Deep Vein Thrombosis Detection

Although magnetic resonance angiography (MRA) is a robust and noninvasive technique for evaluating the vascular system with respect to deep venous thrombosis (DVT) of the lower extremities, there are several competing modalities, which primarily involve duplex sonography and currently, delayed contrast enhanced spiral computed tomography (CT) following a pulmonary CT angiography study. At the authors' institution, patients with suspected pulmonary embolisms and lower extremity DVTs are primarily worked up with lower extremity duplex sonography and spiral (helical) computed tomography of the pulmonary vasculature. Lower extremity MR venography (MRV) is performed primarily in patients where a pelvic source of emboli is suspected and if a duplex sonogram was not performed. In these patients, the groin is evaluated down to the proximal calf and this is supplemented with imaging of the pelvis.

In patients where the pulmonary MRA study, when performed, is equivocal or unremarkable, a lower extremity MRV study is also performed. Multi-station imaging to include the thorax, pelvis, and lower extremities in a patient with suspected pulmonary embolus is certainly time consuming since the patient, including body phased array coils, needs to be repositioned at each respective region of interest. These protocols may be as long as 2 hr, which is prohibitively long in this patient population. Fortunately, with the development of stepping MRI tables, the entire multi-station examination to include the chest, pelvis, and lower extremities can be performed much faster. At the authors' institution, a manually retrofitted stepping MRI table known as the stepping kinematic imaging platform (SKIP, Magnetic Moments) is employed. The SKIP device allows the user to employ the existing body phased array coil for improved spatial resolution and signal-to-noise as compared to a quadrature body coil.

Venous imaging within the pelvis and lower extremities is primarily performed with transverse 2-D TOF (time of flight) techniques employing an arterial traveling saturation band. Although 3-D contrast enhanced MRA techniques utilizing extracellular MRI contrast agents such as Omniscan, ProHance, or Magnevist can be employed, the venous signal is, frequently, not as robust as that on 2-D TOF sequences. Lower venous signal on 3-D contrast enhanced MRA is due to the filtering effect at the capillary bed whereby 50% of the contrast concentration is reduced due to the first pass. In the future, however, implementation of blood-pool agents, such as MS-325 (EPIX Medical) will likely be the preferred agent for evaluating deep venous thrombosis. Finally, MRV within the pelvis can be supplemented with T_1- and T_2-weighted sequences, when the MRV is abnormal, for differentiating intrinsic from extrinsic disease and in characterizing extrinsic pathology.

IMAGING THE PELVIC AND LOWER EXTREMITY VEINS

BASIC PROTOCOL 1

The sequence described herein is based on the authors' experience on a Siemens 1.5T Vision scanner, however, the protocol is likely equally applicable to machines from other manufacturers. Currently, this technique is the protocol of choice since contrast enhanced 3-D MRA techniques employing a blood-pool agent have not yet been tested and have not been FDA (Food and Drug Administration)-approved.

In patients where pulmonary MRA is performed, this protocol is performed after the pulmonary examination has been completed. If the stepping kinematic imaging platform (SKIP) is utilized, the patient is simply manually repositioned to the pelvic station. If a stepping table is not available, the patient is taken out of the magnet bore isocenter and

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Table A13.2.1 Hardware Requirements for Deep Vein Thrombosis Detection

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	No
Peripheral vital sign monitoring	Optional (blood pressure, heart rate, and peripheral O_2 saturation)
Respiratory gating	No
Respirator	If required by patient
Oxygen	Usually administered in these patients (2-3 liters/min by nasal cannula)

the phased array coil and patient is repositioned by centering the coil at the mid-point between the umbilicus and symphysis pubis. The equipment parameters are listed in Table A13.2.1.

The entire examination should take ~40 min.

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
Extracellular contrast agents (e.g., Magnevist, Omniscan, or ProHance)

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

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

   The presence of any ferromagnetic metals may be a health hazard to the patient when he or she is inside the magnet, and will also affect the imaging. If in doubt as to the exact composition of the items, it is best to exclude patients with any metal implants; see Shellock (1996) 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.

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.
   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 other movement, during each scan—i.e., as long as the banging sounds continue.
   d. Nevertheless, the patient may call out at any time if he or she feels it necessary.
6. Establish an i.v. line in the antecubital fossa employing a 20-G angiocatheter needle. Connect the angiocatheter to the saline at a rate to keep the vein open.

   Preferably, however, it is connected to a power injector for more reproducible delivery of contrast agent. At the authors' institution, a MedRad power injector (MedRad) is used.
7. Have the patient lie down on the table, with feet first, over the posterior phased array coil.
8. If needed, place a pillow or other support under the knees to make the patient more comfortable.
9. Use the centering light to position the patient (halfway point between umbilicus and symphysis pubis) 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.
10. If the patient is unable to hold still, provide an appropriate sedative.

    If the patient requires sedation, peripheral monitoring (blood pressure, heart rate, peripheral O_2 saturation, and CO_2 capnometry) is required.

Sequence 1: Rapid three-plane positioning scouts

11. Run the system's pilot scan to insure the correct location of the patient's pelvis according to the imaging parameters given in Table A13.2.2.

    Three orthogonal planes are obtained.

    These positioning scouts are performed to validate the patient's position and to provide anatomical landmarks for subsequent sequences.

Sequence 2: 2-D time-of-flight

12. Prescribe five imaging stacks in an overlapping fashion per region of interest to cover a distance of 35.0 cm. Run sequence 2 according to Table A13.2.3.

    NOTE: *Table A13.2.3 only covers 70 mm.*
13. After obtaining five stacks at the pelvic station, reposition the patient to the mid-thigh level for imaging the superficial femoral veins down to the popliteal vein. Repeat step 12.

    Each imaging stack requires 2 min of acquisition time with ~1 to 2 min of reconstruction time. Typically, the vasculature is covered down to the popliteal trifurcation, since at most institutions, deep venous thrombosis within the calf is typically not sought for since it is not treated.

Table A13.2.2 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 a point halfway between umbilicus and symphisis pubis
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
Scan time	10 sec

[a]Oversampling.

Table A13.2.3 Imaging Parameters for Lower Extremity 2-D TOF MRV

Patient positioning	Supine
Scan type	2-D gradient echo
Imaging plane (orientation)	Transverse
Central slice or volume center	The cranial initial 2-D slab is positioned at a point just above the iliac crest to cover the lower inferior vena cava. The lower stack typically covers a point just below the inguinal region.
Echo time (T_E)	7.0 msec
Repeat time (T_R)	608 msec
Flip angle (FA)	70°
Fields of view (FOV_x, FOV_y)	350 mm[a], 263 mm
Resolution (Δx, Δy)	1.37 mm, 2.31 mm
Number of data points collected (N_x, N_y)	256, 114
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3 mm
Number of slices	32
Slice gap	–0.81 mm (–27%)
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Saturation pulses	Traveling superior saturation pulse for arterial saturation
Scan time	1 min, 57 sec

[a]Oversampling.

Data processing and viewing for sequence 2

14. Use these five stacks acquired at each region of interest to obtain maximum intensity projection images. Use the source data to review for filling defects (see *UNIT A13.1*, Anticipated Results).

Sequence 3: Bolus test assessment

15. Review the rapid three-plane positioning scouts and position the transverse bolus test slice at the midpoint (iliac arteries) within the region of interest. Inject 2 ml contrast agent at a rate of 1.5 ml/sec followed by a saline flush of 15 to 20 ml at a similar rate of 1.5 ml/sec.

16. Perform a transverse bolus test assessment study by running sequence 3 according to imaging parameters in Table A13.2.4. Review the image data and note the time that it takes for the contrast agent to arrive at the imaging slice position. This is the bolus arrival time that can be used as the scan delay time.

Sequence 4: 3-D contrast-enhanced MRV

The pilot scouts (sequence 1) are reviewed and the coronal 3-D contrast enhanced MRV sequence is appropriately placed to evaluate the course of the common and external iliac, common femoral and superficial femoral and finally, popliteal veins. Without a stepping MRI table, the three regions of interest (pelvis, thighs, and legs) are evaluated with three separate injections, however, with an MRI stepping table (see Basic Protocol 2), two regions of interest (pelvis and thighs), can be evaluated with just one contrast agent injection utilizing the bolus chase protocol. At this time, however, implementation of 3-D contrast MRV with extracellular MRV contrast agents is not promoted due to the lower vascular-to-background contrast of the venous signal. This protocol, however, can be employed as a rapid screening procedure for evaluating the presence or absence of gross abnormalities. In the future, it will likely be replaced employing the same sequence but with a blood pool agent such as MS-325, whereby arterial pass imaging is followed by

Table A13.2.4 Imaging Parameters for Test Bolus Assessment

Patient position	Supine
Scan type	2-D gradient echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Slice centered at midpoint within the first region of interest
Echo time (T_E)	2.4 msec
Repeat time (T_R)	5.8 msec
Inversion time (T_I)	300 msec
Flip angle (FA)	8°
Fields of view (FOV_x, FOV_y)	350 mm, 263 mm
Resolution (Δx, Δy)	1.37 mm, 2.05 mm
Number of data points collected (N_x, N_y)	256, 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	8–10 mm
Number of slices	1
Slice gap	Not applicable
Number of acquisitions (N_{acq})	1
Number of repetitions	60
Swap read and phase encoding	No
Saturation pulses	No
Scan time	60 sec[a]

[a]Each acquisition time is 1 sec, and the total scan time is 60 sec.

Table A13.2.5 Imaging Parameters for 3-D Contrast Enhanced MRV of Lower Extremities and Pelvis

Patient position	Supine
Scan type	3-D gradient echo with sync interpolation
Imaging plane (orientation)	Coronal
Central slice or volume center	Coronal slab is centered at the iliac, femoral and popliteal vessels
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
Number of slices	22 (interpolated to 44)
Slab thickness	100–120 mm
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Number of repetitions	2
Swap read and phase encoding	No
Scan time[a]	21 sec

[a]The time delay between two measurements is 60 sec and the total scan time is 102 sec.

steady state image acquisition to obtain the venous anatomy. The arterial first pass anatomy is then used as a mask for subtracting from the steady state image acquisition data to yield venous-only data. The imaging parameters are similar to those described for pulmonary MRA (*UNITA13.1*) but with slight modifications as listed below in Table A13.2.5.

Without a stepping table, each region of interest is imaged with two measurements:the first measurement will display the arterial anatomy; the second, the venous anatomy during steady state. A time delay between two measurements is ~60 sec. Subsequently, the patient and imaging coils are repositioned to the next region of interest (e.g., thighs) and the protocol is repeated as in the pelvis.

17. Leaving the patient in the magnet, inject the contrast agent, flush the line with 20 ml saline, wait for the bolus arrival time, and then run sequence 4 according to Table A13.2.5.

    A dose of 0.1 mmol/kg of contrast agent is usually given.

18. Pull the patient out of the magnet, reposition the coil at the thigh, center the patient into the magnet, and repeat sequences 1, 3, and 4 (steps 11, 15 to 17).

19. Pull the patient out of the magnet, reposition the coil at the legs, center the patient into the magnet, and repeat sequences 1, 3, and 4 (steps 11, 15 to 17).

IMAGING THE PELVIC AND LOWER EXTREMITY VEINS WITH A STEPPING TABLE

If a stepping table is available, sequence 4 can be run differently. During a time difference of 5 sec, the table is manually repositioned from the first region of interest (pelvis) to the second region of interest (thigh) and the bolus is chased to image the arterial anatomy at the second region of interest. After this, a 30- to 45-sec delay is employed followed by two additional measurements, one is at the second region of interest and the other is at the first region of interest. The time difference between the last two measurements is also 5 sec to allow for the table stepping to be repositioned.

Set up patient and equipment

1. Repeat Basic Protocol 1, steps 1 to 11 and 15 to 17.
2. Repeat Basic Protocol 1, step 17, with the number of repetitions set to 4 in Table A13.2.5.
3. Reposition the stepping table from the pelvis to the thigh area by moving the table by one field of view.

   This is done in 5 sec so it is still at the arterial phase.
4. Obtain images according to Table A13.2.5.

   The scan time will be 21 sec in Table A13.2.5.
5. Wait for 30 to 45 sec and repeat step 4.

   This is the venous phase at the thigh.
6. Reverse step 3, i.e., reposition the stepping table from the thigh area to the pelvis area by one field of view.

   This is done in 5 sec.
7. Repeat step 4.

COMMENTARY

Background Information

Primary indications for performing venous MR angiography include: (1) detection and exclusion of deep venous thrombosis, (2) saphenous venous mapping to determine its suitability in coronary bypass, and (3) monitoring post-thrombotic changes. Current developments in magnetic resonance imaging, especially time-of-flight (TOF) techniques and contrast enhanced MR venography have been successful in the study of venous pathology noninvasively without the need for catheter-based angiography.

The imaging techniques are broadly classified into two main categories; (1) bright blood technique and (2) black blood technique. Bright blood signal can be either due to flow-related enhancement such as in TOF techniques or flow-induced phase shifts such as in phase contrast techniques. The black blood technique, on the other hand, is based on nulling the flow signal by using gradients to induce phase shifts. Among the available TOF techniques, a non-ECG triggered sequential 2-D TOF with a traveling saturation band is well suited for venous MRA in the pelvis and lower extremity. A traveling saturation band is placed superior to the slice so that arterial signal is saturated. With a sequential mode of data acquisition, the slice acquisition follows the course of the flow providing uniform signal across each slice.

In the pelvic region, 2-D TOF techniques have been very accurate when compared to conventional venography (Evans et al., 1993; Carpenter et al., 1993). Furthermore, it is robust and easy to implement. However, deep small veins are often missed or not clearly visualized due to insufficient inflow effects. Under these circumstances, subtraction techniques have been useful by eliminating background signal to improve small vessel signal (Lebowitz et al.,

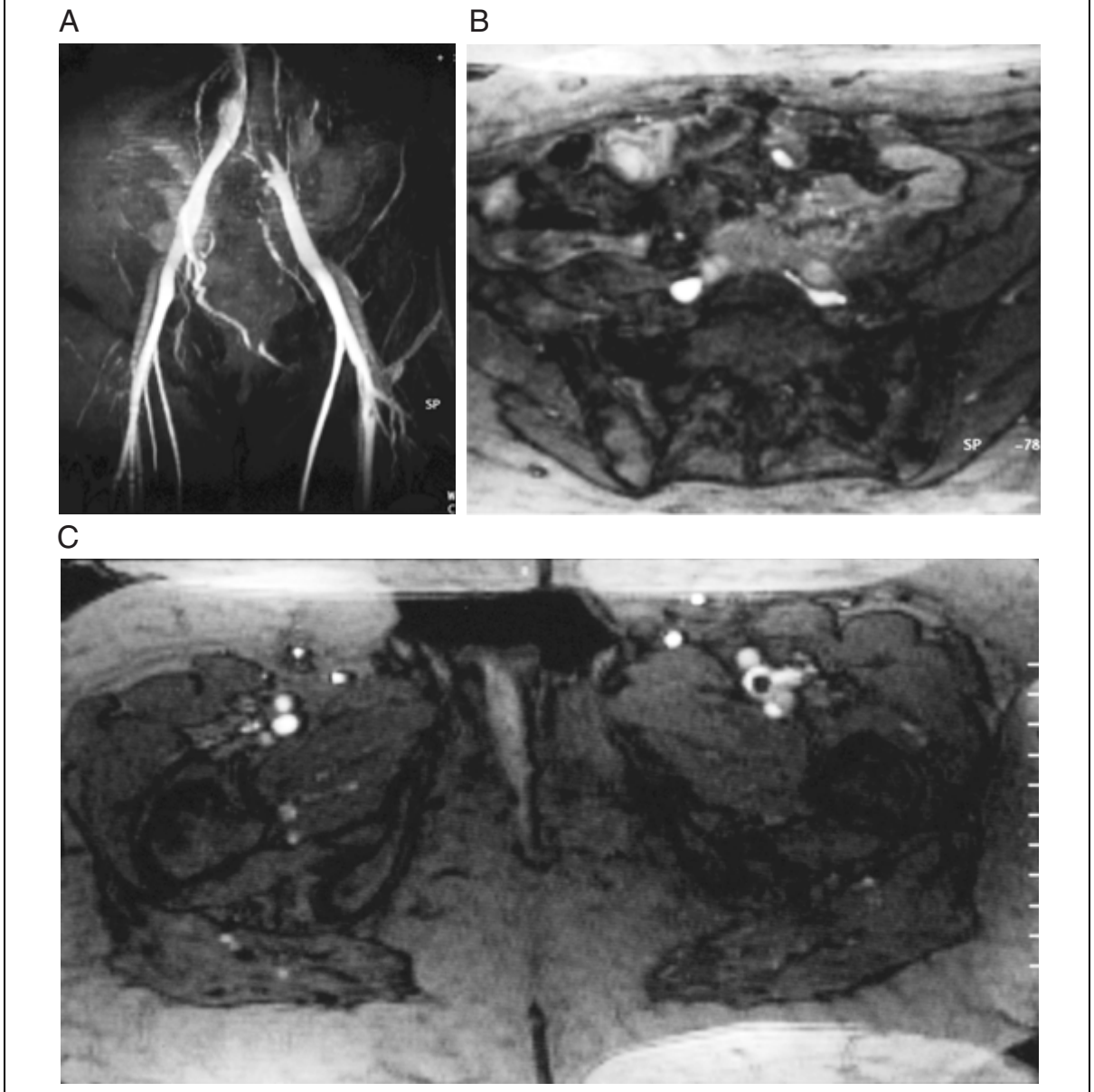

Figure A13.2.1 Acute nonocclusive DVT. The MIP image (**A**) from a 2-D TOF MRV study shows a low intensity defect involving the left common iliac vein. This is a pitfall of extrinsic compression of the vein from the overlying common iliac artery as demonstrated on the transverse 2-D TOF source data (**B**) at that location. A nonocclusive low signal filling defect consistent with acute thrombus is seen in the left proximal superficial femoral vein. This is best visualized by reviewing the transverse 2-D TOF source data (**C**) and can be overlooked if only the MIP images are viewed.

1997). Another disadvantage with the 2-D TOF is the loss of signal due to in-plane saturation when vessels course parallel to the imaging plane. Contrast enhanced angiography, on the other hand, relies on reducing T_1-relaxation, consequently, increasing the blood signal. The reduction in T_1 that results in signal enhancement is independent of flow direction and, hence, is independent of acquisition plane orientation. Recently, blood pool agents have been used to image the pelvis and lower extremities (Saeed et al., 1998).

Critical Parameters and Troubleshooting

Lower extremity MRV imaging is generally tolerated by patients as it does not require patients holding their breath during the scan.

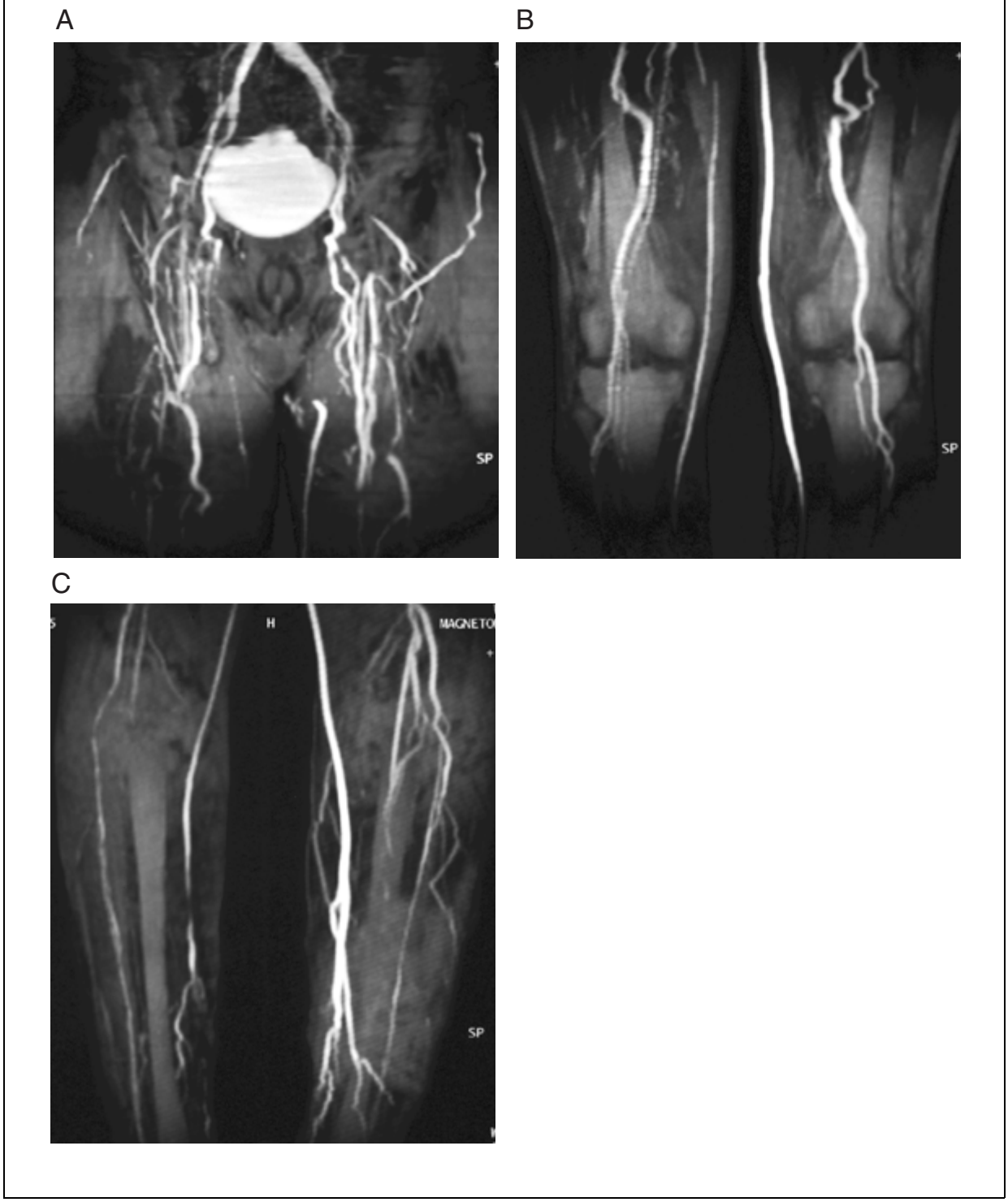

Figure A13.2.2 Chronic lower extremity DVT. MIP images from the proximal (**A**), mid (**B**), and distal (**C**) stations of a 2-D TOF MRV study are shown. The stepping kinematic imaging platform (SKIP) was employed for rapid repositioning of the patient relative to the phased array coils when proceeding from one station to the next. Occlusive disease with collateral veins are shown at all stations.

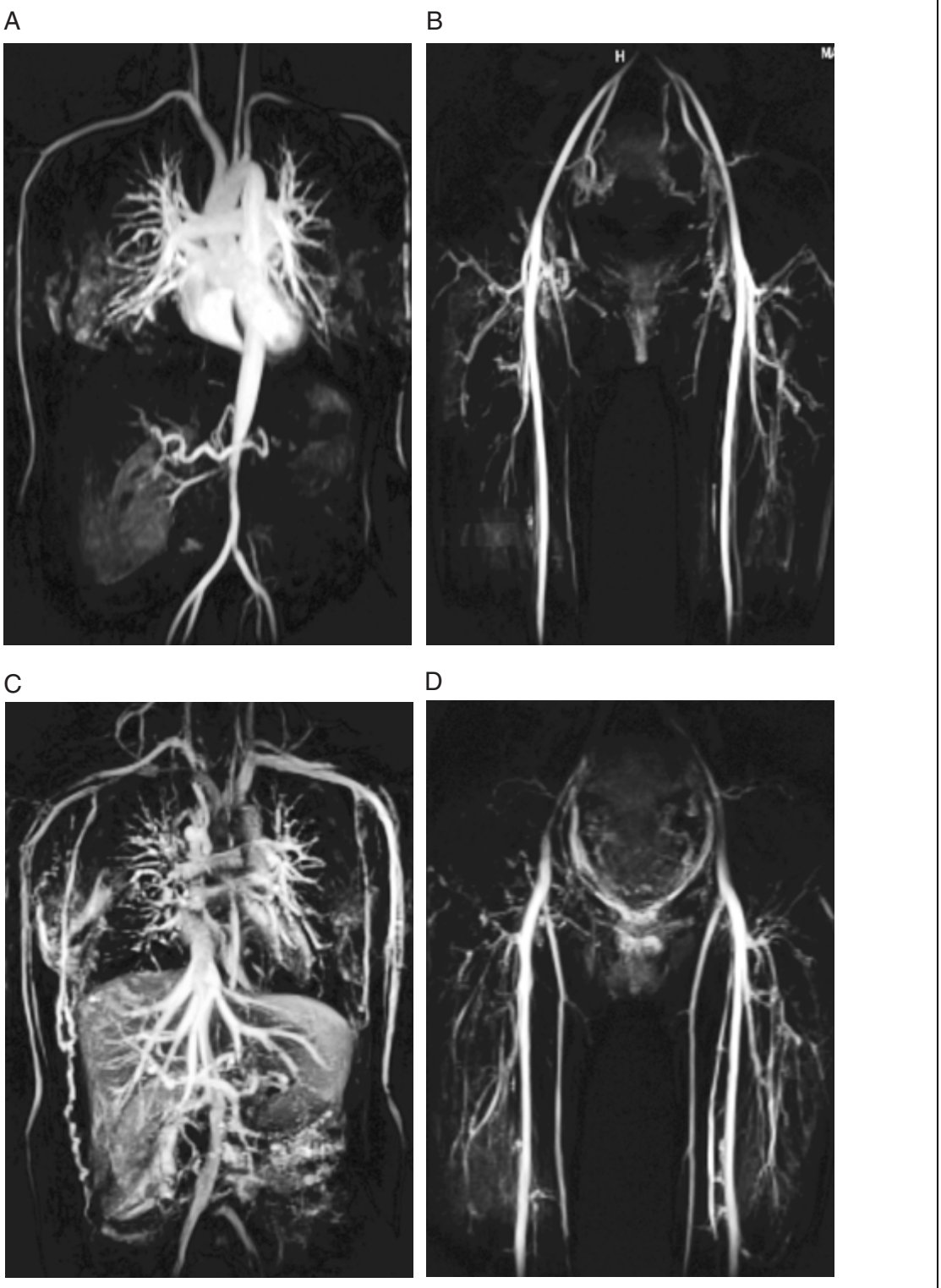

Figure A13.2.3 Pulmonary 3-D contrast enhanced MRA followed by venous steady state imaging. The coronal contrast enhanced (Omniscan, Amersham Health) 3-D MRA MIP image of the proximal station to include the pulmonary vessels is shown (**A**) followed by the pelvic and thigh arterial anatomy (**B**). A single peripheral i.v. injection of contrast was employed along with stepping kinematic imaging platform (SKIP) for MRI table stepping. After stepping the table back to the proximal station, 30 sec later, a steady state image acquisition was made at both imaging stations again. The arterial phase data from (**A**) and (**B**) were used as a mask and subtracted from the steady state data. The MIP images of the subtracted data yield only venous anatomy at both stations (**C**, **D**).

Short T_R gradient echo sequences have been widely applied to clinical MRV.

Saturation Artifacts

Magnetic resonance angiography without the use of a contrast agent works on the principle of signal improvement due to inflow of fresh unsaturated spins into the imaging volume. The conventional 2-D TOF approach, without contrast and with a traveling saturation band (placed superiorly), has a problem associated with motion and in-plane saturation. In areas where vessels become tortuous and parallel to the plane of acquisition (such as the common iliac area), blood spins will be saturated due to repeated application of RF pulses. The in-plane saturation is a well known phenomenon and causes severe loss of signal during imaging when vessels course parallel to the excitation plane and is routinely seen in noncontrast enhanced methods. Contrast enhanced 3-D MRV techniques, on the other hand, do improve vessel visualization due to improved relaxivity of blood spins. Actual application of the sequence presented in this unit may require some modifications depending on the region of interest covered.

Anticipated Results

Nonocclusive thrombus on 2-D TOF MRV presents as a low signal intensity-filling defect. This frequently is detected on source data and can be frequently missed if only maximum intensity projections (MIPs) are reviewed. Occlusive thrombus with collaterals, however, is better appreciated when reviewing the MIPs. Examples of nonocclusive and occlusive thromboses are depicted with 2-D TOF MRV (Figs. A13.2.1 and A13.2.2). Arterial first-pass 3-D contrast enhanced pulmonary and lower extremity imaging followed by steady state imaging to demonstrate the lower extremity venous anatomy is shown in Fig. A13.2.3.

Blood pool contrast enhanced MRV

The availability of blood pool agents in the future is likely to expand beyond the current experimental use of MS-325. Similar protocols that are employed above with extracellular contrast agents can be applied for more robust imaging of the veins in this patient population.

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