Traumatic Brain Injury

Magnetic resonance (MR) imaging of the brain following head injury is used in two distinct clinical contexts, (1) acutely, within days of the injury, to evaluate an unexplained neurologic deficit or to obtain prognostic information, and (2) chronically, to assess the degree of brain injury and explain neurologic or neuropsychologic findings. In this unit, two basic protocols are presented, one for acute imaging (see Basic Protocol 1) and the other for chronic imaging (see Basic Protocol 2). Advanced MR imaging sequences, such as MR spectroscopy (MRS) and diffusion-weighted (DW) imaging can add additional prognostic information in the acute setting and are described. MR angiography (MRA) and direct vessel wall imaging can be important when the question of traumatic vessel dissection is raised. These techniques will be mentioned but are covered fully in other units. The parameters given here are derived from experience at 1.5T and may need to be altered slightly depending on the field strength available and the specific equipment manufacturer.

ACUTE AND SUBACUTE INJURY

BASIC PROTOCOL 1

MR imaging following head injury can be a challenge. Patients are often unable to cooperate with scan instructions or hold still. Many will need monitoring of vital signs during the imaging study and may be intubated. External hardware, such as intracranial pressure monitors, can cause significant artifacts. The goal of this protocol is to expeditiously evaluate the brain for the presence of traumatic injury. Basic Protocol 1 consists of 5 sequences: a fast 3-plane localizer, sagittal T_1-weighted images, transverse fluid-attenuated inversion recovery (FLAIR), fast spin echo (FSE) T_2-weighted images, and coronal gradient echo images. These sequences can be performed on the majority of MR scanners in use today, including most 1.0T and 0.5T systems. For systems without FLAIR capabilities, a conventional spin-echo dual-echo sequence can be substituted for the T_2-weighted FSE and FLAIR sequences. Additional scans, such as diffusion-weighted (DW) and MR spectroscopy (MRS) sequences, can be used if available (see Alternate Protocol). The sequences described herein are based on the authors' experience with a Marconi Medical Systems 1.5T scanner, but are expected to be equally applicable to machines from other manufacturers.

Table A4.4.1 lists the hardware necessary to perform the examination. Gradient coil strength is only a factor for the performance of diffusion imaging and for the determination of the allowable echo train length for FSE sequences.

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 a crash cart or oxygen. Also ensure only magnetic field compatible oxygen tanks are utilized if wall-source oxygen is unavailable.

Table A4.4.1 Equipment Parameters for Head Imaging Sequences

Coil type	Head
Gradient coil strength	25 mT/m (or whatever the system permits)
Gating (cardiac, respiratory, peripheral)	No
Respirator or oxygen	If required by patient
Motion cushions	Recommended
Contrast agents	No

Contributed by Andrew E. Auber and Clifford Belden
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Set up patient and equipment

1. Interview (screen) the patient to ensure that he/she has no contraindication such as cardiac pacemaker or other implants containing ferromagnetic materials. Also be sure to ascertain whether the patient has any health conditions requiring the presence of either special emergency equipment during the scanning procedure, or necessitating special precautions.

   Generally standard screening forms 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 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 form.
3. Have the patient remove all jewelry and change into a gown to eliminate any metal that might be found in clothing.
4. Have the patient remove any mascara or other metal-containing makeup to avoid local tissue heating and image artifacts.
5. Inform the patient about what will occur during the procedure, what he/she will experience while in the magnet, and how to behave, including the following:
   a. If earphones/headphones are used to protect the ears from loud sounds produced by the scanner, the patient will be asked to wear these, but will be able to communicate with the technologist at any/all times during the procedure.
   b. The patient will be given a safety squeeze-bulb or similar equipment to request assistance at any time (demonstrate how this equipment works).
   c. For optimum results the patient should not talk, and should avoid/minimize swallowing or other movement during each scan–i.e., as long as the banging sounds continue. Between scans, talking and swallowing are allowed in most cases, but should be avoided when comparative positional studies are being performed. The patient will be informed in these instances.
   d. Nevertheless, the patient may call out at any time if he/she feels it necessary.
6. Have the patient lay supine on the scanner table. Either before or directly after the patient is positioned on the table, set up any triggering devices or other monitoring equipment necessary.
7. Center the patient in the head coil. Make sure that the head and neck are constrained to prevent unnecessary motion, especially if high-resolution scans are to be run.
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 and place him or her into the magnet centering on the nasion.

   Once this step has been performed, as 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.

Table A4.4.2 Primary Clinical Imaging Parameters for Sequence 1: Rapid Three-Plane Pilot

Patient position	Supine
Scan type	Gradient echo
Imaging plane (orientation)	Sagittal, transverse, and coronal
Central slice or volume center	Midline head
Echo time (T_E)	3.7 msec
Repeat time (T_R)	16 msec
Flip angle (FA)	20°
Fields of view (FOV_x, FOV_y)	300 mm, 300 mm
Resolution (Δx, Δy)	2.34 mm, 2.34 mm
Number of data points collected (N_x, N_y)	128, 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	10 mm
Number of slices	3
Slice gap	NA
Number of acquisitions (N_{acq})	1
Read direction	Left–right
Slice locations	At isocenter, 3 orthogonal planes
Saturation pulses	None
RAM[a]	2X
Scan time	6 sec

[a]Zero padded from 128 by 128 points to 256 by 256 points.

10. If the patient is unable to hold still, either provide an appropriate sedative, or arrange with anesthesiology for conscious or general anesthesia.

    Alternatively, a low-field open magnet may be sought for scanning the claustrophobic patient.

11. This protocol can be performed in <20 min.

Sequence 1: Rapid three-plane pilot

12. Run the three-plane pilot (Table A4.4.2) sequence to evaluate the patient positioning in the magnet.

    This sequence runs in <10 sec and is used to position the remainder of the sequences. It is particularly useful to correct off-axis positioning in the coronal plane.

Sequence 2: T_1-sagittal head

13. Bring the sequence for a sagittal T_1-weighted spin echo scan up on the console. Using the 3-plane pilot, plan the location of the slices, correcting for off-axis positioning of the head in the coronal and transverse planes. Use parameters as specified in Table A4.4.3.

14. Let the patient know you are about to begin the study and start the scan.

Sequence 3: FLAIR transverse head

15. Bring the sequence for a transverse FLAIR scan up onto the console. Set the imaging parameters as shown in Table A4.4.4.

16. Use the sagittal T_1-weighted images and 3-plane pilot to set up the scan levels and a caudal saturation pulse.

17. Let the patient know you are ready, and begin the scan.

Table A4.4.3 Primary Clinical Imaging Parameters for Sequence 2: T_1-Sagittal Head

Patient position	Supine
Scan type	Spin echo
Imaging plane (orientation)	Sagittal
Central slice or volume center	Midline head
Echo time (T_E)	12 msec
Repeat time (T_R)	300 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	240 mm, 240 mm
Resolution (Δx, Δy)	1.25 mm, 0.94 mm
Number of data points collected (N_x, N_y)	192, 256
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	4 mm
Number of slices	15
Slice gap	1 mm
Number of acquisitions (N_{acq})	1
Read direction	Superior–inferior
Slice location	Cover brain parenchyma
Saturation pulses	None
Scan time	1 min, 55 sec

Table A4.4.4 Primary Clinical Imaging Parameters for Sequence 3: FLAIR Transverse Head

Patient position	Supine
Scan type	FLAIR-FSE
Imaging plane (orientation)	Transverse (parallel to AC-PC line)
Central slice or volume center	Mid-cranium
Echo time (T_E)	125 msec (effective)
Echo train length (ETL)	12
Repeat time (T_R)	6000 msec
Inversion time (T_I)	1900 msec
Flip angle (FA)	180°
Fields of view (FOV_x, FOV_y)	240 mm, 197 mm
Resolution (Δx, Δy)	0.94 mm, 0.97 mm
Number of data points collected (N_x, N_y)	256, 204
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	24
Slice gap	1 mm
Number of acquisitions (N_{acq})	1
Read direction	Anterior–posterior
Slice location	Planum sphenoidale-foramen magnum line to vertex
Saturation pulses	Caudal to saturate arterial flow
Scan time	2 min, 48 sec

Table A4.4.5 Primary Clinical Imaging Parameters for Sequence 4: FSE Transverse Head

Patient position	Supine
Scan type	FSE
Imaging plane (orientation)	Transverse
Central slice or volume center	Mid-cranium
Echo time (T_E)	105 msec (effective)
Echo train length (ETL)	16
Repeat time (T_R)	5616 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	240 mm, 180 mm
Resolution (Δx, Δy)	0.63 mm, 0.70 mm
Number of data points collected (N_x, N_y)	384, 256
Display matrix (D_x, D_y)	384, 384
Slice thickness (Δz)	5 mm
Number of slices	24
Slice gap	1 mm
Number of acquisitions (N_{acq})	3
Read direction	Anterior–posterior
Slice location	Planum sphenoidale-foramen magnum line to vertex
Saturation pulses	Caudal to saturate arterial flow
Scan time	3 min, 22 sec

Table A4.4.6 Primary Clinical Imaging Parameters for Sequence 5: Coronal Gradient Echo Head

Patient position	Supine
Scan type	2-D Gradient echo
Imaging plane (orientation)	Coronal
Central slice or volume center	Mid-cranium
Echo time (T_E)	24.6 msec
Repeat time (T_R)	719 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	220 mm, 220 mm
Resolution (Δx, Δy)	0.86 mm, 1.15 mm
Number of data points collected (N_x, N_y)	256, 192
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	5 mm
Number of slices	21
Slice gap	1 mm
Number of acquisitions (N_{acq})	2
Read direction	Superior–inferior
Slice location	Frontal to occipital cerebral poles
Saturation pulses	No
Scan time	4 min, 30 sec

Sequence 4: T_2-weighted FSE transverse head

18. Bring the sequence for a transverse FSE scan up onto the console. Set the imaging parameters as shown in Table A4.4.5.
19. Copy the slice positions from the transverse FLAIR sequence. Place the inferior saturation pulse to saturate arterial inflow.
20. Let the patient know you are ready, and begin the scan.

Sequence 5: Coronal gradient echo (head)

21. Bring the sequence for a gradient echo scan up onto the console. Set the imaging parameters as shown in Table A4.4.6.

    This sequence is optimized to detect the presence of blood products that usually accompany significant head injury.

22. Use the T_1-weighted sagittal midline image to set up the scan levels.
23. Let the patient know you are ready, and begin the scan.

ALTERNATE PROTOCOL

OPTIONAL SEQUENCES

Several sequences can add additional information to the MR evaluation of a head-injured patient. Both DW imaging and MRS have shown promise in providing information about the degree of cerebral injury and/or prognosis. These techniques usually require additional software and high-performance gradients in the case of DW imaging. Both of these sequences are very sensitive to magnetic field inhomogeneity, so careful shimming of the magnet is necessary prior to performing the sequences. In the case of a critically ill patient, the additional time required to perform these sequences may outweigh the benefits.

MRA plays an important role in the diagnosis and follow-up of carotid and vertebral artery dissections. In practice, a 3-D time-of-flight MRA with selected transverse T_1-weighted images are used to diagnose dissections. Contrast-enhanced MRA may be an even more sensitive method for detecting and following dissections. These MRA techniques are detailed in other units (see Chapter A1) and will not be discussed here.

Additional materials

The additional materials needed for the performance of MRS and DW MR are detailed in Table A4.4.7. Many MR manufacturers have integrated semi-automated or completely automated packages for the processing of both diffusion and spectroscopic data. If an analysis package is not available, the data must be analyzed on a separate workstation using outside software.

Sequence 6: DW MR of the brain (optional)

1. Bring the sequence for an echo-planar diffusion scan up onto the console. Set the imaging parameters as shown in Table A4.4.8.
2. Use the scout sequence, midline image, to set up the scan levels.
3. Let the patient know you are ready, and begin the scan. Simulate the echo-planar sequence and adjust the phase offset and delay as needed to optimize the image.

   Optimizing echo-planar scan parameters (phase offset and delay) is important to obtain high quality diffusion images. For this reason, the scan is often simulated prior to being run to allow optimization of these parameters. This may take 1 to 3 min to optimize, even though the actual scan is only 28 sec in length (this is unique to Marconi's system).

4. Pass the changed values to the scanner and run the sequence.

Table A4.4.7 Additional Equipment Needs for Advanced Head Imaging Sequences

Gradient coil strength	High-performance needed for diffusion imaging
Software	For processing diffusion data and MR spectroscopy
Workstation	If analysis package not included in scan software

The sequence obtains echo-planar images with b-values of 0 and 1000 sec/mm^2. The diffusion gradients are applied in 3 directions and from these images, both a diffusion-weighted "trace" image is obtained as well as a map of the Apparent Diffusion Coefficients (ADC) for each pixel. Most manufacturers have built-in automated software for calculating these images.

Sequence 7: MRS of the brain (optional)

5. Bring the MRS scan up onto the console. Set the imaging parameters as shown in Table A4.4.9.

There are 2 basic types of spectroscopic sequences in clinical practice—single voxel and 2-D multi-voxel. Of these, single voxel techniques are the most widely used in non-research environments. PRESS and STEAM (stimulated echo acquisition mode) are the two widely available single voxel localization techniques. PRESS (point-resolved spectroscopic) spectra have a better signal-to-noise ratio but localization is often not as precise as with the STEAM technique. STEAM also allows somewhat shorter T_E values. The authors use a PRESS sequence with a T_E of 35 msec as a compromise. This allows detection of lactate, N-acetyl aspartate (NAA), choline and creatine (Cr) levels.

6. Use previously obtained transverse, sagittal, and coronal images and place the voxel over the region of interest. The voxel is usually a 2 × 2 × 2–cm cube that should be

Table A4.4.8 Primary Clinical Imaging Parameters for Sequence 6: DW MR of the Brain (Optional)

Patient position	Supine
Scan type	Diffusion EPI
Imaging plane (orientation)	Transverse
Central slice or volume center	Mid-cranium
Echo time (T_E)	100 msec
Repeat time (T_R)	5629 msec
Flip angle (FA)	90°
Fields of view (FOV_x, FOV_y)	240 mm, 240 mm
Resolution (Δx, Δy)	2.96 mm, 3 mm
Number of data points collected (N_x, N_y)	81, 80
Display matrix (D_x, D_y)	81, 80
Slice thickness (Δz)	5 mm
Number of slices	20
Slice gap	1 mm
Number of acquisitions (N_{acq})	1[a]
Read direction	Left–right
Slice locations	Whole brain or area of interest
Saturation pulses	Fat
b value	0 and 1000 sec/mm^2
Scan time	28 sec

[a]See also Table A4.1.12.

Table A4.4.9 Primary Clinical Imaging Parameters for Sequence 7: MRS of the Brain

Patient position	Supine
Scan type	PRESS single voxel (STEAM may also be used)
Voxel center	Area of interest
Echo time (T_E)	35 msec (PRESS) or 20 msec (STEAM)
Repeat time (T_R)	1500 msec
Flip angle (FA)	90°
Voxel size (Δx, Δy, Δz)	2 cm, 2 cm, 2 cm
Number of acquisitions (N_{acq})	192 (signal[a]), 8 (reference[b])
Saturation pulses	Water
Scan time	5 min, 50 sec

[a]These 192 acquisitions are done with water suppression.
[b]These 8 acquisitions are done without water suppression and are used for phase correction of the free induction decay scans.

placed in a region that avoids contamination from fat and cerebrospinal fluid and gross magnetic field inhomogeneities, such as above the sinuses.

7. Let the patient know you are ready, and begin the scan. Before the sequence can be run two important steps need to be completed: shimming over the voxel and water suppression.

   Many scanners have somewhat automated packages to perform these functions. These preliminary steps may take 5 to 10 min to perform.

8. Pass the scan values to the scanner and run the spectroscopy sequence.

   Often you will want to do more than one voxel—one over a lesion and another in a "normal" area of brain. This will necessitate repeating steps 5 to 8 again. Overall time for the scan (including the water suppression and shimming) is 10 to 15 min per voxel.

9. The spectroscopy data will need to be analyzed to obtain useful information. Again, many manufacturers have automated this process to get reliable spectroscopic data.

BASIC PROTOCOL 2

CHRONIC INJURY

Months to years after a traumatic injury to the brain the primary focus of imaging is not the acute diagnosis of cerebral injury but rather the assessment of the degree and location of brain injury. The protocol used for chronic injury is similar to Basic Protocol 1 for acute injury with the exception of the addition of a T_1-weighted 3-D gradient echo sequence. This sequence provides an excellent map of brain architecture and enables detailed localization of brain injury. In the chronic phase, diffusion imaging and MR spectroscopy play less of a role and at this time are not routinely used.

This protocol consists of 6 sequences: a fast 3-plane localizer, sagittal T_1-weighted images, transverse FLAIR and FSE T_2-weighted images, coronal gradient echo images, and transverse T_1-weighted 3-D gradient echo sequence. The protocol takes 20 to 22 min to run.

Set up patient and equipment

1. The equipment needed is identical to that identified for Basic Protocol 1 in Table A4.4.1. Set-up and run the first 5 sequences of Basic Protocol 1, steps 1 to 23.

Table A4.4.10 Primary Clinical Imaging Parameters for Sequence 8: 3-D Gradient Echo

Patient position	Supine
Scan type	3-D gradient echo
Imaging plane (orientation)	Transverse
Central slice or volume center	Mid-cranium for whole brain, or area of abnormality
Echo time (T_E)	5 msec
Repeat time (T_R)	11.2 msec (or minimum)
Flip angle (FA)	35°
Fields of view (FOV_x, FOV_y)	240 mm, 187 mm
Resolution (Δx, Δy)	0.94 mm, 0.97 mm
Number of data points collected (N_x, N_y)	256, 192
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	1–1.5 mm
Number of slices	120
Slab thickness	120–180 mm, depending on patient size
Slice gap	0 mm
Number of acquisitions (N_{acq})	1
Read direction	Anterior–posterior
Slice location	Whole brain
No phase wrap (NPW)[a]	Yes
Saturation pulses	NA
Scan time	4 min, 19 sec

[a]Phase oversampling or anti-aliasing.

Sequence 8: 3-Dimensional transverse gradient echo head

2. Bring the sequence for a 3-D volumetric gradient echo scan on to the console. Set the imaging parameters as shown in Table A4.4.10.

   This sequence allows thin slice (i.e., 1 to 1.5 mm) images through the entire brain. The dataset can be re-sliced in any plane desired. The images are T_1-weighted and show areas of encephalomalacia, and in addition, the fact that the images are a gradient echo sequence provides some blooming artifact around areas of axonal injury, allowing precise localization of damage.

   To obtain T_1-weighting, a relatively large flip angle is needed. This becomes a trade-off between time and T_1-weighting as the T_R increases. With the parameters given, decent T_1-weighting is obtained with an imaging time of 7 to 8 min.

3. Use the scout sequence, midline image, to set up the scan levels.
4. Let the patient know you are ready, and begin the scan.

COMMENTARY

Background Information

Traumatic brain injury (TBI) is a major health problem throughout the world. In the United States there are over 50,000 deaths per year related to TBI (Thurman and Guerrero, 1999). The number of patients left with significant mobidity following head injury is many times greater than those who die of their injuries. Imaging plays an important role in these patients. Computed tomography (CT) is the mainstay of imaging in cerebral trauma. CT is able to quickly assess which patients need emergent treatment for intracranial injuries (usually extra-axial hematomas). It is well documented that CT misses many of the traumatic lesions in the brain, particularly small subdural collections and cortical contusions. MR imaging in patients with normal head CTs show abnor-

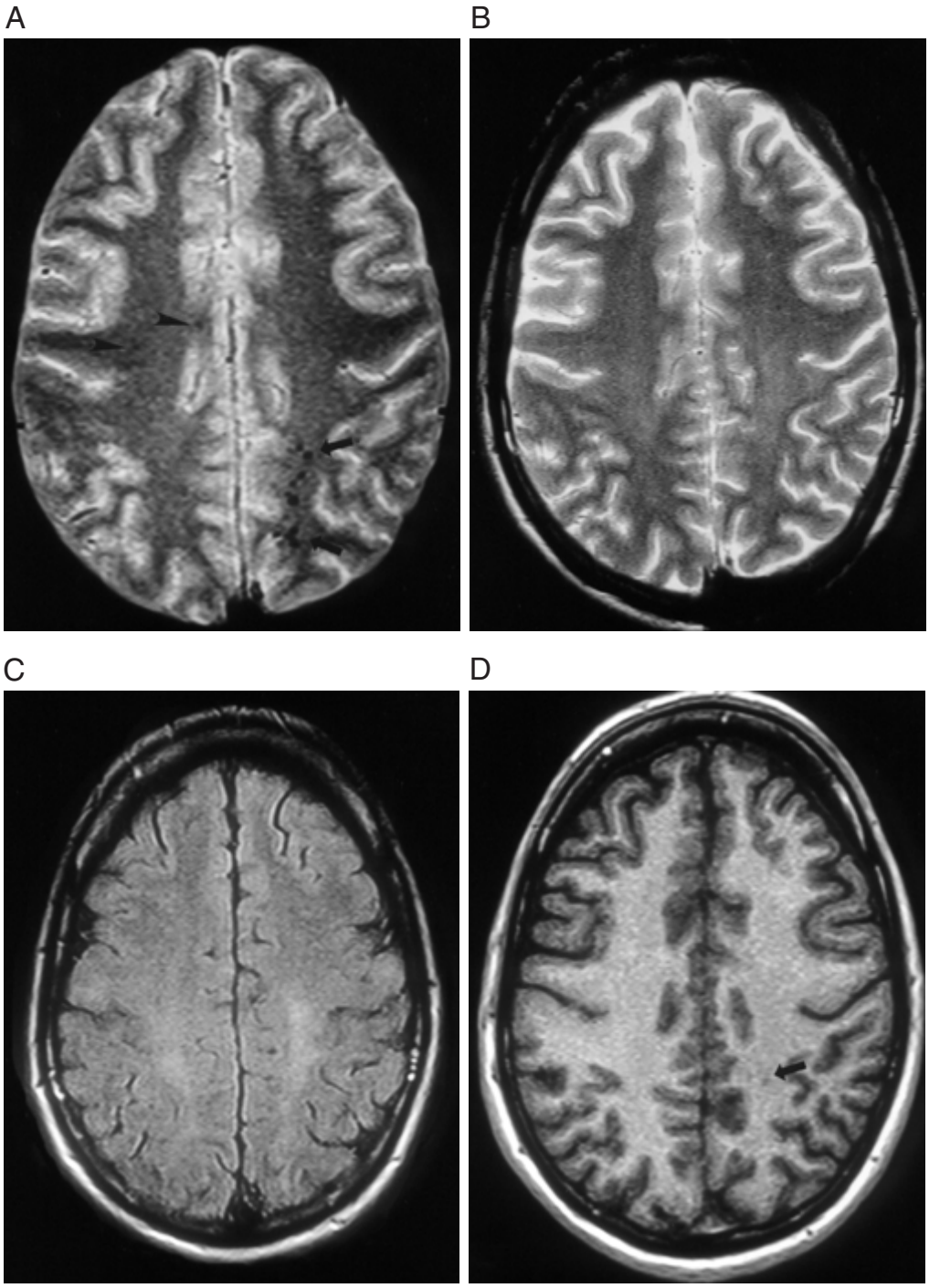

Figure A4.4.1 21 year-old male one year following closed head injury. (**A**-**D**) and (**E**-**H**) demonstrate the appearance of shear injury using hemosiderin sensitive gradient echo, FSE T_2-weighted, FLAIR, and 3-D gradient echo sequences, respectively, at two imaging levels. (**A**-**D**). The large region of shear injury near the vertex of the left parietal lobe is best seen on the 2-D gradient echo sequence (**A**, arrows), with several smaller foci of signal dephasing (arrowheads), likely representing smaller areas of shear injury. The parietal region is essentially normal on T_2-weighted FSE (**B**) and FLAIR (**C**) images and barely discernible on a short echo 3-D gradient echo sequence (**D**, arrow). (**E**-**H**). At the level of the third ventricle, shear injury to both basal ganglia (**E**, arrows), an old parenchymal hematoma in the right frontal lobe (**E**, open arrow) and the old hemorrhagic contusion in the left frontal lobe (**E**, arrowhead) are best seen on the 2-D gradient echo sequences. The old right frontal lobe hematoma is easily seen on T_2-weighted FSE, FLAIR and 3-D gradient (*continued on next page*)

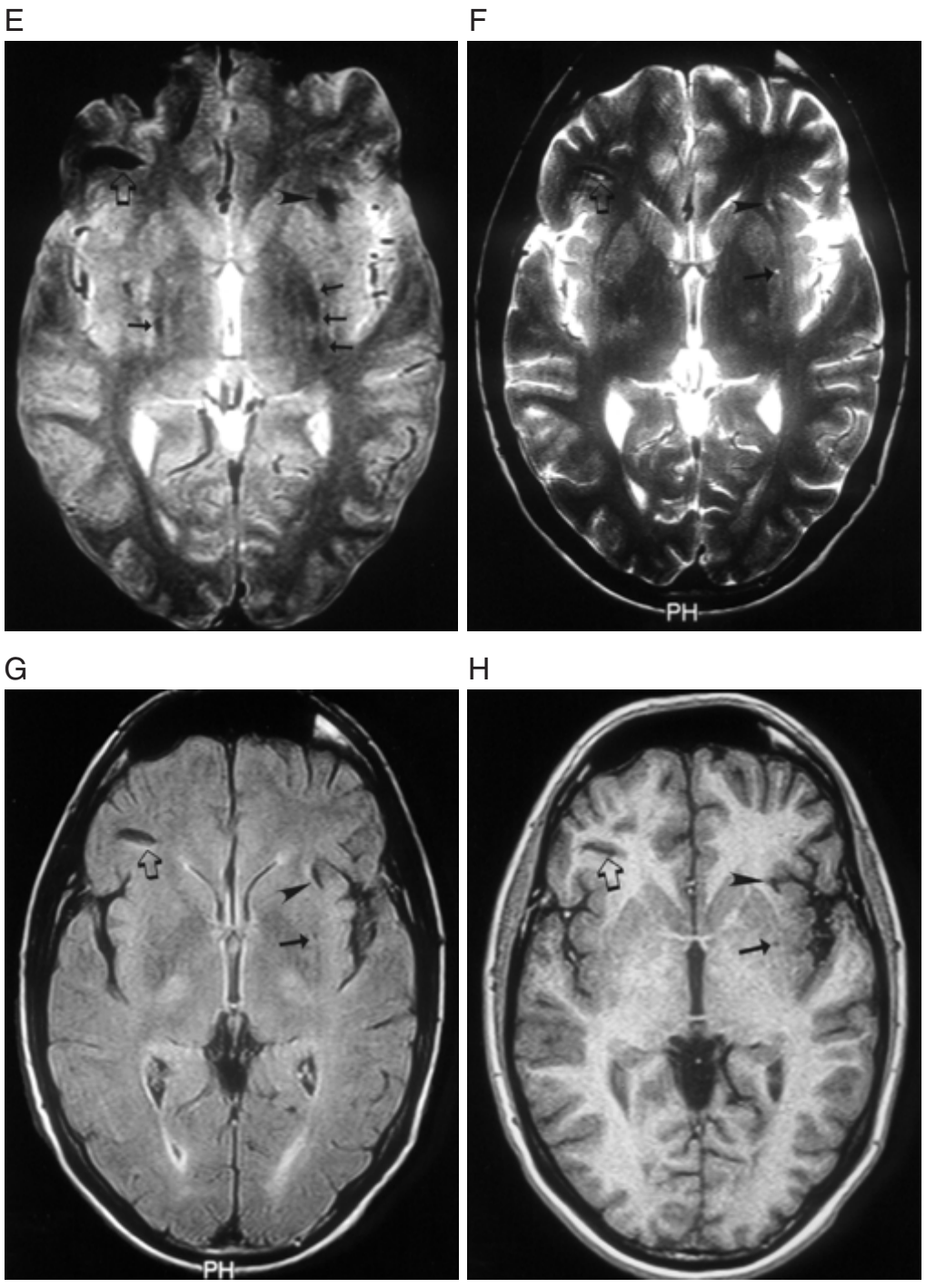

Figure A4.4.1 *(continued)* echo sequences as signal dephasing (open arrow **F**, **G**, **H**). The smaller area of contusion in the left frontal lobe is present on all sequences, but appears bright on T_2-weighted FSE (**F**, arrowhead), and dark on both FLAIR and 3-D gradient echo sequences (**G**, **H** arrowhead). The presence of shear injury in the basal ganglia is only confidently made on the gradient echo sequence, though there is a small focus of increased signal on T_2-weighted FSE images (**F**, arrow) and decreased signal on FLAIR (**G**, arrow) and 3-D gradient echo (**H**, arrow) sequences. (NOTE: The described protocol uses coronal gradient echo images. Transverse images are presented to optimally demonstrate the relative lesion conspicuity between basic sequences.)

malities 30% to 60% of the time (Levin et al., 1992; Mittl et al., 1994). In one study, small subdural collections were detected by MR alone in 58% of cases and CT missed the majority of cases of shear injury and non-hemorrhagic contusions (Kelly et al., 1988).

Currently, there is no specific treatment for the majority of the additional lesions that MR is able to detect. This, along with the difficulties in scanning acutely head-injured patients, has been the major reason MR has not been adopted for routine use in acute trauma settings. It is becoming increasingly clear, however, that significant brain damage can occur in patients with even mild head injuries. Presently, MR is the only tool we have to document the location and extent of these injuries. In the future, neuroprotective agents may play an important role in limiting the long-term brain damage in these patients.

In the chronic state, head-injured patients are often scanned to depict the location and extent of brain injury. The impetus for the scan is usually a persistent impairment in some aspect of cognitive function or abnormal performance on neuro-psychologic testing. The treatment for these patients is usually recognition of their limitation and introduction of skills to help them cope with their disabilities.

Critical Parameters and Troubleshooting

The major technical challenge in imaging patients with head injury is patient cooperation. Methods to decrease overall scanning time and ensure relative immobilization are essential to high-quality imaging. The two most critical sequences in Basic Protocols 1 and 2 are the transverse FLAIR sequence and the coronal gradient echo sequence. These have the highest sensitivity for non-hemorrhagic contusions and diffuse axonal injury (shear damage), respectively (Figure A4.4.1; Ashikaga et al., 1997; Parizel et al., 1998).

FLAIR sequence

The FLAIR sequence can be one of the more difficult sequences to optimize. The majority of FLAIR is done as an FSE acquisition, giving 4 parameters to adjust: echo train length (ETL), T_R, T_E, and T_I. The goal of the optimization is to limit the signal in the CSF while maintaining reasonable gray-white matter differentiation and minimizing time. The T_I should be selected to null CSF (cerebrospinal fluid) signal. T_R and T_E can be adjusted to enhance the gray-white matter differentiation. The echo train length can be increased to decrease the time of the scan, but often at the expense of increased CSF flow artifact.

Hemosiderin sensitive gradient echo sequence

The gradient echo sequence has parameters selected to optimize the blooming effect seen around blood products. The sequence described is a T_2^*-weighted sequence with a relatively long T_E to enhance the blooming artifact.

Anticipated Results

MRI is used in the acute and subacute trauma setting to identify a cause for neurologic deficits that are not explained by findings present on CT. Basic Protocol 1 is designed to give a fairly quick assessment of the degree of cerebral damage following head injury. The sagittal T_1-weighted images are useful for the detection of subacute blood products (methemaglobin). The transverse FSE T_2-weighted sequence is the primary sequence for assessing overall brain structure and anatomy. The FLAIR sequence has been shown to be the most sensitive to cortical contusions as well as deep contusions of the fornix and corpus callosum. Finally, the coronal gradient echo scan is optimized to detect blood products. Blooming around areas of shear injury are fairly characteristic, and this is often the only sequence on which they are seen.

The optional sequences for Alternate Protocol are designed to give additional prognostic information. DW images can depict areas of cellular injury. DW MR has been used in some patients and animal models following TBI (Hanstock et al., 1994; Smith et al., 1995; Alsop et al., 1996; Assaf et al., 1997; Barzo et al., 1997; Stroop et al., 1998; Werring et al., 1998). It is known in animal models that following head injury, the ADC is significantly decreased in areas of trauma, and that by 7 days following injury the ADC is larger than that in normal brain parenchyma (Assaf et al., 1997). At the 1 week time there was good correlation between regions of diffusion abnormality and pathologic evidence of brain injury (Assaf et al., 1997).

Investigators have had some success attempting to correlate MRS data with outcome after TBI (Ross et al., 1998; Friedman et al., 1999). Friedman showed early gray matter NAA predicted overall neuropsychologic performance in 14 patients imaged 1 to 2 months post injury (Friedman et al., 1999). In 25 patients with TBI, Ross et al. (1998) showed decreased NAA correlated with outcome following TBI, and that in children, decreased

NAA/Cr and lactate portended a poor outcome (Ross et al., 1998).

Basic Protocol 2 for use in chronic head injury is similar to Basic Protocol 1 with the exception of the addition of a volumetric T_1-weighted gradient echo sequence. This sequence demonstrates the areas of brain injury (encephalomalacia) better than most and allows for reslicing in multiple planes as well as for volumetric measurements to be made. In at least one study, a sequence similar to this one was the optimal sequence for defining the location and extent of parenchymal damage (Herskovits et al., 1999).

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Key References

Mittl et al., 1994. See above.

MRI demonstrates abnormalities in mild head injury patients with normal CT. Axonal injury was found in 30% of patients.

Kelly et al., 1988. See above.

This article demonstrates the ability of MR to depict many more lesions in the traumatized patient compared with CT. Over half of contusions and subdurals were seen by MR.

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