Pulmonary Embolism

There have been a number of approaches taken to image the pulmonary vasculature. Black blood spin echo and/or gradient echo techniques have been applied for detection of pulmonary embolisms and deep vein thrombosis. On the other hand, the entire vascular tree can be visualized with the bright blood magnetic resonance angiography (MRA) technique, 2-D time-of-flight (TOF), and 3-D contrast-enhanced MRA. Although non-contrast-enhanced 3-D TOF MRA techniques have been described for imaging the pulmonary vessels, adequate vascular signal-to-noise ratio without respiratory- or cardiovascular-related motion artifacts requires respiratory gating (or navigator echo respiratory compensation) as well as electrocardiogram (ECG) triggering. This leads to a time consuming scan, the results of which are often not reproducible on most MRI systems. This method will not be discussed. The parameters provided in this unit are from the authors' experience with the Siemens 1.5T Vision Scanner. These parameters may need to be altered depending on the field strength and equipment manufacturer.

IMAGING THE PULMONARY ARTERIES WITH BLACK BLOOD SPIN ECHO AND GRADIENT ECHO TECHNIQUES

BASIC PROTOCOL 1

The sequences described in this section are based on the authors' experience with a Siemens 1.5T Vision Scanner, but are expected to be equally applicable to machines from other manufacturers. It should be noted that with current experience employing these sequences, small thrombi beyond the interlobar vessels are very difficult to diagnose with confidence. The turbo spin echo (fast spin echo) techniques, described herein, are optional at the authors' imaging facility, but provide higher resolution imaging of the pulmonary arterial wall than the gradient-echo techniques. They are frequently omitted due to time constraints (3 to 4 min) and the presence of artifacts in patients who are not stable and who have dyspnea. Table A13.1.1 lists the hardware required for the sequences. The entire examination time is 45 min, which includes patient set-up with ECG gating hardware.

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

Set up patient and equipment

1. Interview (screen) the patient to ensure that he or she has no contraindications such as cardiac pacemakers or other implants containing ferromagnetic materials. Also, be sure to find out if the patient has any health conditions that may require the

Table A13.1.1 Hardware Requirements for Black Blood Imaging of Pulmonary Arteries

Coil type	Body phased array coil preferred over quadrature body coil
Maximum gradient coil strength	25 mT/m (or whatever the system permits)
Cardiac triggering	Yes
Peripheral vital sign monitoring	Optional (blood pressure, heart rate, peripheral O_2 saturation, and CO_2 capnometry)
Respiratory gating	No
Respirator	If required by patient
Oxygen	Usually administered in these patients (2-3 liters/min) by nasal cannula

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Table A13.1.2 Imaging Parameters for Sequence 1 (Localizers)

Patient position	Supine
Scan type	2-D gradient echo
Imaging plane (orientation)	Transverse, sagittal, and coronal
Central slice or volume center	Laser light centered at mid-sternum
Echo time (T_E)	6.0 msec
Repeat time (T_R)	15.0 msec
Flip angle (FA)	30°
Fields of view (FOV_x, FOV_y)	450 mm, 450 mm
Resolution (Δx, Δy)	1.76 mm, 3.52 mm
Number of data points collected (N_x, N_y)	256[a], 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	10 mm
Number of slices	3
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Slice location	Not applicable
Saturation pulses	Not applicable
Slice series	Not applicable
Scan time	16 sec[b]

[a]Oversampling

[b]Sequential 2-D-TOF sequence takes about 6 sec per slice.

presence of special emergency equipment during the scanning procedure, or necessitate any other precautions.

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

The presence of any ferromagnetic metals may be a health hazard to the patient when he or she is inside the magnet, and will 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 (1997) for discussion of what implants may be safely scanned using a magnetic resonance imager.

Patients may be accompanied into the magnet room by a friend or a 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 forms.
3. Have the patient remove all jewelry and change into a gown to eliminate any metal that might be found in clothing.
4. Have the patient wash off any mascara and other makeup to avoid local tissue heating 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 procedure.

Table A13.1.3 Imaging Parameters for Sequence 2 (Black Blood Multi-Cardiac Phase Multi-Slice Turbo Spin Echo)[a]

Patient position	Supine
Scan type	Turbo spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Top slice of first stack at top of aortic arch. Second stack below first stack with one slice overlap.
Echo time (T_E)	12 msec
Echo train length (ETL)	3 (the echo spacing is 12.4 msec)
Repeat time (T_R)	Set 100 msec less than R-to-R interval but not >750 msec. Alternatively, use 80% of R-to-R interval.
Delay time (T_D) after R-wave	50 msec
Flip angle (FA)	180°
Fields of view (FOV_x, FOV_y)	400 mm[b], 300 mm
Resolution (Δx, Δy)	1.56 mm, 1.92 mm
Number of data points collected (N_x, N_y)	256, 156
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6 mm
Number of slices	~13 (80% of R-to-R interval/duration of ETL)
Slice gap	1.2 mm (20%)
Number of acquisitions (N_{acq})	5
Swap read and phase encoding	No
Saturation pulses	Yes, parallel, i.e., superior and inferior, T_R may increase
Scan time	>2 min, 43 sec

[a]Use black blood preparation pulse.
[b]Oversampling.

b. The patient will be given a safety squeeze-bulb or similar equipment to request assistance at any time (demonstrate how this works). It is provided in any event requiring urgent intervention.

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 during the scanning procedure if he or she feels it necessary.

e. The patient is provided with instructions on being very still during the acquisition of black blood spin echo sequences. He or she is also informed on holding his or her breath on inspiration for the breath-holding turbo spin echo and breath-hold gradient echo sequences.

6. Have the patient lie down supine on the table over the posterior phased-array coil. Place the ECG triggering leads appropriately over the chest. Either before or right after the patient lies down, set up any ECG triggering devices, or other monitoring equipment, that are to be used.

Table A13.1.4 Imaging Parameters for Breath-Holding Turbo Spin Echo Sequence[a]

Patient position	Supine
Scan type	Turbo spin echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Centered at the central pulmonary arteries where an accurate assessment of pulmonary arterial wall thickness is needed or in suspicious areas
Echo time (T_E)	76 msec
Echo train length (ETL)	23
Repeat time (T_R)	800 msec (based on R-to-R interval, keep nearly equal to R-to-R interval)
Delay time (T_D)	500 msec
Flip angle (FA)	160°[b]
Fields of view (FOV_x, FOV_y)	400 mm[c], 300 mm
Resolution (Δx, Δy)	1.56 mm, 2.17 mm
Number of data points collected (N_x, N_y)	256, 138
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5-7 mm
Number of slices	1/breath-hold
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Scan time	>9 sec

[a]Black blood preparation pulse.
[b]The system displays the flip angle of the refocusing pulse. The flip angle of the first pulse of this sequence is 180°.
[c]Oversampling.

7. If needed, place a pillow or other support under the knees to make the patient more comfortable.
8. Use the centering light to position the patient (at mid-sternum) and put him or her into the center of 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 replaced in the same position as before without jeopardizing the positioning of one scan relative to another.

9. Do not sedate the patient.

   Sedation is not appropriate for patients with pulmonary embolisms.

Sequence 1: Rapid three-plane positioning scouts

10. Run the system's pilot scan according to the imaging parameters given in Table A13.1.2 to insure the correct location of the patient's chest.

    Three orthogonal planes are obtained.

Sequence 2: Multi-slice multi-cardiac phase turbo spin echo (nonbreath-hold)

11. Bring the multi-slice multi-cardiac phase turbo spin echo sequence onto the console.

Table A13.1.5 Imaging Parameters for Breath-Holding Cine MRI

Patient position	Supine
Scan type	Segmented *k*-space gradient echo with echo sharing
Imaging plane (orientation)	Transverse
Central slice or volume center	Begin first slice at aortoco-pulmonic window and then proceed inferiorly with ~10 breath holding acquisitions
Echo time (T_E)	4.8 msec
Number of lines per segment	5 or 7
Repeat time (T_R)	80.0 msec (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	20°
Fields of view (FOV_x, FOV_y)	350 mm[a], 263 mm
Resolution (Δx, Δy)	1.37 mm, 2.09 mm
Number of data points collected (N_x, N_y)	256, 126
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6-8 mm
Number of slices	1/breath-hold
Slice gap	1.2-1.6 mm (20%)
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	No
Number of cardiac phases	$2n - 1$ (two phases per T_R)[b]
ECG gating	Yes
Scan time	15 sec/breath-hold

[a]Oversampling.

[b]Due to interleaved segmentation with shared echo, 2 phases per T_R result in twice as many cardiac phases, n = (80% of R-to-R interval/T_R), approximately equal to 10.

The T_R is set to be ~80% of the patient's R-to-R interval, and a trigger delay of 50 msec is also used. Generally, only two stacks of 2-D slices are obtained, beginning from the top of the aortic arch. Parallel (superior and inferior) saturation bands are also employed.

12. Run sequence 2 according to Table A13.1.3.

Sequence 3: Breath-holding turbo spin echo

This optional sequence can be employed on suspicious areas after reviewing the transverse multi-slice, multi-cardiac phase turbo spin echo images. In patients with pulmonary thrombo-embolism, this is usually not performed since the patient will tire and abort the examination. This can, however, be applied for better depiction of the pulmonary arterial wall for assessment of pulmonary wall thickness, especially if there are many motion artifacts related to respiration on sequence 2.

13. Instruct the patient to hold his or her breath and run sequence 3 according to Table A13.1.4.

Sequences 4 and 5: Imaging the pulmonary arteries with dynamic 2-D time-of-flight cine MRI

Currently, segmented gradient echo sequences are employed for this form of white blood imaging and can be applied as a breath-holding protocol whereby one slice is obtained per breath-holding period or whereby multiple slices can be obtained over a nonbreath-holding period. The multi-slice nonbreath-holding protocol is applied to patients who

Table A13.1.6 Imaging Parameters for Multi-Slice Nonbreath-Hold Cine MRI

Patient position	Supine
Scan type	Segmented *k*-space gradient echo with sequential mode
Imaging plane (orientation)	Transverse
Central slice or volume center	5 slices are positioned with the top slice through the aortico-pulmonic window. Two stacks are obtained by shifting the stack exactly 1-slice thickness to fill in the gap.
Echo time (T_E)	6.8 msec
Number of lines per segment	7
Repeat time (T_R)	40.0 msec (temporal resolution)
Delay time (T_D)	0 msec
Flip angle (FA)	30°
Fields of view (FOV_x, FOV_y)	350 mm[a], 263 mm
Resolution (Δx, Δy)	1.37 mm, 1.99 mm
Number of data points collected (N_x, N_y)	256, 132
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	7-8 mm
Number of slices	5 per stack
Slice gap	7-8 mm (one slice thickness)
Number of acquisitions (N_{acq})	3
Swap read and phase encoding	No
Saturation pulses	No
Number of cardiac phases	~20× (80% of R-to-R interval/T_R)
Slice series	Interleaved
ECG gating	Yes
Scan time	8 min, 50 sec

[a]Oversampling.

cannot hold their breath. Although both techniques provide white blood imaging for detection of low signal intensity thrombo-emboli, both are time consuming and predominantly employed for the detection of major central thrombo-embolic pulmonary disease down to the proximal lobar branches. The application of these techniques is primarily in situations where 3-D contrast enhanced MRA sequences are not available. The multi-slice nonbreath-holding cine protocol is performed with two interleaved stacks, each stack consisting of five slices. The breath-holding protocol employs the acquisition of ten different slices with ten different breath-holding acquisitions.

14. Instruct the patient to hold his or her breath and run sequence 4 according to Table A13.1.5.
15. *Optional*: If the patient cannot hold his or her breath, run sequence 5 according to Table A13.1.6.

BASIC PROTOCOL 2

CONTRAST ENHANCED PULMONARY MRA

Contrast enhanced pulmonary MRA protocols are currently preferred over the black blood and white blood techniques already described. This protocol is conducted over a breath-hold period and, as such, it is the most rapid protocol for imaging more of the pulmonary vascular bed. The imaging acquisition plane can be applied parallel to the vascular course without the associated in-plane saturation effects that are seen with TOF techniques.

Although this is the preferred MRA technique for imaging the pulmonary vessels for pulmonary emboli, many centers, including the authors', primarily use computed tomography (CT) angiography since it is more readily available and has higher spatial resolution. MRA, therefore, is reserved at the authors' institution for patients that have a contraindication to iodinated contrast agents such as, severe allergic reaction or renal insufficiency. In addition, MRA is frequently preferred in the patient who has severe pulmonary hypertension.

The scan time is on the order of 16 to 19 sec, making it easier to perform while the patient is holding his or her breath. The entire examination time is 15 min.

Materials

Normal saline (0.9 % NaCl), sterile
Extravascular contrast agent (i.e., Magnevist, Omniscan or ProHance)
20-G angio-catheter needle
Power injector

Set up patient and equipment

1. Repeat Basic Protocol 1, steps 1 to 7 (skip step 5e).
2. Establish an i.v. line in the antecubital fossa with a 20-G angio-catheter needle. Connect the angio-catheter to the saline at a rate to keep the vein open.

   It is preferred, however, to connect a power injector for more reproducible delivery of contrast. At the authors' institution, a Medrad power injector is used.

3. Repeat Basic Protocol 1, steps 8 and 9.
4. Run sequence 1 (see Basic Protocol 1).

   From this, the coronal 3-D gradient echo sequence can be positioned frequently. If there is not enough anatomical detail for accurate placement, the same positioning scouts can be applied in a transverse fashion through the main pulmonary artery to unfold the main pulmonary artery and its bifurcation.

Sequence 6: 3-D MRA

5. Instruct the patient to hold his or her breath and run the rapid 3-D gradient echo scan according to Table A13.1.7 (with one repetition) before i.v. contrast administration in the coronal plane.

   If the patient is unable to hold his or her breath for the longer coronal acquisition, individual sagittal acquisitions with lesser partitions (shorter scan time) are performed in the right and left pulmonary artery distributions. These are run as a mask for subsequent subtraction of contrast enhanced data in the same orientations.

6. Inject the extravascular contrast agent, flush the line with saline, and instruct the patient to hold his or her breath and run sequence 6 according to Table A13.1.7.

   A dose of 0.1 mmol/kg of contrast agent is usually given at a rate of 2 to 3 ml/sec followed by a saline flush consisting of 15 ml at 2-3 ml/sec.

7. At the end of the first repetition, allow the patient to breathe for 8 sec, then ask the patient to hold his or her breath on inspiration, and run the second repetition of the MRA sequence according to Table A13.1.7. This technique ensures that the bolus is not missed.

   Utilizing this timing, the pulmonary arteries are usually visualized but there is often some venous contamination. After injecting the contrast agent, the images display both the pulmonary arteries and the pulmonary veins, the former with greater signal. For patients

with suspected or proven poor cardiac function and low cardiac output, the initial 3-D sequence measurement can be delayed by an additional 5 to 10 sec. This protocol is employed at the authors' institution avoiding a timing bolus. Alternatively, however, a 2-ml test bolus may be performed to time the acquisition of the first arterial pass accurately (see Table A10.1.10).

Table A13.1.7 Imaging Parameters for 3-D Contrast Enhanced MRA for Breath-Holding

Patient position	Supine
Scan type	3-D gradient echo with sinc interpolation. Interpolation requires zero filling of high *k*-space data and then subjecting to fast Fourier transform.
Imaging plane (orientation)	Coronal, if the patient is able to hold their breath using the thicker coronal 3-D slab. Alternatively, a thinner sagittal 3-D slab (with lesser partitions) may be employed to separately image the right and left central pulmonary arteries for reducing the imaging time in patients who have difficulty in holding their breath.
Central slice or volume center	The coronal slab is centered at the pulmonary artery bifurcation. The sagittal 3-D slab, when performed, is placed to include the main pulmonary artery and respective ipsilateral vascular bed.
Echo time (T_E)	As short as possible. Currently, 1.8 msec
Receiver bandwidth (RBW)	390 Hz
Repeat time (T_R)	4.6 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	450 mm, 338 mm
Resolution (Δx, Δy)	0.88 mm, 1.72 mm
Number of data points collected (N_x, N_y)	512, 196
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	4.55-5.45 mm (coronal) or 3.18-4.55 mm (sagittal)
Number of slices	22 interpolated to 44 (coronal); 16-18 interpolated to 32-36 (sagittal)
Slab thickness	100-120 mm (coronal) or 51-82 mm (sagittal)
Slice gap	0
Number of acquisitions (N_{acq})	1
Number of repetitions	2
Swap read and phase encoding	No
ECG gating	No
Scan time[a]	18 sec per repetition, 44 sec total (coronal); 14 sec per repitition, 36 sec total (sagittal)

[a]The scan delay between two repetitions is 8 sec.

Post process the 3-D gradient echo sequence

8. Use the mask image and data prior to i.v. contrast administration, and subtract them from the post-contrast enhanced data. Use the subtracted images to perform maximum intensity projection.

All source data prior to subtraction are reviewed for presence or absence of filling defects. This can also be subjected to multi-planar reformation for further evaluating the pulmonary vascular bed. At the authors' institution, typically, a transverse multi-planar reformation with a slice thickness of 3 mm in a contiguous fashion through the central pulmonary arteries is employed. The original source data and multi-planar reformations are reviewed followed by the maximum intensity projections.

COMMENTARY

Background Information

Magnetic resonance angiography has been utilized to evaluate the pulmonary vasculature, noninvasively. Both 2-D and 3-D time-of-flight techniques have been performed without the use of intravenous contrast agents. More recently, however, MRA of the pulmonary vasculature has been performed with the use of intravascular paramagnetic contrast agents (Simonetti et al., 1996).

Magnetic resonance imaging of the chest has been challenging because of problems of artifacts from respiratory and cardiac motion. Techniques to deal with respiratory motion include respiratory gating/compensation (Westbrook and Kaut, 1993), pseudogating (Laub and Kaiser, 1988), and the use of single breath-holding acquisitions (Shetty et al., 1995). Cardiac gating or triggering (Simonetti et al., 1996) has been used to decrease or eliminate cardiac motion artifact. Motion at the proton spin level of moving blood has also been a problem. The dephasing effects of moving spins within a voxel can result in signal loss with techniques relying on in-flow effect of TOF techniques. Gradient moment rephasing (velocity compensation; Wielopolski, 1993) and use of cardiac gating have been used to decrease or eliminate this problem.

Another challenge to pulmonary MRA is obtaining satisfactory vascular signal-to-noise ratio (SNR). The air-containing lungs produce magnetic susceptibility artifacts that can decrease the SNR of pulmonary vessels. Time-of-flight techniques relying on in-flow effect suffer from signal loss secondary to in plane saturation effects. The use of intravenous gadolinium, however, can markedly shorten the T_1 of blood (Wielopolski et al., 1993) and, thereby, markedly increase the signal intensity of moving blood independent of in-flow effects needed in TOF techniques. In addition, by giving all blood an intrinsically bright signal, the problem of in-plane saturation from slow flow is eliminated. These factors improve the signal-to-noise ratio and can allow imaging of the peripheral pulmonary arterial system to the subsegmental level. Another important factor in the improvement of the signal-to-noise ratio is the development and use of phased array surface coils (Hatabu et al., 1992). Cardiac gating has also been utilized to improve the signal-to-noise ratio in techniques depending on in-flow effects and this holds true for techniques utilizing an intravascular paramagnetic contrast agent. Cardiac gating allows for acquisition of information during diastole, which is when dephasing from moving spins of blood is minimized.

An important consideration of any pulmonary MRA technique is the ability to image the pulmonary arteries of both lungs in a reasonable time period. The 3-D gradient echo technique described in this unit utilizes gradients, which allow for use of short T_R and short T_E. The combination of short T_R and T_E, intravascular contrast, and phased array surface coils allows imaging of the pulmonary arterial tree with high signal-to-noise ratio and spatial resolution in a reasonable single breath-hold period.

Critical Parameters and Troubleshooting

The preferred imaging techniques to evaluate pulmonary embolism (PE) are of the breath-holding type. Most patients presenting with PE are severely dyspneic and are not able to hold their breath >14 to 16 sec. Therefore, when considering different imaging options that involve breath holding, care must be given in optimizing sequence parameters to reduce imaging time under ≤16 sec.

However, for high spatial resolution, it is imperative to use a higher acquisition matrix which increases scan time. A better balance is achieved by changing phase encoding lines and

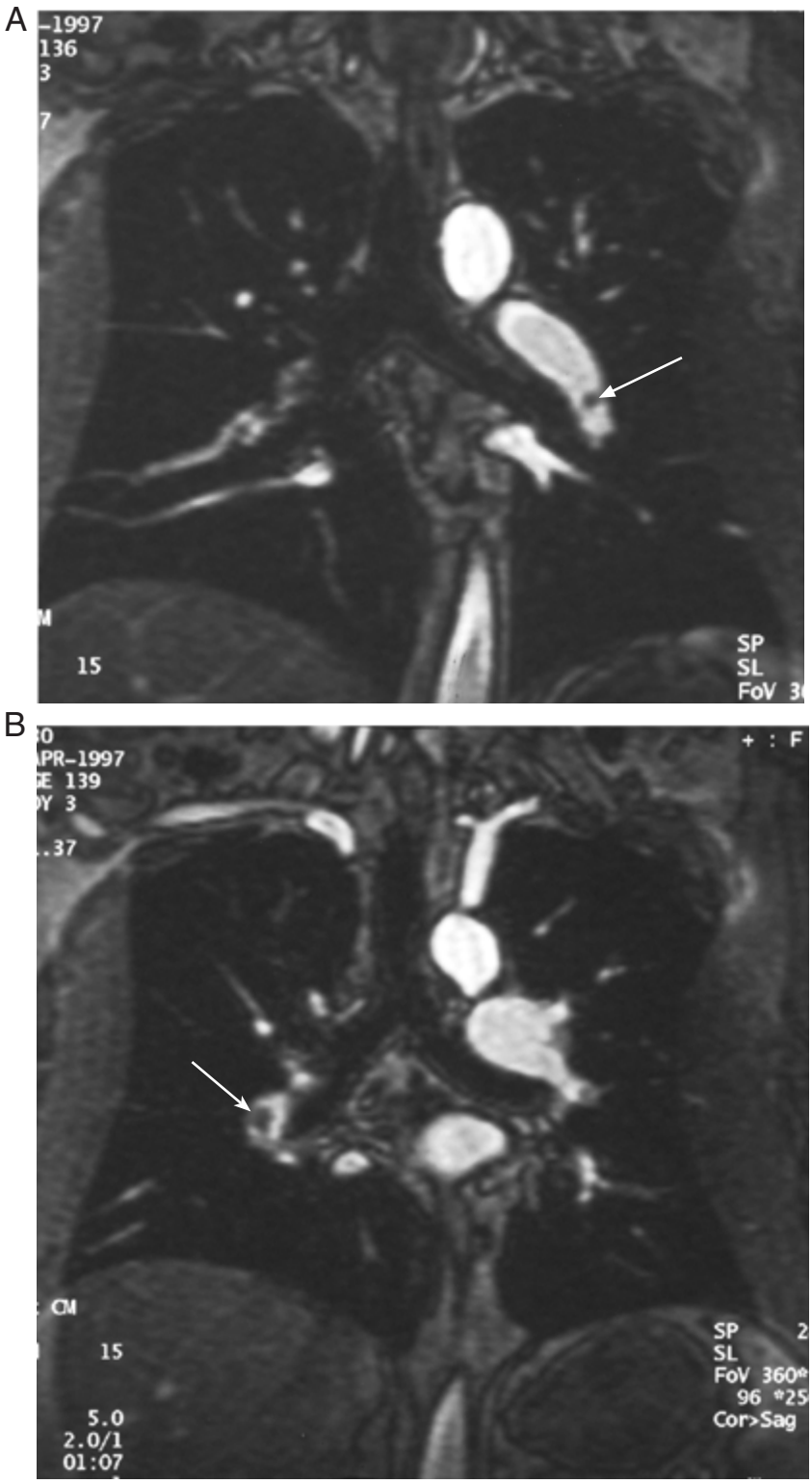

Figure A13.1.1 Acute pulmonary thrombo-embolism. Coronal contrast enhanced 3-D gradient echo partitions display central low signal filling defects (arrows) in the left (**A**) and right (**B**) interlobar pulmonary arteries.

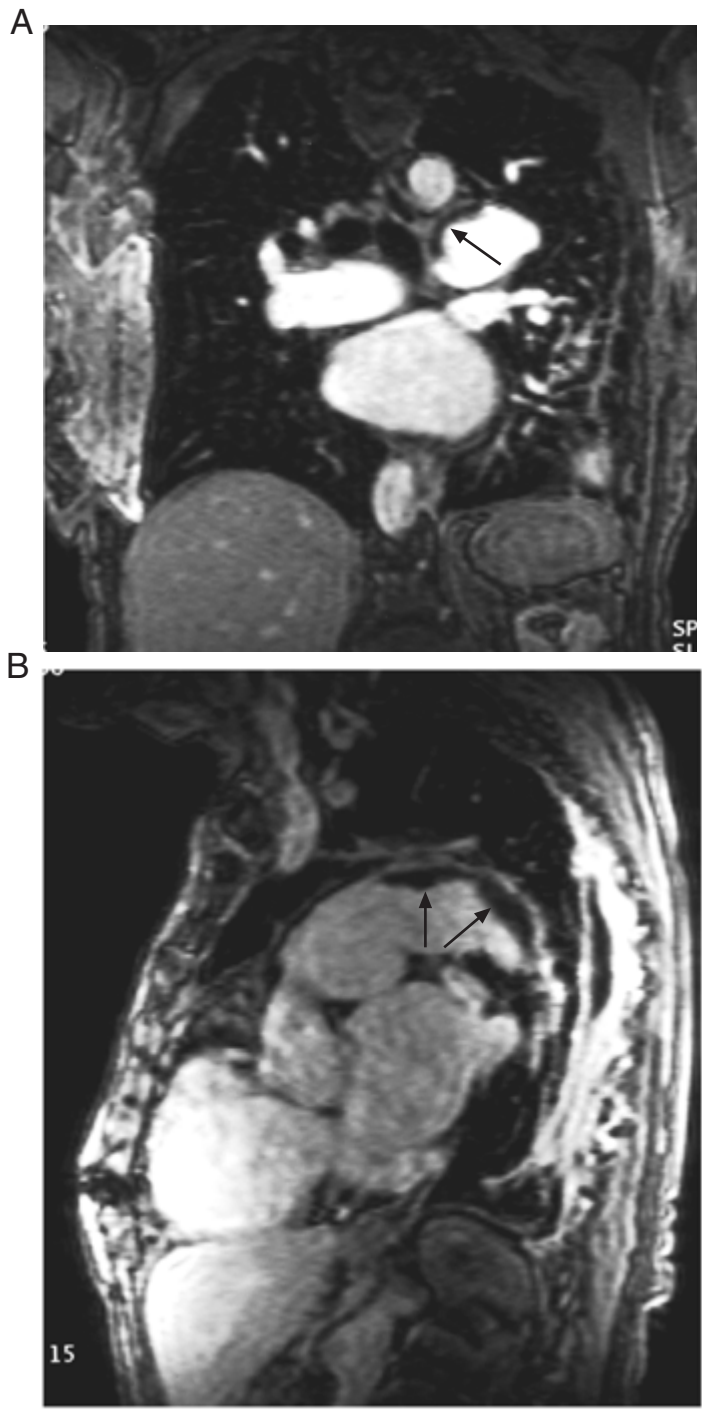

Figure A13.1.2 Chronic pulmonary thrombo-embolism. Coronal (**A**) and sagittal (**B**) contrast enhanced 3-D gradient echo partitions display low signal organized thrombus (arrows) within the roof of the left pulmonary artery.

slice partitions to reduce scan time. In addition, providing oxygen and hyperventilation prior to the examination does help to increase the patients' breath-holding capacity even if they are sick.

Actual application of techniques for imaging pulmonary arteries and their branches may require some modification of the pulse sequence parameters based on patient circulation time and anatomical region of interest. For example, the RF flip angle may be increased if the imaging interest lies in observing the main pulmonary artery with a sufficiently high blood flow. Use of the lowest T_R and T_E always helps and is dictated by the system manufacturer.

Even with breath-holding techniques, it is not uncommon to see respiratory related artifacts. These are the primary sources of ghosting artifacts and tend to obscure the details of vascular anatomy. It is important to educate patients in holding their breath in a consistent manner.

The bolus arrival time can also be assessed using "smart prep" developed by Foo et al. (1997). The smart prep technique uses a small sampling volume placed downstream in a vessel to sense the arrival of contrast agent. It then triggers the acquisition of a measurement scan to correspond to the arrival of gadolinium within the region. Other techniques such as fluoroscopic triggering, developed by Riederer et al. (1988) or 3-D-TRICKS (time-resolved imaging of contrast kinetics), developed by Korosec et al. (1996) may also be used. We used the test bolus approach because of its simplicity.

Anticipated Results

Pulmonary thrombus or embolus presents itself as intermediate to high signal on the black blood sequences. On cine gradient echo sequences, thrombus and/or embolus are usually depicted with low signal intensity compared to the higher signal of moving spins of the blood pool. Acute thrombus usually presents as an intraluminal filling defect, typically more round in morphology. Chronic embolus or thrombus, due to its incorporation within the aortic wall with subsequent endothelialization, presents as crescentic thickening of the pulmonary arterial wall. Similarly, contrast enhanced 3-D MRA (Figs. A13.1.1 and A13.1.2) will depict the emboli as low signal intensity filling defects. In patients with pulmonary hypertension due to chronic thrombo-pulmonary disease, the central pulmonary arteries may be enlarged and this may be associated with peripheral arterial pruning.

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