient should not talk, and should avoid or minimize other movement during each scan—i.e., as long as the banging sounds continue. Between scans, talking is 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. Educate the patient on how to hold his or her breath at the end of deep inspiration. Practice the breath-hold method with the patient. Advise the patient of the importance of not moving during the data acquisition periods and not taking deep breaths during the non-breath-hold acquisitions.

   Patients are instructed to take a breath in, blow it out, take a breath in again, relax,and hold it. This allows images to be obtained in mid-respiratory cycle (~15 to 20 sec will be required for each breath-hold for each 3-D acquisition). Some of the newer sequences, such as true FISP (true fast imaging with steady-state free precession), may require shorter breath-holds. Breath holding is critical to obtaining motion-free images. Most patients find it easier to hold their breath following a maximum inspiration cycle. At the authors' institution, patients are asked to hold their breath following a deep inspiration.

7. Have the patient mount onto the table. Either before or right after the patient lies down, set up any triggering devices or other monitoring equipment that is to be used.
8. Establish an intravenous (i.v.) line from which the contrast agent can be injected, and attach the i.v. line securely to the patient so that movement into or out of the magnet will not pull at the patient's arm.

It is preferable to insert the i.v. line prior to imaging and to leave the patient in the magnet, so that there is no intervening motion between the scans run before and after contrast agent injection. Also, it is preferable to keep-veins-open (KVO) so that there are no air bubbles in the i.v. line.

9. Estimate the amount of contrast agent to be used based on patient weight. Set up both contrast-agent and saline syringes on the injector.

   A general rule is to use 1 ml contrast agent for every 10 lb. of patient weight when injecting as a single dose (0.1 mmol/kg), followed by 15 ml saline to flush the contrast agent.

10. Once the patient is on the table, place the anterior phased-array or torso-array coil. Center the patient's kidneys in the phased-array coil and fix it with the Velcro or buckle straps provided by the manufacturer. Make sure that the phased-array body coil (and spine coil if necessary) are plugged in.

    For some systems, it will be important that the patient lie within the center of the spine coil,which may be the posterior elements for the phased-array coil system.

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

12. Use the laser light available on most systems to center the phased-array coil or torso-array coil at the "0" location and move the patient into the magnet.

    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.

13. Assess the need for supplementary oxygen to improve the breath-holding capacity. If the patient is not able to hold his or her breath, administer oxygen (2 liters) through a nasal cannula.

    For severely ill patients who cannot hold their breath, cannulas are necessary for basic breath-hold studies. If the patient still cannot hold his/her breath during the scanning, imaging can be performed during free breathing in which scan time is considerably reduced using low acquisition matrix size (number of data points collected) as described in Anticipated Results (breath-holding). This will improve temporal resolution at the expense of spatial resolution.

Sequence 1: Rapid three-plane positioning localizers

14. Ask the patient to take a breath in, blow it out, take a breath in again, relax, and hold it.

15. To validate the correct position for imaging, run the localizer (or pilot) scan of the system according to Table A28.1.2.

    This is done using fast-gradient-recalled imaging sequences with three orientations, prescribed with multiple slices in each orientation. Refer to the manufacturer's specifications for standard default settings and swap as necessary. It is preferable to obtain localizers in a breath-hold mode. The subsequent placement of an imaging slab will be more accurate with breath-hold localizers.

Sequence 2: Transverse true-FISP imaging

16. Bring up the sequence for a rapid transverse scan using the parameters defined in Table A28.1.3.

    At the authors' institution, a true FISP sequence is used to survey both kidneys in a transverse orientation. This allows for visualizing any disease processes, such as cysts in the kidneys.

Table A28.1.2 Clinical Imaging Parameters for Sequence 1 (Rapid Localizers)

Patient position	Supine
Scan type	2-D gradient echo
Imaging plane (orientation)	Transverse, sagittal, coronal
Central slice or volume center	Xyphoid
Echo time (T_E)	6.5 msec (1.56 msec)[a]
Receiver bandwidth (RBW)	390 Hz/pixel (781 Hz/pixel)[a]
Repeat time (T_R)	15 msec (3.12 msec)[a]
Delay time (T_D)	0 msec
Flip angle (FA)	30° (55°)[a]
Fields of view (FOV_x, FOV_y)	450 mm, 450 mm (400 mm, 400 mm)[a]
Resolution (Δx, Δy)	1.76 mm , 3.52 mm (1.56 mm, 1.68 mm)[a]
Number of data points collected (N_x, N_y)	256, 128 (256, 238)[a]
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	10 mm
Number of slices	5
Slice gap	Variable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Scan time	10 sec (12 sec)[a]

[a]Information in parentheses refers to parameters for a Sonata scanner. Scan time for the Sonata is based on 15 slices.

Table A28.1.3 Imaging Parameters for Sequence 2 (True-FISP Survey of Kidneys)

Patient position	Supine
Scan type	3-D gradient echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Xyphoid
Echo time (T_E)	2.3 msec (1.56 msec)[a]
Receiver bandwidth (RBW)	650 Hz/pixel (781 Hz/pixel)[a]
Repeat time (T_R)	4.8 msec (3.12 msec)[a]
Delay time (T_D)	0 msec
Flip angle (FA)	70° (55°)[a]
Fields of view (FOV_x, FOV_y)	350 mm, 350 mm (400 mm, 400 mm)[a]
Resolution (Δx, Δy)	1.37 mm, 1.37 mm (1.56 mm, 1.68 mm)[a]
Number of data points collected (N_x, N_y)	256, 256 (256, 238)[a]
Display matrix (D_x, D_y)	256, 256 (256, 256)[a]
Slice thickness (Δz)	6 mm (6 mm)[a]
Number of slices	15 (15)[a]
Slice gap	1.2 mm (1.2 mm)[a]
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Scan time	18 sec (11 sec)[a]

[a]Information in parentheses refers to parameters for a Sonata scanner.

Table A28.1.4 Imaging Parameters for Sequence 3 (Bolus Arrival Time Estimation)

Patient position	Supine
Scan type	2-D gradient echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Renal hilum
Echo time (T_E)	2.4 msec (1.66 msec)[a]
Repeat time (T_R)	5.8 msec (500 msec)[a]
Inversion time (T_I)	300 msec (250 msec)[a]
Delay time (T_D)	0 msec
Flip angle (FA)	12° (20°)[a]
Fields of view (FOV_x, FOV_y)	380 mm, 380 mm (400 mm, 400 mm)[a]
Resolution (Δx, Δy)	1.48 mm, 2.97 mm (1.56 mm, 3.13 mm)[a]
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 (2)[a]
Number of repetitions	40
Swap read and phase encoding	No
Saturation pulses	No
Scan time	~40 sec (40 sec)[a]

[a]Information in parentheses refers to parameters for a Sonata scanner. The T_R on the Sonata is based on echoplanar sequence that includes 128 lines in 0.5 sec (1 slice). The number of acquisitions is doubled to make 1 sec per slice.

17. Use the pilot (scout) images run earlier to locate both kidneys and set up imaging in a transverse orientation.

18. Let the patient know you are ready to image during breath-hold state. Repeat step 14 and begin the scan during suspended respiration following inhalation.

    Some of the newer sequences, such as true FISP, may require shorter breath-holds. In cases where multiple breath-holds are needed, assess the need for supplementary oxygen to improve the breath-holding capacity, and, if necessary, administer 2 liters of oxygen via a nasal cannula. Advise the patient of the importance of not moving during the acquisition.

Sequence 3: Estimation of bolus arrival time (BAT)

19. Using orthogonal localizers (coronal and transverse), set up the imaging sequence with parameters as described in Table A28.1.4 for estimating the bolus arrival time.

    At the author's institution, a rapid imaging pulse sequence is used with a nonselective inversion pulse to null blood.

20. Position a single 10-mm slice in a transverse orientation near the renal hila.

21. Set up the power injector so that 2 ml of contrast agent will be injected followed by 15 ml of saline. Set up the injection rate at 2.5 ml/sec for both contrast agent and saline injections.

    The imaging allows for one image per second. By setting the number of repetitions in scans to ~40, upon visual inspection of each of these images, one can see the signal changing in the abdominal aorta as the contrast agent transits through that section.

Table A28.1.5 Sequence 4 for Acquiring Pre-Contrast MASK Images

Patient position	Supine
Scan type	Spoiled 3-D-gradient echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Xyphoid
Echo time (T_E)	1.8 msec (1.22 msec)[a]
Receiver bandwidth (RBW)	390 Hz/pixel (390 Hz/pixel)[a]
Repeat time (T_R)	4.6 msec (3.37 msec)[a]
Delay time (T_D)	0 msec
Flip angle (FA)	25° (25°)[a]
Fields of view (FOV_x, FOV_y)	420 mm, 420 mm (390 mm, 341 mm)[a]
Resolution (Δx, Δy)	0.82 mm, 1.62 mm (0.80 mm, 1.40 mm)[a]
Number of data points collected (N_x, N_y)	512, 260 (512, 246)[a]
Display matrix (D_x, D_y)	512, 512 (512, 512)[a]
Slice thickness (Δz)	2.5–3.00 mm; 1.25–1.5 mm after interpolation (3.1 mm interpolated to 2 mm)[a]
Number of slices	20 (40 after interpolation); 26 (40 after fractional interpolation)
Slice gap	0
Number of acquisitions (N_{acq})	1 (or 2)
Number of repetitions	1
Swap read and phase encoding	No
ZIP 2	Yes
Saturation pulses	No
Scan time	23 sec (16 sec)[ab]

[a]Information in parentheses refers to parameters for a Sonata scanner.
[b]The scan times are doubled if $N_{acq} = 2$.

22. Instruct the patient to take in a deep breath and exhale, take in another deep breath, relax, and hold it. Simultaneously start the injection and initiate the measurement while the patient is holding his/her breath.

    This procedure is preferably performed using a breath-hold mode. Even with proper hyperventilation, patients may not be able to hold their breath beyond 25 sec. In such cases, advise the patient to commence slow and shallow breathing when he/she cannot hold his/her breath any longer.

    On newer scanners (e.g., Siemens' Sonata or Symphony or GE's Signa Advantage), one can reconstruct images in real time as they are acquired. This helps to visually confirm the arrival of the contrast agent. At this point, abort the scan and stop the patient from holding his/her breath.

Sequence 4: Pre-contrast MASK imaging

23. Using localizer or scout images, place a 3-D imaging slab in a coronal orientation with the parameters described in Table A28.1.5 for acquiring MASK imaging for subtraction.

24. Have the patient hyperventilate so that he/she is ready to hold his/her breath. Repeat step 14. Start the scan according to the parameters listed in Table A28.1.5.

    In some institutions, a MASK is obtained with 2 acquisitions (or NEX = 2) to provide better subtraction of background tissue signal. Remember that the scan time is doubled in that case.

    On a Sonata scanner using partial Fourier 6/8 along phase encoding direction, the scan time is further reduced to 16 sec.

Table A28.1.6 Imaging Parameters for Sequence 5 (Contrast-Enhanced Imaging)

Patient position	Supine
Scan type	Spoiled 3-D-gradient echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Xyphoid
Echo time (T_E)	1.8 msec (1.22 msec)[a]
Receiver bandwidth (RBW)	390 Hz/pixel (390 Hz/pixel)[a]
Repeat time (T_R)	4.6 msec (3.37 msec)[a]
Delay time (T_D)	0 msec
Flip angle (FA)	25° (25°)[a]
Fields of view (FOV_x, FOV_y)	420 mm, 420 mm (390 mm, 341 mm)[a]
Resolution (Δx, Δy)	0.82 mm, 1.62 mm (0.80 mm, 1.40 mm)[a]
Number of data points collected (N_x, N_y)	512, 260 (512, 246)[a]
Display matrix (D_x, D_y)	512, 512 (512, 512)[a]
Slice thickness (Δz)	2.5–3.00 mm; 1.25–1.5 mm after interpolation (3.1 mm interpolated to 2 mm)[a]
Number of slices	20 (40 after interpolation); 26 (40 after fractional interpolation)
Slice gap	0
Number of acquisitions (N_{acq})	1
Number of repetitions	2 (no pause between measurements)
Swap read and phase encoding	No
ZIP 2	Yes
Saturation pulses	No
Scan time	23 sec (16 sec)[a]

[a]Information in parentheses refers to parameters for a Sonata scanner.

Sequence 5: Contrast-enhanced MRA

Immediately following the MASK image reconstruction, the patient is ready to receive a contrast agent for post-gadolinium (Gd) imaging using the same pulse sequence parameters used in MASK imaging.

25. Set up the pulse sequence with the number of acquisitions (N_{acq}) = 1 and number of repetitions (or measurements) = 2.

    Typically, two repetitions are performed to provide both an arterial and a delayed phase, which includes both arteries and veins. The first repetition (or first measurement) provides the arterial phase and the second repetition (or second measurement) provides the venous phase.

26. Set up the power injector with the remaining contrast agent (estimated based on patient weight in step 9) followed by 15 ml of saline at an injection rate of 2.5 ml/sec for both.

27. Estimate measurement start time (delay time) based on the method described in Critical Parameters and Troubleshooting (see Effects of Bolus Timing; Equation A28.1.3); or in *UNIT A10.1*.

    On a power injector, one can set this delay time as a countdown time to remind the operator when to initiate the pulse sequence.

28. Inform the patient to be ready to hold his/her breath. Inject the contrast agent. During the delay time, between the start of the injection and the start of the measurement, hyperventilate the patient, repeat step 14, and run sequence 5 according to the parameters described in Table A28.1.6.

    The power injector automatically flushes saline after the injection of the contrast agent.

    Two repetitions (measurements) are performed back-to-back without any delay between measurements. Therefore, the total scan time is doubled. Make sure that the patient is sufficiently hyperventilated to hold his/her breath for the entire duration of the measurement.

    The first measurement provides images of arteries only and the second measurement provides images with arteries and veins.

Post-processing

29. Prior to subjecting the data to a vessel rendering routine, perform the subtraction of the pre-contrast MASK data (from sequence 4) from post-contrast imaging data (from sequence 5).

    If multiple measurements are performed, subtract MASK data from each of these sets.

30. Input these subtracted data to a vascular rendering program such as the maximum intensity projection (MIP), which is available on the scanner.

    Alternatively, volume rendering is used to render vessels using surface rendering logarithms with some translucency. With tortuous vascular anatomy, this method has an advantage over MIP in accurately reflecting vascular pathology.

COMMENTARY

Background Information

The prevalence of renal artery stenosis is ~45% in patients with peripheral vascular disease (Iglesias et al., 2000). Renal artery stenosis has long been recognized as a cause of hypertension and progressive renal insufficiency. Such a high prevalence demands techniques that will provide sensitivity and specificity better than 90%. Over the years, the technical developments in the field of MR angiography have tremendously improved the ability to visualize vessels with sensitivity and specificity well over 93% (Holland et al., 1996; Hany et al., 1998; Schoenberg et al., 1998; Lee et al., 1999). Over the past 10 years, MRA has been suggested as a cost-effective alternative to digital subtraction angiography (DSA) and Doppler sonography.

Among available MRA techniques, contrast-enhanced magnetic resonance angiography (CE-MRA) is more robust and reproducible compared to traditional non-contrast-enhanced time-of-flight and phase-contrast techniques. By virtue of its insensitivity to flow artifacts and slab orientation, CE-MRA is an ideal method to precisely depict the arterial morphology in the assessment of renal artery disease. The vascular signal increase is primarily due to T_1 reduction and is achieved by introducing a paramagnetic contrast agent. The end result is the reduction in signal loss from intra-voxel phase dispersion and from in-plane saturation. The principal advantage is that it allows for placing the imaging slab in a coronal orientation covering a larger field-of-view and thinner partitions. In addition, the RF-spoiled 3-D-gradient recalled echo (GRE) sequence, together with T_1 shortening effects from the contrast agent, leads to a further reduction in the surrounding stationary tissue signal, thus providing an MR luminogram.

Critical Parameters and Troubleshooting

Why use a contrast agent?

The majority of pulse sequences used in dynamic 3-D imaging require a short T_R to complete a measurement in a breath-held period. There are several consequences of reducing the T_R and T_E that can work against the inflow enhancement of the signal. When the repeat time, T_R, is shortened, the product of flow velocity (v) and T_R, which is the distance traveled within a slice, becomes much smaller than the thickness of the slice. As a

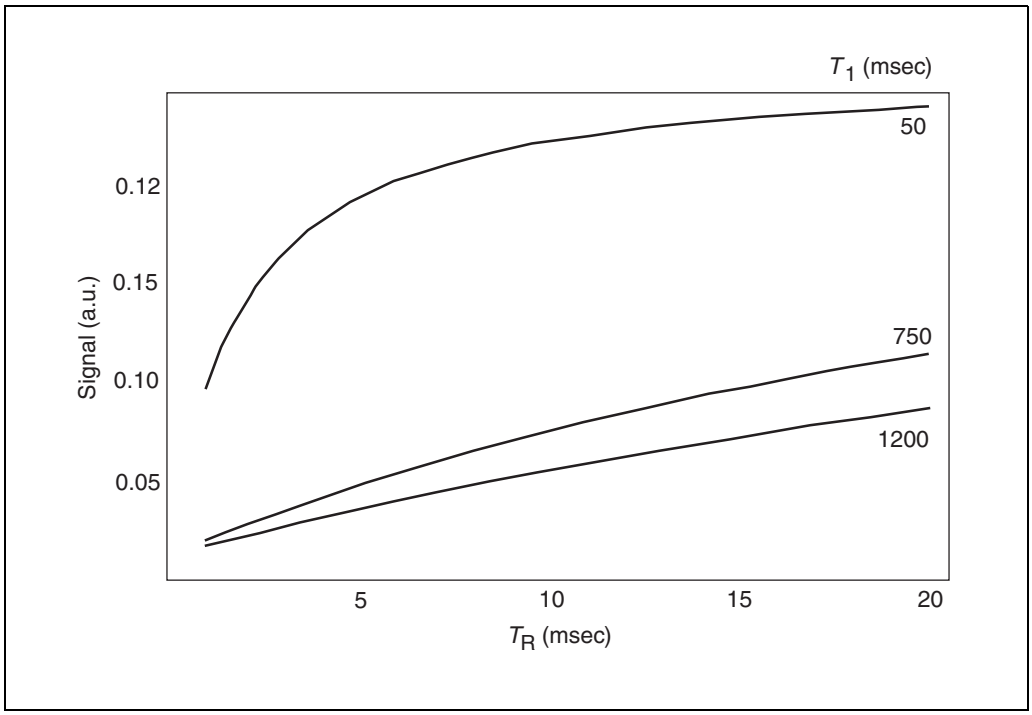

Figure A28.1.1 A simulation of the variation in signal intensity as a function of T_R. At a relatively short T_R, spins experience a relatively large number of RF pulses while within the slice. This results in a slow recovery of longitudinal magnetization causing saturation in their signal. Therefore, as T_R is reduced, the relative contrast between unenhanced blood (T_1 = 1200) and tissue (T_1 = 750) is considerably reduced. Experimental T_R for rapid imaging is generally held for <5 msec. With a T_R <5 msec, there is no noticeable contrast between blood and tissue (long T_1). However, shortening T_1 (~50 msec) dramatically improves contrast between blood and tissue. Abbreviation: a.u., arbitrary units.

result, spins in the blood experience many RF pulses [$n = d/(vT_R)$, where n = no. of RF pulses and d = slice thickness] while inside the same slice (also see *UNIT B7.3*). This leads to saturation of spin signal with a smaller contribution from inflow enhancement. The mathematical simulation of signal with an ultrashort T_R (Fig. A28.1.1) shows that when T_R is reduced considerably, the contrast between blood and the surrounding tissue is very poor prior to injection (long T_1) and dramatically improves following gadolinium injection (short T_1).

However, blood/tissue contrast can be dramatically increased using a paramagnetic contrast agent. The increase in signal is due to the fact that with contrast agent injection, there is a dramatic reduction in T_1 of blood spins, causing a rapid recovery of its magnetization. This rapid recovery of magnetization between RF pulses is crucial in increasing the net longitudinal magnetization available during the subsequent application of RF pulses, which results in an overall increase in signal (Fig. A28.1.2). Since it is the reduction in T_1 and not the time-of-flight effect that is the key to signal improvement, imaging is truly orientation-independent. This may be helpful in imaging that will acquire a larger FOV (coronal or sagittal orientation) with a minimum number of partitions.

Pulse sequence parameter optimization

The paramagnetic contrast agent is a gadolinium chelate, an extracellular agent, and its concentration in blood rapidly decreases following injection during longer scan times. Approximately 50% of the injected contrast agent is washed out from the blood pool during the first pass, with ~80% of the contrast agent washing out of the blood pool within the first 5 min. Since, the concentration of gadolinium is maximum during the first pass; it is best to image arteries during this phase.

The optimization of the pulse sequence is, therefore, dependent on several key parameters: (1) the effective relaxation times (T_1 and T_2) of blood spins during the first passage of gadolinium agent during circulation; (2) the circulation time and injection rate to determine the exact time location of the peak bolus signal; and (3) the correct flip angle that provides the maximum signal (based on fixed short T_R).

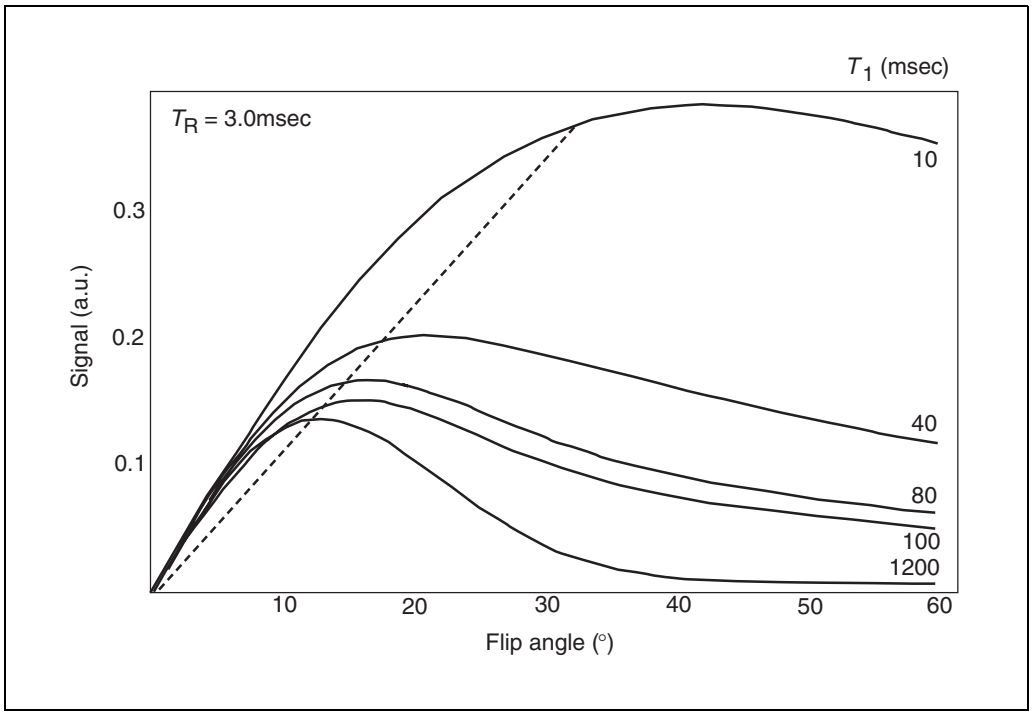

Figure A28.1.2 A simulation of the variation in overall signal intensity as a function of RF flip angle at different longitudinal relaxation times, T_1. The optimum flip angle for the peak signal shifts towards high angles as T_1 is shortened as shown by the dashed line. The results from this simulation show that a higher flip angle is suitable for a shorter T_1 (from a faster injection) and a longer T_R, whereas a shorter flip angle is suitable at a longer T_1 (from slow injection rates) and a short T_R. The dashed line passing through the peaks shows the shift in optimal flip angle as T_1 is varied. This simulation is based on a fixed T_R = 3.0 msec. Abbreviation: a.u., arbitrary units.

Although the above conditions vary from patient to patient, a qualitative understanding of their effects can be understood by using the following simple model (Earls et al., 1996; Hany et al., 1997).

T_1 and T_2 at the region of interest (ROI) during the first-pass

When the measurement time onset is set to coincide with the first-pass contrast bolus arrival time at the ROI, the overall signal is based on the effective relaxation times (T_1, T_2) of protons in the blood at the ROI during data acquisition. Since the recovery of magnetization is based on the relative T_1, the shorter the T_1, the stronger the signal. The relative change in signal (contrast) is based on the differences in T_1 of the blood and tissue following contrast agent injection. The effectiveness of gadolinium in reducing T_1 and T_2 of blood is based on its relaxivity ($r_{1,2}$), a relationship between the relaxation rate and the concentration of the contrast agent. In addition, the circulatory condition of the patient also influences the change in relaxation times. The correlation between T_1, T_2, post-injection and the T_1, T_2, prior to injection is based on the first-pass concentration of gadolinium chelate and is described by the following equation (Johansson and Ahlstrom, 1998; Shetty et al., 2000):

$$R_{1,2}^{\text{post-Gd}} = R_{1,2}^{\text{pre-Gd}} + r_{1,2} \times C_{\text{fp}}$$

Equation A28.1.1

where $R_{1,2}^{\text{pre–Gd}}$ is the relaxation rates (inverse of T_1 and T_2) prior to injection and $R_{1,2}^{\text{post–Gd}}$ is the resulting relaxation rates (inverse of T_1 and T_2) following injection, and $r_{1,2}$ are the longitudinal (r_1) and transverse (r_2) relaxivities of a paramagnetic agent. C_{fp} is the first-pass concentration of gadolinium in the bloodstream. The relaxivity of commercial gadolinium chelates are constant over a wide range of magnetic field strength and is between ~4 liter/sec/mM (r_1) and ~6 liter/sec/mM (r_2) (see also *UNIT B6.4*). The first-pass arterial Gd concentration (C_{fp}) is an important factor that determines the overall T_1 and T_2 at the time of data acquisition and is related to the circulation status of the patient (expressed in cardiac output, ϕ), concentration of the contrast agent (C), and the injection rate (T_{rate}). Because of the inverse relationship between C_{fp} and ϕ, it is important to ensure that when a patient is inside the magnet, he/she is

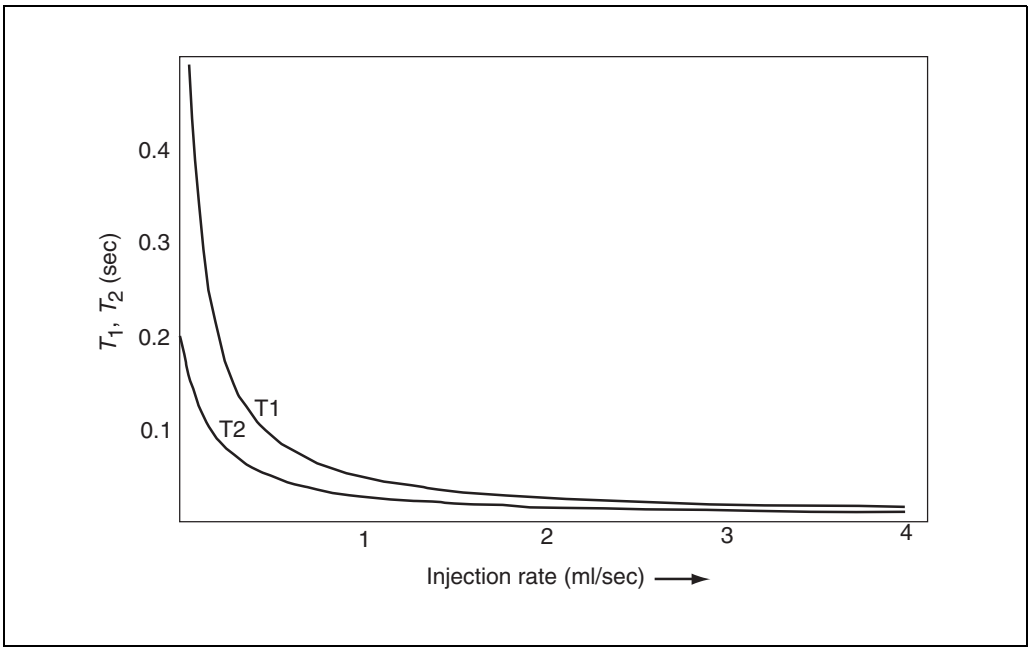

Figure A28.1.3 The relative changes in T_1 and T_2 as a function of injection rate. First-pass values of T_1 and T_2 do not change significantly when the injection rate is increased beyond 2.5 ml/sec. A reasonable injection rate would be between 1.5 and 2.5 ml/sec.

more relaxed so that cardiac output remains low (Brandfonbrener et al., 1955). In most patients, this can easily be achieved with simple instructions and education, along with music.

The corresponding expression for T_1 and T_2 during the peak arterial flow at the region of interest is given by the following equation (Shetty et al., 2000):

$$T_x^{\text{post-Gd}} = \frac{\phi \times T_x^{\text{pre-Gd}}}{\phi + T_x^{\text{pre-Gd}} \times r_x \times C_{fp} \times T_{\text{rate}}}$$

Equation A28.1.2

where, x = 1,2 refers to T_1 and T_2. These transient values of T_1 and T_2 are based on other variables that are intrinsic and extrinsic to blood. Figure A28.1.3 shows the relative changes in T_1 and T_2 during first pass at different injection rates.

Amount of contrast agent

The literature cites various investigators using a range of contrast agent strategies. One approach is to administer a fixed amount (40 ml) regardless of patient weight. While this may help in simplifying the injection protocol, it may not be economical for patients who do not require that volume of contrast agent. Many have advocated imaging with doses of 0.1 or 0.2 mmol/kg. A lower-dose regimen works best with perfect bolus timing, a rapid injection rate, and faster scan times. Higher doses may help increase signal with proper injection rates to coincide with the scan duration. At the authors' institution, a single-dose (0.1 mmol/kg) contrast agent protocol is calculated based on the weight of the patient. A general rule is to use 1 ml for each 10 lb. of patient weight.

Optimum injection rate

It is clear from Fig. A28.1.3 that at an injection rate beyond ~2.5 ml/sec, there are no significant changes in T_1 and T_2 values. It is also possible that at an injection rate higher than 3 ml/sec, signal loss from T_2* effect will start to dominate and overwhelm the gain from T_1 enhancement effects. A higher injection rate necessitates the use of shorter imaging time (with lower doses) to fit the injection duration. The other consequence of shortening the scan time by reducing T_R is the increase in bandwidth (causing higher noise). A reasonable rate of injection is ~2.5 ml/sec with a single dose. For a consistent injection rate throughout the scan period, an MR-compatible power injector is recommended.

Optimum T_E

Scanners equipped with high-performance gradients allow for a much shorter T_E. The advantage of having a short T_E is that the susceptibility-induced dephasing (T_2*) artifacts are greatly reduced. This may be useful in

imaging the lungs, where the air-tissue interface may cause magnetic susceptibility artifact. With a renal MRA, it is helpful in minimizing metallic susceptibility artifact originating from surgical clips or stents. However, shortening the T_E may have an inadvertent effect on widening the bandwidth, causing a lower signal-to-noise ratio. Also, a choice of shorter T_E may have an effect on fat-water signal cancellation, causing a signal loss artifact at tissue boundaries. An appropriate choice of T_E is the minimum achievable by the scanner at a reasonable receiver bandwidth of ~350 to 450 Hz/pixel for an MRA sequence (sequences 4 and 5).

Optimum T_R

The reduction in overall scan time can be achieved by reducing the T_R. Most scanners allow for a T_R as short as 1.5 msec. However, the reduction in T_R is a direct effect of widening the receiver bandwidth. The reduction of T_R is also achieved by using narrow RF pulses. Most newer scanners provide shorter RF pulse lengths for 3-D MRA. However, this has an effect of aliasing along the slice-select direction, rendering many end partitions useless. Selection of T_R is made based on the required scan time for 512 sampling points to fit within the injection duration. Frequently, the scan time with a very short T_R can be matched with a shorter injection duration and an appropriate rate of injection. Although a short T_R provides minimum signal, and, consequently, a lower signal-to-noise ratio (SNR), the effect of rapidly injecting the contrast agent creates a counterbalancing increase in the signal-to-noise ratio (SNR).

Optimum flip angle

The optimum flip angle depends upon the T_R/T_1 ratio, which depends on the injection rate. While any reasonable choice of flip angle may provide a good signal, it may not be optimal given the other parameters. At the authors' institution, a flip angle of 25° is used with a T_R ~4 to 5 msec, whereas a flip angle of 15° is used with a shorter T_R (Fig. A28.1.2).

Bolus arrival (transit) time

The peak enhancement is visualized with the arrival of a bolus during the first pass. The peak signal is found when the bolus arrival coincides with the time corresponding to the central *k*-space of the data acquisition. Thus, the knowledge of the bolus arrival time at the intended target is an important first step in the optimization of the protocol. This is particularly challenging in contrast-enhanced MRA, as the bolus arrival time varies from patient to patient depending on circulation time and cardiac output. Other timing strategies include automated bolus detection (Ho and Foo, 1998) and MR fluoroscopy (Willman et al., 1997). The authors' approach was to use a small amount (~2 ml) of contrast agent for estimating bolus arrival time and use the remaining amount for the full contrast agent injection as described in steps 21 and 26.

Effects of bolus timing

The signal component of the data is contained in the central portion of *k*-space (Shetty et al., 1998). Also, the signal peaks during maximum arterial concentration, which is reached during the first-pass phase of arterial circulation. In an ideal situation, the contrast agent must be delivered in such a way that the arterial phase occurs during the central portion of *k*-space. Based on the transit time of the bolus, one can set up imaging parameters in the sequence delayed to acquire the data during the peak signal. The scan time and the type of scan order in lines will determine the delay time from the injection. Due to the symmetric temporal location of *k*-space, the scan delay time was set up for a reverse centric sequence as:

$$T_{\text{delay}} = T_{\text{BAT}} - \left(T_{\text{acq}}\right)/2 + \left(\text{injection duration}\right)/2$$

Equation A28.1.3

where T_{delay} is the measured sequence delay time from the start of the injection, T_{BAT} is the experimentally determined bolus arrival time, and T_{acq} is the data acquisition time for a single measurement. Notice that the term (injection duration)/2 was added to T_{delay} in order to account for the delayed arterial peak with full-dose injection when compared with test bolus dose (Fig. A28.1.4). The possible options are shown in Figure A28.1.5, in which the acquisition of the central ⅔ of the *k*-space is shown with respect to the bolus profile. In all, the signal is based on the relative position of the central *k*-space with respect to the bolus arrival (Ito et al., 1997). If the central *k*-space is spanned too early or too late with respect to the bolus peak, the signal will be poor for arteries. The best situation is when the contrast agent is present throughout the data acquisition, which is usually the case when slow infusion bolus is used (Fig. A28.1.5A). In this case, high signal is maintained for all *k*-space data. However, a long injection time is necessary to span the entire *k*-space, requiring more contrast agent.

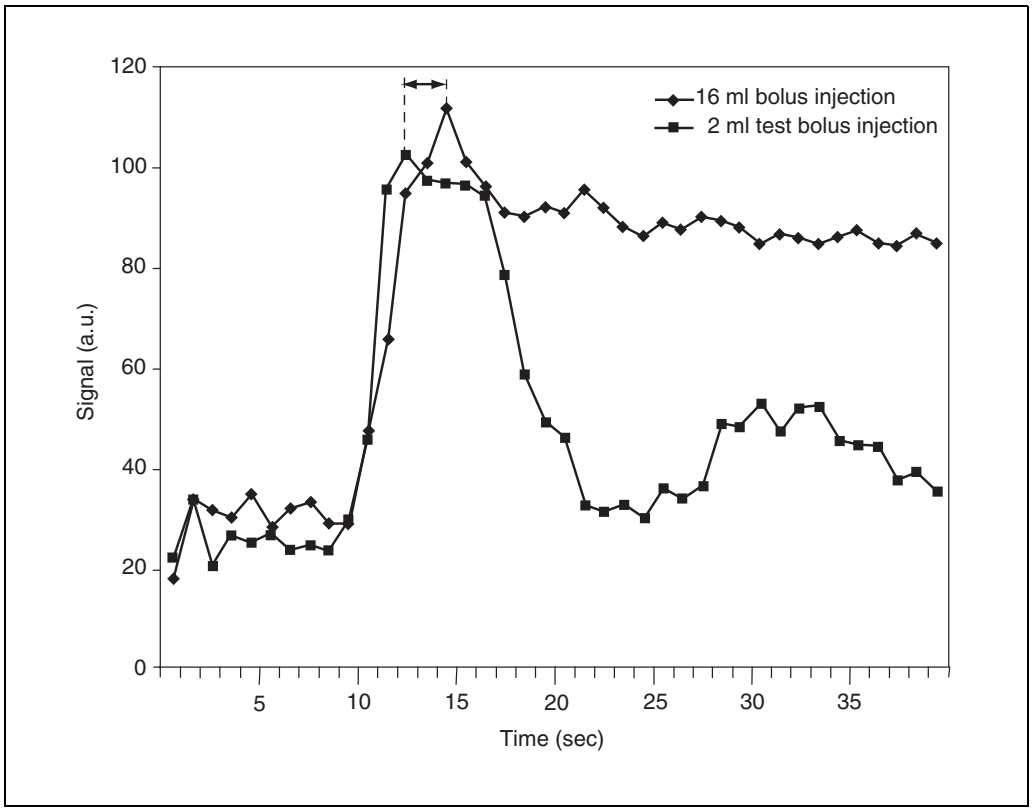

Figure A28.1.4 The bolus arrival time differs with different amounts of injected contrast agent as shown in this graph. The test bolus (2 ml) plot is shown in square boxes and the injection of an amount (16 ml) is shown in diamond boxes. Both are injected at 1.5 ml/sec followed by a 15-ml saline flush at the same rate. The shift in peak position increases with injection duration and is approximated in Equation A28.1.3. Abbreviation: a.u., arbitrary units.

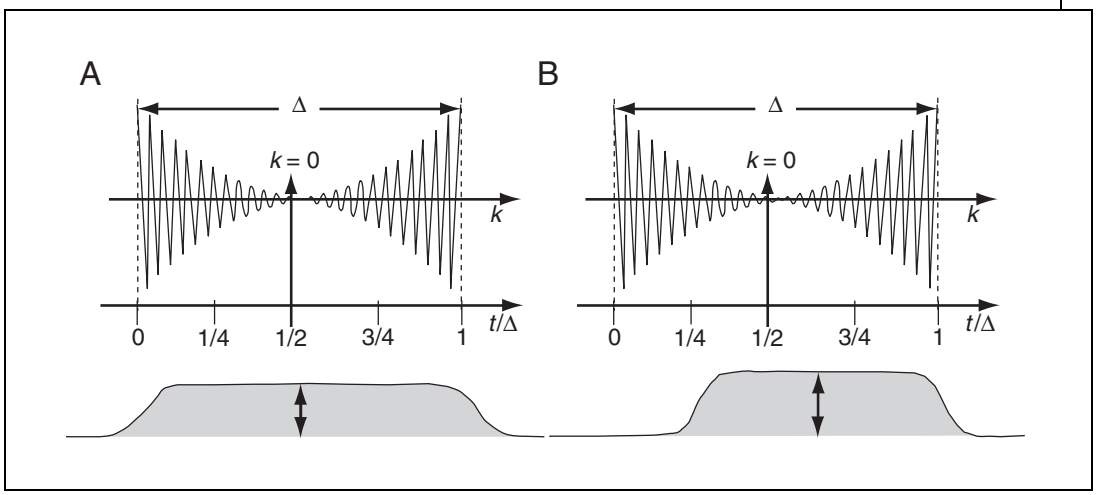

Figure A28.1.5 (**A**) With a reverse centric ordered pulse sequence where the center of *k*-space lies in the middle of the acquisition window, the injection rate is adjusted so that its duration spreads across the acquisition window. (**B**) With a tight bolus, injection rate is increased and its duration is shorter than the acquisition window but spreads at least 2/3 of the range. This is an ideal situation. Δ, duration of data acquisition; *t*/Δ, shows fraction of *k*-space covered.

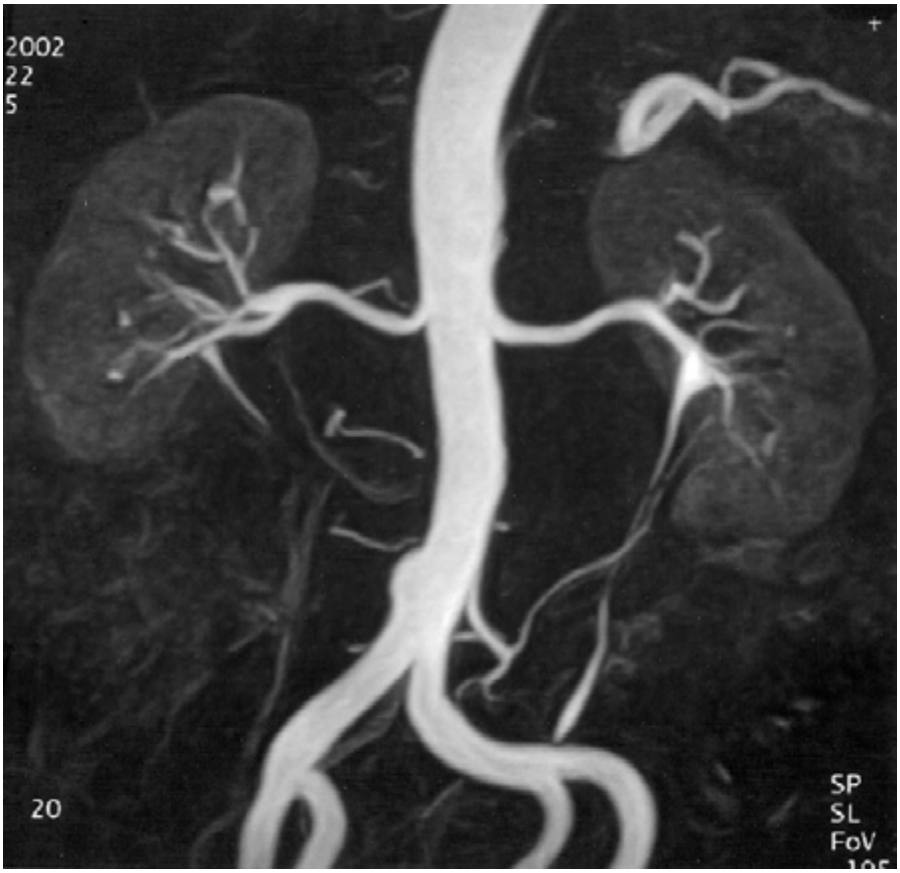

Figure A28.1.6 Normal bilateral renal arteries. The bolus arrival timing was estimated by placing a transverse slice at the mid field-of-view or center of the coronal image. The injection rate was 2.5 ml/sec and the amount of Gd contrast agent was based on a single dose strength (0.1 mmol/kg) and patient weight. The bolus injection of contrast agent was followed by a 15-ml saline injection at the same rate.

On the other hand, an ideal situation is when a tight bolus injection is used with a bolus spread that enhances 2/3 of the *k*-space including the central *k*-space frequencies (Fig. A28.1.5B).

Anticipated Results

Post-processing of data

The maximum intensity projection (MIP) processing of subtracted data for rendering vessels can be performed on a main console, on a satellite console, or on a stand-alone workstation. Most scanners and workstations do provide standard software that provides MIP processing (Figs. A28.1.6 and A28.1.7). In addition, some workstations provide the capability to perform volume rendering of the data. MIP images are produced with a ray-tracing algorithm. Images are stacked together and a ray is cast through a single pixel in the same location of all image slices to pick the highest (maximum) intensity and project it on a plane perpendicular to the ray. By orienting the ray at an angle, another projection image is formed. The projection images are obtained at various view angles from 0° to 360°. These projection images can be viewed in a cine loop to provide a 3-D rotational perspective. Sometimes, choosing a target volume is helpful in minimizing the processing time and removing the presence of other high-intensity structures that are not vessels. A major drawback in MIP is the stepladder effect when a view angle is away from the normal projection to the slices. This becomes progressively worse as the view angle is increased (Anderson et al., 1990).

Subtraction process

Use of pre-Gd MASK images to remove surrounding unenhanced soft tissue signal pro-

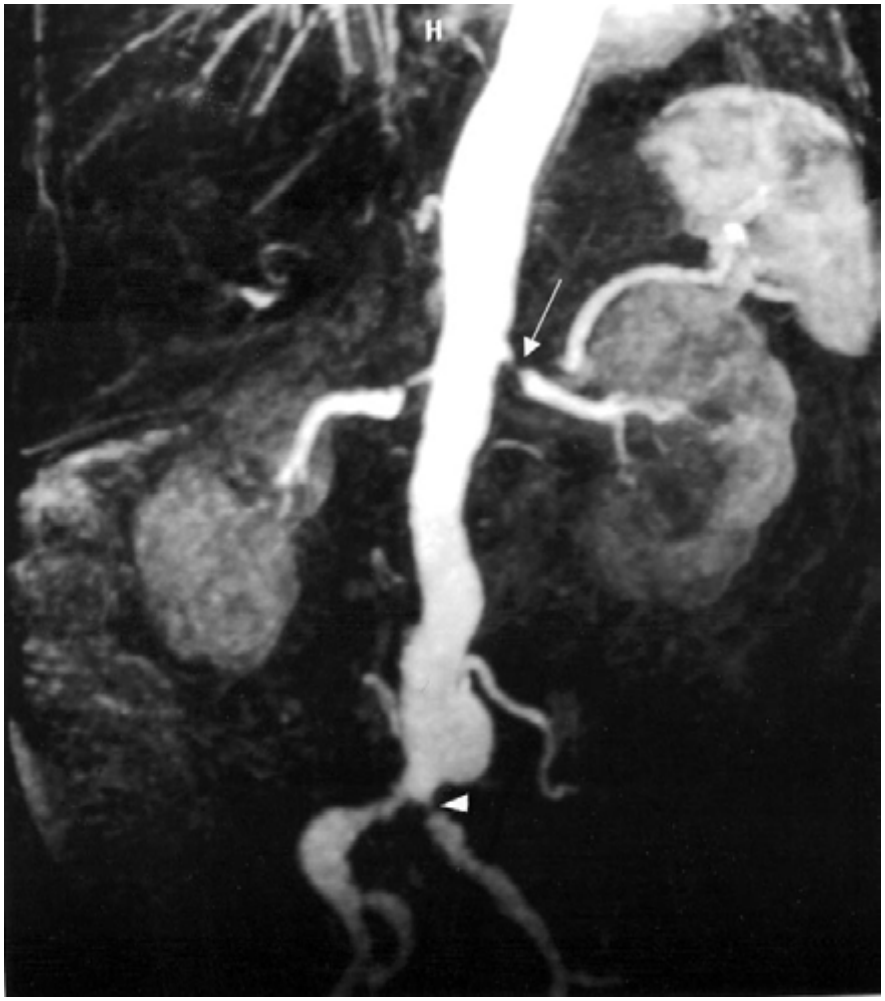

Figure A28.1.7 An image of a bilateral renal artery stenosis. The left renal artery (arrow) appears occluded; however, a slight hypoperfusion in the left kidney possibly indicates a critical stenosis and not an occlusion. This was confirmed by viewing source images. In addition, iliac artery stenosis at the origin (arrowhead) is visualized along with an aneurysm of the aorto-iliac junction.

vides images similar to those obtained in a digital subtraction angiography (DSA; Watanabe et al., 1998). Most CE-MRA methods use a 3-D-FLASH (fast low angle shot)-type pulse sequence with RF spoiling. The purpose of RF spoiling is to remove any residual transverse magnetization following the data acquisition, which helps reduce background tissue signal. This type of spoiling further improves T_1 contrast against reduced background signal. Although the background suppression is not fully achievable with RF spoiling alone, additional background suppression is achieved by using the subtraction method at the expense of a loss in SNR. Many institutions use an additional fat saturation pulse to suppress the fat signal, which has an isointense appearance with blood signal following the injection. However, this is achieved at the expense of an increase in scan time. Another way to reduce the fat signal is to use a T_E that corresponds to a fat-water out-of-phase image to minimize the fat signal. The downside of this technique is the presence of prominent signal loss artifact at the fat-tissue boundaries. Using MASK images to subtract the surrounding background tissue signal appears to be appropriate given the short T_R. Another reason for using the subtraction technique is to remove signal enhancement from collecting systems that were present due to a small amount of contrast agent injected during the test bolus procedure.

Breath-holding

In some cases where patients find it very difficult to hold their breath despite administer-

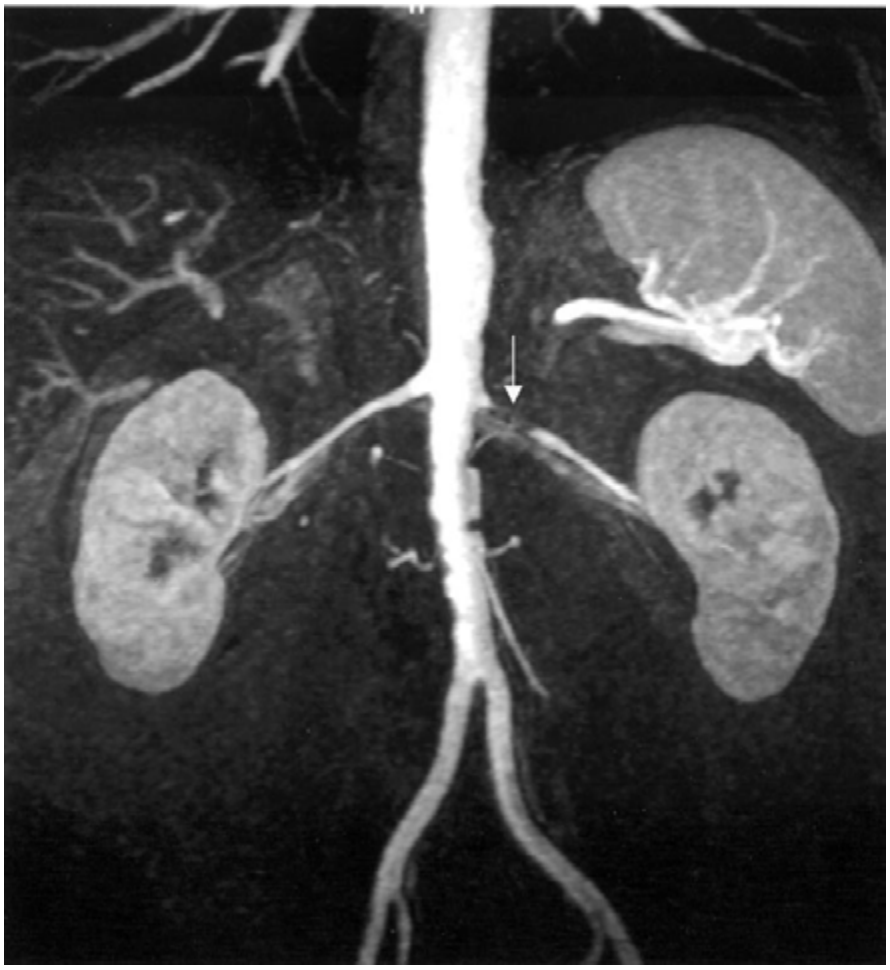

Figure A28.1.8 An image from a patient with a left renal artery stent. The presence of a stent (arrow) was visualized from the loss of signal. CE-MRA is a useful technique in visualizing the presence of a stent, but not very useful in evaluating stenosis within the stent. This is accomplished by further imaging using a triggered phase-contrast technique. The flow is estimated at the level of the stent and is compared with flow in the opposite kidney at the same level.

ing oxygen and hyperventilation, one might consider reducing the scan time to ~3 to 4 sec by reducing either the number of slices or the acquisition matrix size. The latter change will severely compromise the spatial resolution. The advantage of using short-time acquisition techniques is that time-resolved imaging can be generated. In this case, the estimating of bolus arrival time may not be crucial. With the number of repetitions increased to 7 to 8 and the patient freely breathing, at least one, if not several, of the repetitions (measurements) will acquire data during peak arterial concentration.

Presence of stent

The presence of any metal tends to dephase the spin signal significantly, causing a wide halo of dark signal around the metal location (Fig. A28.1.8). MRA is still a robust technique for evaluating in-stent stenosis. Although, there is signal loss around the region where the stent is placed, one can use phase-contrast imaging to assess the flow beyond a stent. Using an electro-cardiograph (ECG)-triggered phase-contrast imaging sequence (see Table A28.1.7), multiple images (different phases of the same imaging slice) are obtained during the entire cardiac cycle. The selection of a proper velocity encoding (V_{enc}), at 150 cm/sec, is important to eliminate any aliasing. This is compared to flow at the same level in the renal artery from a normal kidney. A prolonged rise time (defined as time from onset of systole to the first systolic peak) beyond 70 msec is considered to be indi-

Table A28.1.7 Sequence for Acquiring Phase Images with ECG Triggering for Flow Quantification[a]

Patient position	Supine
Scan type	2-D-phase contrast cine gradient-echo
Imaging plane (orientation)	Perpendicular to vessel in question
Central slice or volume center	Xyphoid
Echo time (T_E)	5 msec (3.2 msec)[b]
Receiver bandwidth (RBW)	195 Hz/pixel (391 Hz/pixel)[b]
Number of lines per segment	3 (3–7)[b]
Repeat time (T_R)	24 msec (28 msec)[b] (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	30° (30°)[b]
Fields of view (FOV_x, FOV_y)	180 mm, 135 mm (180 mm, 135 mm)[b]
Resolution (Δx, Δy)	0.70 mm, 0.75 mm (0.70 mm, 0.75 mm)[b]
Number of data points collected (N_x, N_y)	256, 180 (256, 180)[b]
Display matrix (D_x, D_y)	256, 256 (256,256)[b]
Slice thickness (Δz)	6 mm (5 mm)[b]
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	2 (3)[b]
Swap read and phase encoding	No
Number of cardiac phases[c]	(90% R-to-R interval)/T_R (e.g., if R-to-R interval = 800 msec, number of cardiac phases = 720/24 = 30)
Vascular options	Velocity encoding (V_{enc}) = 150 cm/sec
ECG gating	Yes
Scan time[d]	~3 min, 31 sec (~2 min, 14 sec to 5 min)[b]

[a]If flow quantification is suggested, the patient will require ECG leads placed on his/her chest. Follow the standard procedure of placing leads on chest to obtain good ECG signal.
[b]Information in parentheses refers to parameters for a Sonata scanner.
[c]Based on the number of lines per segment. On a Vision scanner, the number of segments is fixed at 3, whereas it is variable on a newer Sonata scanner. By increasing the number of lines per segment per R-to-R interval, the temporal resolution is increased, but the number of cardiac phases is decreased.
[d]This time is dependent on the R-to-R interval of the patient.

rect evidence for stenosis within the stent based on the Doppler literature for the assessment of renal artery stenosis (Desberg et al., 1990). At the authors' institution, flow assessment is performed in patients with renal artery stents for excluding in-stent stenoses.

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