Head and Neck MRA at 3.0T

This unit comprises two protocols for vascular imaging of the head and neck, respectively, at a field strength of 3.0T. The protocol for imaging intracranial circulation (Basic Protocol 1) acquires MR data for ∼10.5 min. The time it takes to complete other tasks such as to get the patient on and off the table, communicate with the patient in between sequences, and perform the pre-scan calibration must be considered. We expect that this protocol can realistically be completed in ∼20 to 25 min, plus the time to post-process the 3DTOF images.

The second protocol, for imaging intracervical circulation (see Basic Protocol 2) acquires MR data for ∼12.5 min, including the additional tasks mentioned for Basic Protocol 1, as well as time to attach the i.v. line, interpret the test bolus timing run, and reconstruct the 1024 images. We expect that this protocol can be completed in ∼30 min, plus the time it takes to post-process the maximum intensity projections (MIP).

We are using a General Electric (GE) 3T Signa EXCITE system, commonly known as their "short-bore," running G3 M4 software, which is the version of 11.0 software for the 3.0T scanner. Currently the intracranial and cervical protocols are separate. This is mainly due to the unavailability (at least to us, at the current time) of an adequate integrated neurovascular phased array coil. Perhaps in the future when more RF coils are available for 3.0T, we will combine the two protocols in a revised version of this unit.

IMAGING INTRACRANIAL CIRCULATION AT 3.0T

BASIC PROTOCOL 1

This protocol provides relatively high-spatial-resolution images of the intracranial circulation using a multi-slab 3-D time of flight (3DTOF) technique, also known as MOTSA (Parker et al., 1991). The entire protocol comprises four sequences that acquire MR data for ∼10.5 min, but will probably require 20 to 25 min to complete, considering the usual additional tasks like getting the patient on and off of the scanner.

Parallel imaging techniques are used to reduce the scan time of the 3DTOF series to less than 7 min. This helps to minimize patient motion artifacts that occur with longer acquisitions. The higher SNR available at 3.0T and 8-channel receive coils facilitate the use of parallel imaging. Table A7.8.1 lists the necessary hardware to perform scans under this protocol.

Set up patient and equipment

1. Interview (screen) the patient to ensure that he or she has no contraindications such as a cardiac pacemaker or other implants containing conducting or ferromagnetic materials that may be problematic for patient safety or image quality. 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. At this time, it is our practice to image patients with MR-compatible aneurysm clips on one of our 1.5T scanners, rather than at 3.0T.

   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 (2005) for discussion of which implants may be safely scanned using magnetic resonance imaging.

Contributed by Matt A. Bernstein and John Huston III
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Table A7.8.1 Equipment Parameters for 3.0T Intracranial MRA

Main magnet	3.0T
RF coil type	8-channel receive-only head phased-array
Gradient coil strength	40 mT/m, 150T/m/sec (zoom mode) 22 mT/m, 77T/m/sec (whole-body mode)
Cardiac gating	No
Peripheral gating	No
Respiratory gating	No
Respirator	Only if required by patient
Oxygen	Only if required by patient
Motion cushions	Yes
Use of contrast agents	No

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. The companion should be also be given hearing protection, as described below.

2. If the procedure is a research protocol, informed consent is obtained, and the patient signs any necessary consent forms, as directed by the local Institutional Review Board (IRB) or equivalent.
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 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. Earplugs, earphones, and/or headphones are used to protect the ears from the loud sounds produced by the gradients, and the patient will be asked to wear these devices. The patient, however, will be able to communicate with you at any time during the imaging.
   b. The patient will be given a squeeze-bulb-activated alarm 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 head movement, during each scan—i.e., as long as the banging sounds continue. Between scans, talking and swallowing are allowed, 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 (and is encouraged to) call out or use the squeeze-bulb alarm at any time if he or she feels it necessary. In particular, the patient is coached that some minor warming during an MRI procedure is normal, but painful heating is never normal.
6. Have the patient lie down on the scanning table. Set up any monitoring equipment that is to be used.
7. Center the patient's head in the 8-channel head coil. Make sure that the head is comfortably, but firmly, constrained with pads to reduce motion.
8. Place a triangular-shaped support or other pillow under the knees to make the patient more comfortable.

9. Ensure that the patient fan is on. If the patient desires, he or she will be given a sheet or lightweight blanket.

10. Position the patient so that the centering light is at the level of the eyebrows, and then advance him or her into the center of the magnet. Place two additional pads at this time: one on each side where the magnet's bore wall contacts the patient's arm and shoulder.

    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.

11. Coach the patient to remain still during the scans. If the patient is unable to hold still, an appropriate sedative might be helpful. Before the sedative is prescribed, however, ensure that the patient does not plan to operate an automobile or other heavy machinery.

Sequence 1: Phase-contrast localizer (scout)

12. To visualize the major vessels of the head in anterior projection, run the phase-contrast localizer scan according to the parameters listed in Table A7.8.2.

Table A7.8.2 Primary Clinical Imaging Parameters for Sequence 1 (Phase-Contrast Localizer of the Head)

Patient position	Head first, supine
Scan type	Phase contrast localizer (head)[a]
Imaging plane (orientation)	Coronal
Pulse sequence database (PSD)	2-D fast gradient echo
Central slice or volume center	Nasion
Echo time (T_E)	9.8 msec
Receiver bandwidth (RBW)	±15.6 kHz (i.e., 61 Hz/pixel)
Repeat time (T_R)	40 msec
Flip angle (FA)	20°
Fields of view (FOV_x, FOV_y)	220 mm, 220r mm, with $r = 3/4$ (rectangular field of view)
Resolution (Δx, Δy)	0.43 mm, 0.86 mm
Number of data points collected (N_x, N_y)	512, 256r, with $r = 3/4$ (rectangular field of view)
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	90 mm
Number of slices	1
Slice gap	n/a
Number of excitations (NEX)	6
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Read direction	Superior-to-inferior
Slice location	Center single slice at approximately A30
Flow compensation	Yes
Saturation pulses	No
Vascular options	Velocity encoding sensitivity (V_{enc}) of 60 cm/sec in all directions; complex difference reconstruction
Scan time	3 min, 5 sec

[a]The gradient mode of this sequence is set at the zoom mode.

Sequence 2: ASSET calibration

This acquisition provides a low-spatial-resolution sensitivity map for the coil elements of the 8-channel receive-only head coil. The images are later used by the ASSET reconstruction for Sequence 3. ASSET is a GE acronym for Array Spatial Sensitivity Encoding Technique. ASSET is also commonly referred to as "SENSE" on other scanner brands, and in the literature (Pruessmann et al., 1999).

13. Acquire ASSET calibration with the parameters listed in Table A7.8.3.

    Note that on some MR systems, this calibration scan might be automatically embedded into the pre-scan or into the acquisition of the 3DTOF data itself.

Sequence 3: Transverse 3DTOF

14. Run the transverse 3DTOF with acquisition parameters listed in Table A7.8.4.

    We prescribe three transverse slabs from superior to inferior to obtain the desire d coverage.

    The use of parallel imaging keeps the acquisition time below 7 min. Without the use of parallel imaging, few patients could remain motionless for the duration of the exam, which would be twice as long.

    The 3DTOF acquisition results in 144 0.7-mm thick transverse images.

15. Obtain sub-volume maximum intensity projections (MIPs) with the interactive vascular imaging (IVI) post-processing program.

    We obtain three sets of sub-volume MIPs: the left carotid, right carotid, and posterior circulation, with each carotid volume containing both anterior cerebral arteries. In order to cover the entire volume, each set contains 19 projections spaced evenly at intervals of 10°, including lateral and anterior views.

Table A7.8.3 Primary Clinical Imaging Parameters for Sequence 2 (ASSET Calibration)

Patient position	Head first, supine
Scan type	ASSET (i.e., SENSE) calibration[a]
Imaging plane (orientation)	Transverse
Pulse sequence database (PSD)	2-D fast gradient echo
Central slice or volume center	Nasion
Echo time (T_E)	2.8 msec
Receiver bandwidth (RBW)	±32 kHz (i.e., ~977 Hz/pixel)
Repeat time (T_R)	150 msec
Flip angle (FA)	50°
Fields of view (FOV_x, FOV_y)	300 mm, 300 mm
Resolution (Δx, Δy)	4.69 mm, 9.38 mm
Number of data points collected (N_x, N_y)	64, 32
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	3.0 mm
Number of slices	64
Slice gap	0 mm
Number of excitations (NEX)	1
Number of acquisitions (N_{acq})	2 (to interleave contiguous slices)
Swap read and phase encoding	Yes
Read direction	Right-to-left
Slice location	Most superior slice covers top of head
Flow compensation	No
Saturation pulses	No
Scan time	18 sec[b]

[a]The gradient mode of this sequence is set at the whole-body mode.

[b]The image sets include images acquired from the body coil and the phased array coil.

Table A7.8.4 Primary Clinical Imaging Parameters for Sequence 3 (Transverse 3DTOF of the Head)

Patient position	Head first, supine
Scan type	3DTOF of intracranial vessels[a]
Imaging plane (orientation)	Transverse
Pulse sequence database (PSD)	3-D spoiled gradient echo
Central slice or volume center	Nasion
Echo time (T_E)	3.9 msec (minimum partial echo)
Receiver bandwidth (RBW)	±15.6 kHz (i.e., ~81.3 Hz/pixel)
Repeat time (T_R)	38 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	180 mm, 180r mm, with $r = 0.9$ (rectangular field of view)
Resolution (Δx, Δy)	0.47 mm, 0.70 mm
Number of data points collected (N_x, N_y)	384, 256r, with $r = 0.9$ (rectangular field of view)
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	1.4 mm
Number of slices	32 slices per slab (with 12 slices overlap per slab, it yields 72 un-interpolated slices)
Slab thickness	44.8 mm
Number of slabs	3
Slab overlap	12 slices per slab
Slice gap	0 mm
Number of excitations (NEX)	1
Number of acquisitions (N_{acq})	3 (for 3 sequential slabs)
Swap read and phase encoding	No
Read direction	Anterior-posterior
Slice location	Cranially-caudally from the posterior inferior cerebellar artery (PICA) origins to the level where the anterior cerebral artery branches into the pericallosal and callosomarginal arteries.
Flow compensation	Yes
ZIP 2	Yes, reconstruction generates twice as many 1.4-mm slices that are overlapped by 0.7 mm
Extended dynamic range (EDR)	Yes
Saturation pulses	Superior (S)
Magnetization transfer	Yes, see Commentary
Parallel imaging	Yes
Acceleration factor	2
Scan time	6 min, 59 sec

[a]The gradient mode of this sequence is set at the zoom mode.

IMAGING OF THE CAROTID-VERTEBRAL-BASILAR SYSTEM USING GADOLINIUM BOLUS

BASIC PROTOCOL 2

This protocol provides high-spatial-resolution images of the cervical circulation, including the carotid, vertebral, and basilar arteries, using a gadolinium bolus protocol (Prince et al., 1999). The protocol acquires MR data for ~12.5 min, but will probably require 30 min to complete, considering additional tasks like getting the patient on and off of the table and interpreting the test-bolus timing images. Note that unlike time-resolved methods like TRICKS (Mistretta et al., 1998), the method described here acquires data at only

Table A7.8.5 Equipment Parameters for Basic Protocol 2 (Gadolinium Bolus of the Carotid-Vertebral-Basilar System)

Main magnet	3.0T
RF coil type	8-channel CTL array spine coil (8USCTL123)
Gradient coil strength	22 mT/m, 77T/m/sec (whole-body mode) 40 mT/m, 150T/m/sec (zoom mode)
Cardiac gating	No
Peripheral gating	No
Respiratory gating	No
Respirator	Only if required by patient
Oxygen	Only if required by patient
Motion cushions	Yes
Use of contrast agents	Yes

a single (arterial) phase. That single acquisition, however, occurs over extended period of time (i.e., >1 min). The advantage of this strategy is to maximize spatial resolution and coverage.

As of 2005, there is a dearth of commercial neck or neurovascular coils available for the 3.0T system that we are using. Consequently, the protocol here uses the cervical portion of an 8-channel CTL coil (i.e., 8USCTL123). In the future, as more coils become available, it might be possible to further increase the spatial resolution, for example, with the use of parallel imaging techniques as employed in Sequence 3 in the previous protocol. Table A7.8.5 lists the necessary hardware to perform scans under this protocol.

Materials

20 ml of gadolinium chelate contrast agent and 50 ml of saline

Set up patient and equipment

1. Load 20 ml of gadolinium chelate contrast agent into one chamber of a power injector and 50 ml of saline into the second chamber.
2. Carry out steps 1 to 5 in Basic Protocol 1.
3. Have a nurse prepare an i.v. in the antecubital vein of the right arm.
4. Have the patient lie down on the scanning table. Set up any monitoring equipment that is to be used.
5. Center the patient's neck in the 8-channel CTL coil. Make sure that the head and neck are comfortably, but firmly, constrained with pads to reduce motion.
6. Place a triangular-shaped support or other pillow under the knees to make the patient more comfortable.
7. Ensure that the patient fan is on. If the patient desires, he or she will be given a sheet or lightweight blanket.
8. Position the patient so that the centering light is at the level of the angle of the mandible and advance him or her into the center of the magnet. Place two additional pads at this time: one on each side where the magnet's bore wall contacts the patient's arm and shoulder.

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.

9. Coach the patient to remain still during the scans. If the patient is unable to hold still, an appropriate sedative might be helpful. Before the sedative is prescribed, however, ensure that the patient does not plan to operate an automobile or other heavy machinery.

Sequence 4: 2-D phase contrast localizer (neck)

10. Obtain a localizer (i.e., scout) image of the vessels of the neck in coronal projection by running the 2-D phase contrast with the acquisition parameters listed in Table A7.8.6.

Sequence 5: Transverse 2DTOF (2-D time of flight)

11. Obtain a set of transverse 2-D time-of-flight images according to the acquisition parameters listed in Table A7.8.7. Graphically prescribe the slices from superior-to-inferior to maximize flow-related enhancement. The transverse coverage of the set of 100 slices is 15 cm. Place the most superior slice ~1 cm above the petrous portion of the carotid arteries.

12. Using the software provided by the MRI scanner, obtain the MIP images.

    The vascular projections that are obtained automatically are full-volume MIPs, and are useful for graphically prescribing Sequence 7.

Table A7.8.6 Primary Clinical Imaging Parameters for Sequence 4 (Phase Contrast Localizer of the Neck)

Patient position	Head first, supine
Scan type	Phase contrast localizer (neck)[a]
Imaging plane (orientation)	Coronal
Pulse sequence database (PSD)	2-D fast gradient echo
Central slice or volume center	Neck
Echo time (T_E)	9.8 msec
Receiver bandwidth (RBW)	±15.6 kHz (i.e., 61 Hz/pixel)
Repeat time (T_R)	40 msec
Flip angle (FA)	20°
Fields of view (FOV_x, FOV_y)	220 mm, 220r mm, with $r = 3/4$ (rectangular field of view)
Resolution (Δx, Δy)	0.43 mm, 0.86 mm
Number of data points collected (N_x, N_y)	512, 256r, with $r = 3/4$ (rectangular field of view)
Display matrix (D_x, D_y)	512, 512
Slice thickness (Δz)	90 mm
Number of slices	1
Slice gap	n/a
Number of excitations (NEX)	6
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Read direction	Superior-to-inferior
Slice location	Center single slice at approximately A30
Flow compensation	Yes
Saturation pulses	No
Vascular options	Velocity encoding sensitivity (V_{enc}) of 60 cm/sec in all directions, complex difference reconstruction
Scan time	3 min, 5 sec

[a]The gradient mode of this sequence is set at the whole-body mode.

Table A7.8.7 Primary Clinical Imaging Parameters for Sequence 5 (Transverse 2DTOF of the Neck)

Patient position	Head first, supine
Scan type	2DTOF[a]
Imaging plane (orientation)	Transverse
Pulse sequence database (PSD)	2-D fast gradient echo
Central slice or volume center	Neck
Echo time (T_E)	8.7 msec
Receiver bandwidth (RBW)	±15.6 kHz (i.e., 122 Hz/pixel)
Repeat time (T_R)	27 msec
Flip angle (FA)	40°
Fields of view (FOV_x, FOV_y)	160 mm, 160 mm
Resolution (Δx, Δy)	0.63 mm, 1.25 mm
Number of data points collected (N_x, N_y)	256, 128
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	1.5 mm
Number of slices	100
Slice overlap	0
Slice gap	0
Number of excitations (NEX)	1
Number of acquisitions (N_{acq})	100
Swap read and phase encoding	No
Read direction	Anterior-posterior
Slice location	Most superior transverse slice prescribed 1 cm above petrous carotids
Flow compensation	Yes
Saturation pulses	Yes (superior to slice)
Vascular projections[b]	19
Scan time	6 min, 1 sec

[a]The gradient mode of this sequence is set at the whole-body mode.

[b]Vascular projections are automatically generated full-field of view maximum intensity projection (MIP) images.

Sequence 6: Test bolus circulation timing

The purpose of this sequence is to determine the circulation time for the arrival of the gadolinium bolus at the arteries of the neck. If instead fluoroscopic triggering (see discussions under Critical Parameters and Troubleshooting) is used in Sequence 7, then Sequence 6 can (and should) be omitted.

13. Communicate with the patient, and explain that during this acquisition he or she will receive an injection.

14. Set up the real-time acquisition with the acquisition parameters listed in Table A7.8.8. Verify that the spatial saturation pulses are properly suppressing both the arterial and venous signal in the transverse slice.

15. Store the images in an intermediate buffer by clicking on the "pause when full" option on the GE system. On other scanners, images may be automatically saved. *Simultaneously* start the timer feature (that time-stamps the resulting images), Sequence 6, and the power injector sequence. Inject 2 ml of contrast agent at a rate of 3 ml/sec, immediately followed by 25 ml of saline flush injected at a rate of 2 ml/sec.

16. Detect the arrival of the bolus by noting the increased signal intensity in the carotid and vertebral arteries.

It is important not to define the circulation time as the first faint appearance of contrast but the time point when strong signal intensity within the arteries is first achieved.

Table A7.8.8 Primary Clinical Imaging Parameters for Sequence 6 (Test Bolus Timing)

Patient position	Head first, supine
Scan type	Test bolus timing[a]
Imaging plane (orientation)	Transverse
Pulse sequence database (PSD)	2-D fast gradient echo, real-time
Central slice or volume center	Neck
Echo time (T_E)	2.7 msec
Receiver bandwidth (RBW)	±31.25 kHz (i.e., 244 Hz/pixel)
Repeat time (T_R)	17.4 msec
Flip angle (FA)	25°
Fields of view (FOV_x, FOV_y)	400 mm, 400r mm, with $r = 1/2$ (rectangular field of view)
Resolution (Δx, Δy)	1.56 mm, 3.12 mm
Number of data points collected (N_x, N_y)	256, 128r, with $r = 1/2$ (rectangular field of view)
Display matrix (D_x, D_y)	256, 256
Slice thickness (Δz)	6 mm
Number of slices	Acquire 1 slice repeatedly until test bolus is detected
Slice gap	N/A
Number of excitations (NEX)	1
Number of acquisitions (N_{acq})	Repeat until several seconds after the test bolus is detected. Usually 60 acquisitions after the injection is sufficient.
Swap read and phase encoding	No
Read direction	Anterior-posterior
Slice location	Single transverse slice 1 cm superior to carotid bifurcation
Flow compensation	No
Saturation pulses	Yes (superior and inferior to slice)
Scan time	~1 min

[a]The gradient mode of this sequence is set at the zoom mode.

17. Continue acquiring images until the venous return is also detected, which usually occurs 5 to 7 sec later.

    At that time, the acquisition can be terminated.

18. Save all the stored images to the image database by using the start and end sliders and the "save range" command on the GE system.

19. Determine and record the circulation time for the arrival of the bolus in the carotid arteries.

    This measured circulation time will be used to initiate Sequence 7 at a proper delay after the injection of the contrast bolus.

Sequence 7: Coronal gadolinium bolus

20. Set up the coronal gadolinium bolus acquisition with the parameters listed in Table A7.8.9.

21. Using the 2DTOF MIP images obtained from Sequence 5 and 3-plane graphic prescription in transverse, sagittal, and coronal projections, ensure that the entire coronal 3-D slab is positioned in the anterior-to-posterior direction such that it covers the carotid, vertebral, and basilar arteries.

Table A7.8.9 Primary Clinical Imaging Parameters for Sequence 7 (Coronal Gadolinium Bolus of the Arteries of the Neck)

Patient position	Head first, supine
Scan type	Gadolinium bolus[a]
Imaging plane (orientation)	Coronal
Pulse sequence database (PSD)	3-D fast spoiled gradient echo
Central slice or volume center	Neck
Echo time (T_E)	1.6 msec
Receiver bandwidth (RBW)	±50 kHz (or 195 Hz/pixel)
Repeat time (T_R)	6.4 msec
Flip angle (FA)	40°
Fields of view (FOV_x, FOV_y)	240 mm, 240r mm, with $r = 5/8$ (rectangular field of view)
Resolution (Δx, Δy)	0. 47 mm, 0.94 mm
Number of data points collected (N_x, N_y)	512, 256r, with $r = 5/8$ (rectangular field of view)
Display matrix (D_x, D_y)	1024, 1024
Slice thickness (Δz)	1.2 mm
Number of slices	64 (before discarding 2 end slices at each end and before interpolation)
Slice gap	0 mm
Number of excitations (NEX)	1
Number of acquisitions (N_{acq})	1
Swap read and phase encoding	No
Read direction	Superior-inferior
Slice location	Cover carotid-vertebral-basilar system. Place superior edge of FOV 2 cm superior to petrous carotids.
Flow compensation	No
ZIP 1024	Yes, see Commentary
ZIP 2	Yes, reconstruction generates twice as many 1.2-mm slices that are overlapped by 0.6 mm
Saturation pulses	No
Control variables (CV)	Elliptical centric = 1, Turbo mode = 2
Scan time	1 min, 10 sec

[a]The gradient mode of this sequence is set at the whole body mode.

22. Position the coronal slab cranial-caudally so that it extends ∼2 cm superior to the petrous portion of the carotid arteries.
23. Communicate with the patient, and explain that during this acquisition he or she will also receive an injection. Select the "prep for scan" button on the GE scanner, which will complete the pre-scan.
24. Start the power injector sequence. Inject 18 ml of contrast agent at a rate of 3 ml/sec, immediately followed by 25 ml of saline flush injected at a rate of 2 ml/sec.
25. After the start of the power injector sequence, wait the predetermined circulation time that was measured with the test bolus (Sequence 6), then start the 3-D scan of Sequence 7.
26. The coronal gadolinium bolus acquisition results in 120 coronal images that are each 0.6 mm thick.

27. Obtain sub-volume maximum intensity projections (MIPs) with the interactive vascular imaging (IVI) post-processing program.

We obtain three sets of sub-volume MIPs: the left carotid, right carotid, and posterior circulation, including both vertebral arteries and the visualized basilar artery. In order to cover the entire volume, each set contains 19 projections spaced evenly at intervals of 10°, including lateral and anterior views.

COMMENTARY

Background Information

Adaptation and optimization of a 1.5T MR imaging protocol to 3.0T is guided by coil availability, and the scaling relationships (Hoult, 2000) for physical parameters such as SNR and susceptibility. For comparable geometry of RF coils, the SNR at 3.0T approximately doubles compared to 1.5T. Chemical shift and susceptibility variation usually have a value in parts per million (ppm), but when measured in frequency (hertz), they both double as well when the field strength is increased from 1.5T to 3.0T. The T_1 of gadolinium chelates increases only slightly going from 1.5T to 3.0T. That is, the R_1-relaxivity decreases only by about 7% (Bernstein et al., 2001). Finally, RF power, as measured by the specific absorption rate (SAR, in W/kg), quadruples at 3.0T compared to 1.5T. The regulatory limits for SAR are the same at both 1.5T and 3.0T, but those limits are reached sooner at 3.0T, assuming comparable RF pulses.

This increased SNR can be used to increase spatial resolution, to decrease acquisition time, or for a combination of the two. Smaller voxel volume is measured by increased spatial resolution. For example, the voxel volume for the gadolinium bolus protocol listed in Sequence 7 is $0.47 \times 0.94 \times 1.2\ \text{mm}^3 = 0.53\ \text{mm}^3$, which is approximately one-half the value that we typically use at 1.5T. Besides increasing the confidence when visualizing smaller structures (e.g., a tight stenosis), decreasing the voxel size at 3.0T is beneficial to reduce T_2^* signal-loss artifacts in regions of rapid susceptibility variation, e.g., in the carotid artery as it passes near the petrous bone. This is because, in imaging, T_2^* is measured per voxel, so that a smaller voxel can result in a longer value of T_2^*. Alternatively, scan time can be decreased by reducing the number of signal averages.

If the number of signal average is at its minimal value, and a compatible phased array receive coil is available, then the scan time can be decreased with the use of parallel imaging, as we recommend in Sequence 3.

The doubling of the chemical shift and susceptibility artifacts (as measured in hertz) has several protocol implications. Often, the receiver bandwidth is increased for a 3.0T protocol compared to its 1.5T counterpart. Also, at 3.0T, the echo times T_E at which fat and water have opposed phase for gradient echo imaging are roughly:

$$T_E = 1.2\ \text{msec}, 3.5\ \text{msec}, 5.8\ \text{msec}\ldots$$

assuming that water resonates at a Larmor frequency that is 3.4 ppm higher than lipids. Thus, in Sequence 3, $T_E = 3.9$ msec, which is intentionally chosen to be close to a fat/water out-of-phase echo time of 3.5 msec.

The increased susceptibility variation (again, as measured in Hz) can also increase pulsatile flow artifact (Drangova and Pelc, 1996). Pulsatile flow artifact is an issue both for the 3DTOF intracranial protocol (Sequence 3) and the 2DTOF neck protocol (Sequence 5). For the 2DTOF series (Sequence 5), we have not yet found a practical countermeasure for the increased susceptibility artifact. Peripheral or cardiac triggering, while effective in reducing the pulsatile flow artifact, prolongs the scan time, so we have not used it regularly. The increased pulsatile flow artifact on the 2DTOF has not been problematic for the diagnosis, since the coronal gadolinium bolus series (Sequence 7) contains the highest-quality anatomical information.

Increased pulsatile flow artifact at 3.0T is more problematic for the 3DTOF intracranial series (Sequence 3). The increased artifact arises not only because of the increased susceptibility changes mentioned earlier, but also because the increased SNR at 3.0T means that the ghosting artifact is less likely to be buried in the noise, and hence is more detectable. Fortunately there is an effective countermeasure to reduce the pulsatile flow artifact for 3DTOF at 3.0T. By replacing the standard sequential 3-D view order with the elliptical centric view order (Wilman et al., 1997), the pulsatile flow artifact propagates in an entire plane rather than along a line, and its intensity is reduced. An imaging comparison between a sequential

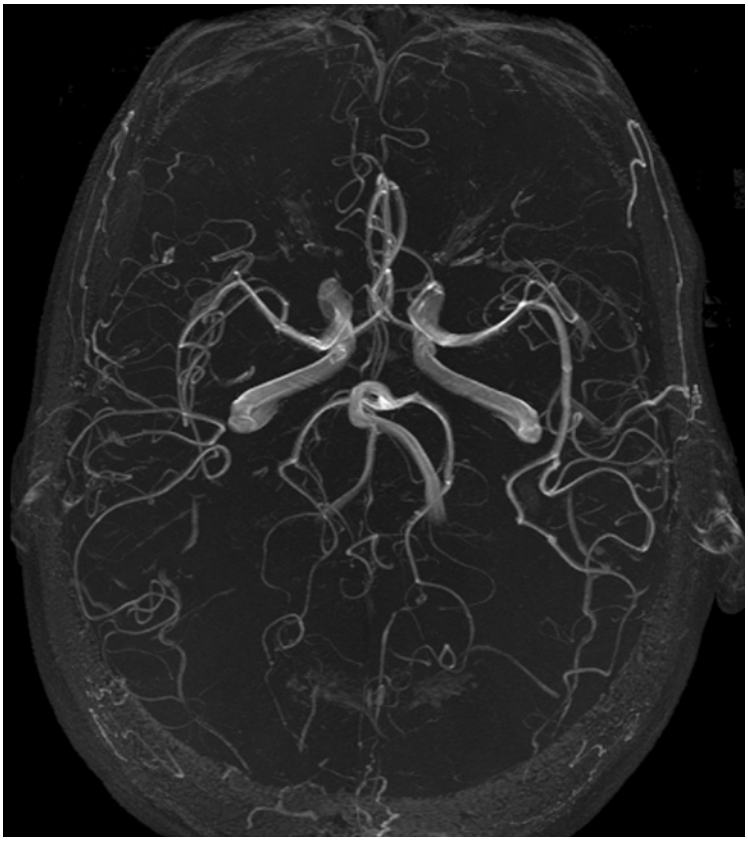

Figure A7.8.1 Transverse full-volume MIP of the intracranial circulation obtained with the 3DTOF as described in Sequence 3 (also see Table A7.8.4).

and the elliptical centric view order is given in Figure 15.21 in Bernstein et al. (2004). Currently, the elliptical centric view order is not available with our commercial 3DTOF pulse sequence, but our local group has implemented a prototype pulse sequence, and has used it successfully to reduce the pulsatile flow artifact. We also note that the use of other non-sequential view orders (e.g., a random view order) is expected to similarly reduce pulsatile flow artifact.

Just like at 1.5T, the 3DTOF exam benefits from the use of magnetization transfer (MT) contrast. The RF pulses used for MT invariably carry large values of SAR, which is especially problematic at 3.0T. In order to avoid having the 3DTOF pulse sequence exceed regulatory limits on patient heating, generally the MT pulses are only applied when the center of *k*-space is acquired (Parker et al., 1995, Lin et al., 2003). This provides nearly the full benefit of MT while applying only a fraction of the RF power to the patient. If such an implementation of MT is available on your 3.0T scanner, it can provide a useful increase in vessel-tissue contrast. We note that when limited *k*-space MT is used in conjunction with the elliptical centric view order mentioned earlier, special pulse sequence design considerations arise (Lin et al., 2004).

Critical Parameters and Troubleshooting

For the gadolinium bolus series (Sequence 7), it is critical to use the elliptical centric view order (Wilman et al., 1997) or a closely related view order such as CENTRA (Willinek et al., 2002). If the initiation of the 3-D acquisition is properly synchronized with the arrival of the contrast material in the arteries, good arterial signal and venous suppression will result. A common mistake is to start the 3-D acquisition too early, which will result in poor signal in the vessels (Maki et al., 1996). On the other hand, if the 3-D scan is initiated too late, then the venous suppression will be poor. With proper experience, very reliable results can be obtained (Riederer et al., 2000).

In our experience, both test bolus timing (Earls et al., 1997) and fluoroscopic triggering (Wilman et al., 1997; Riederer et al.,

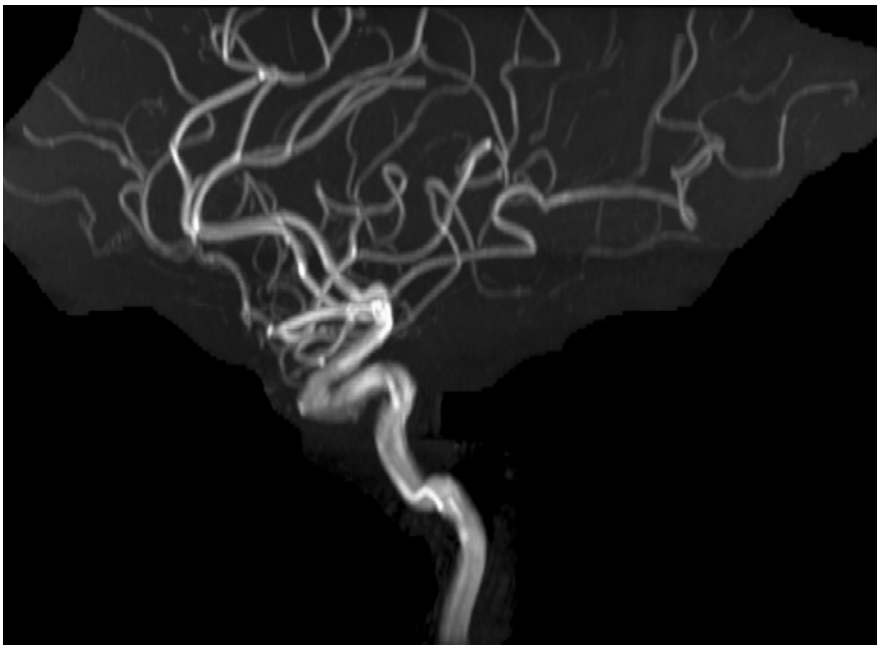

Figure A7.8.2 Lateral MIP from the same image set shown in Fig. A7.8.1 from a sub-volume covering the right side.

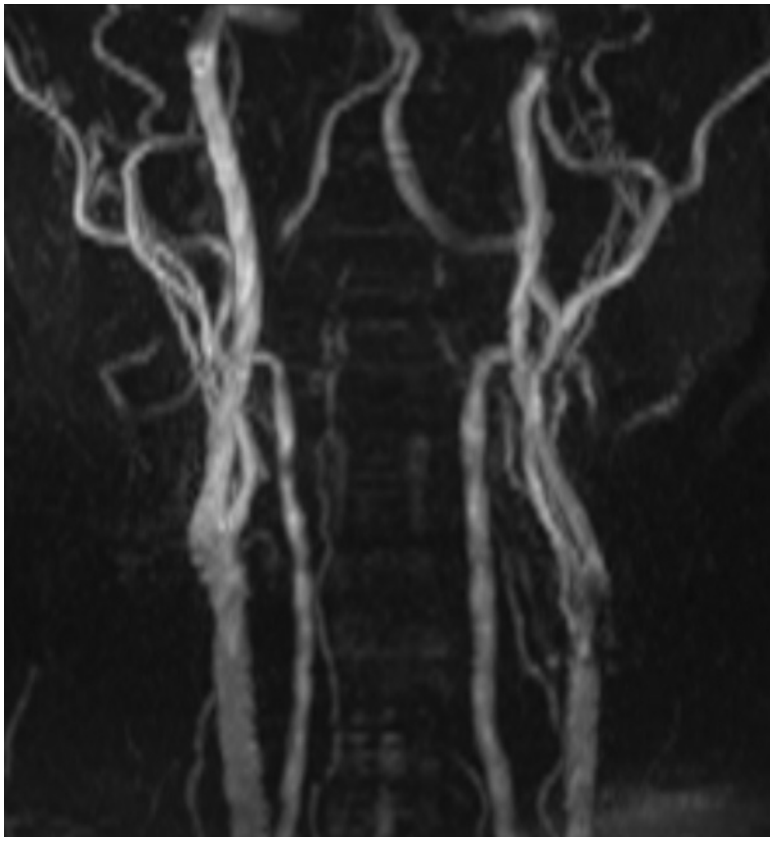

Figure A7.8.3 Coronal full-volume MIP of the cervical circulation from the 2D time of flight as described in Sequence 5 (also see Table A7.8.7).

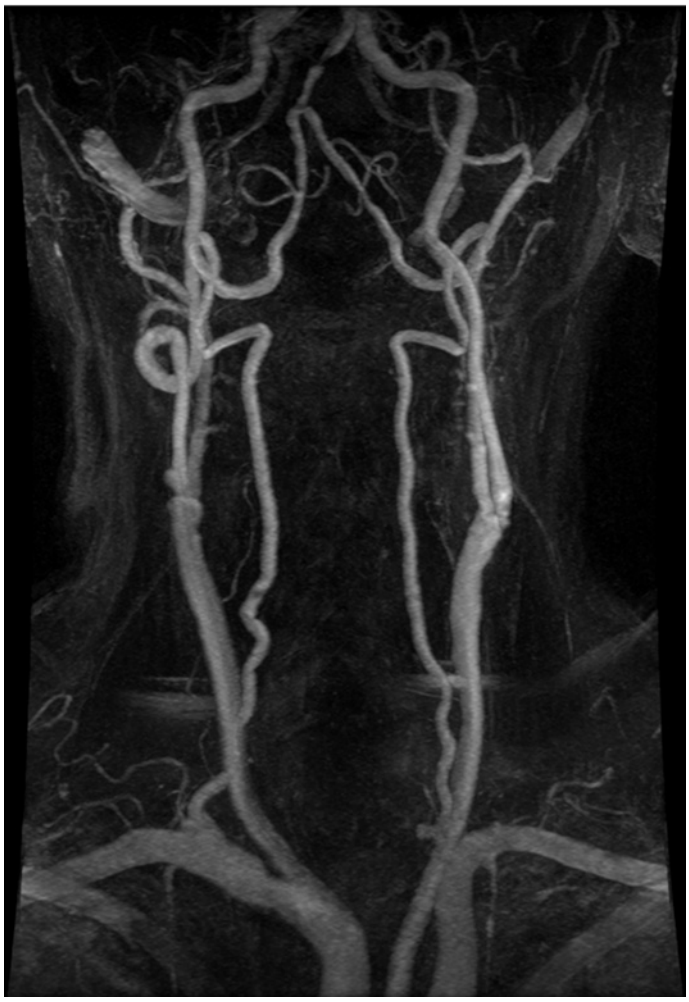

Figure A7.8.4 Coronal full-volume MIP of the cervical circulation obtained with the gadolinium bolus technique described in Sequence 7 (also see Table A7.8.9).

2000; Huston et al., 2001) work very reliably. Sequence 6 provides the details for performing test bolus timing. If fluoroscopic triggering is used instead, then Sequence 6 should be omitted. We note that with our current revision of GE software (G3, version M4), the use of fluoroscopic triggering does lead to an unacceptable increase in T_R to above 8 msec. We have worked with the manufacturer, and expect that this issue will be resolved in the next GE software release.

RF power limitations may also limit the maximal flip angle that is allowed for the gadolinium bolus series (Sequence 7). In general, as the flip angle increases, the suppression of stationary tissue such as fat becomes more effective. Currently we are using a 40° flip angle, which we have found to provide a good trade-off between RF power deposition and image quality. Note that to obtain the 6.4 msec repeat time, it may be necessary to accept the pop-up window, which allows a higher SAR limit under the International Electrotechnical Commission (IEC) guidelines. The pop-up query on our system states "Scan SAR may exceed clinical mode limits. Operator/physician confirms awareness of potential risks, and accepts responsibility." On some systems, or with heavier patients (e.g., greater than 100 kg), it also may be necessary to reduce the flip angle to keep RF power deposition within acceptable limits. Generally, the MRI system will make these calculations automatically. Keep in mind that the RF power deposited is proportional to the square of the flip angle. For example reducing the flip angle by a small amount, e.g., from 40° to 35°, reduces the RF power by a factor of $(35/40)^2 = 0.766$, or by about 23%.

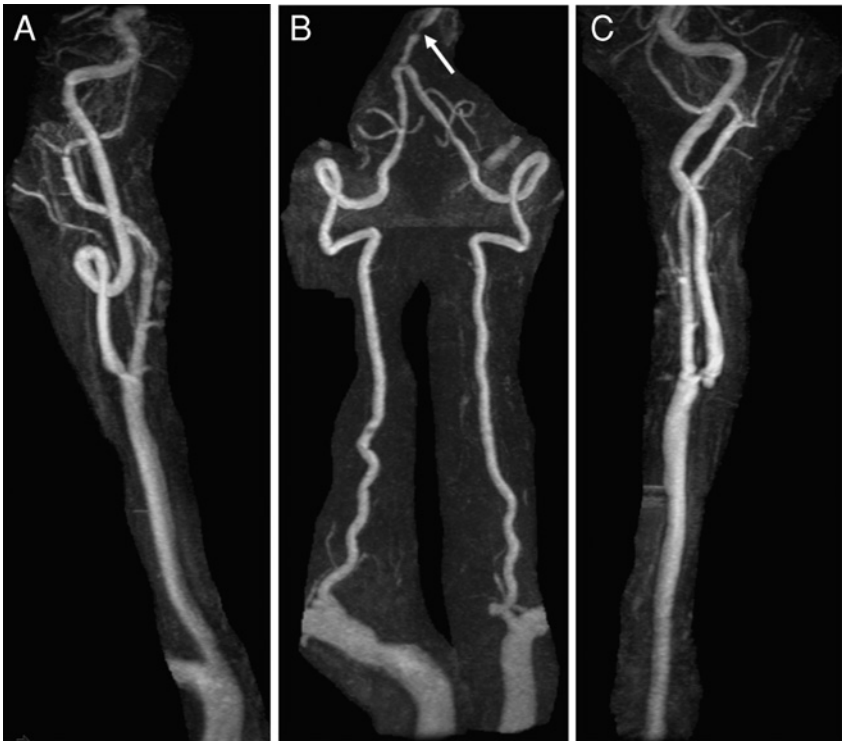

Figure A7.8.5 Sub-volume MIPs from the (**A**) right, (**B**) posterior, and (**C**) left portions of the image set shown in Fig. A7.8.3. A stenosis of the basilar artery is indicated (arrow).

Also, as listed in Table A7.8.9, Sequence 7 uses zero-filled reconstruction to obtain a 1024 × 1024 display (i.e., the "zip1024" option). This can improve the apparent spatial resolution, but does slow down reconstruction, display, and archiving. If performance in those areas is a concern, then a 512 × 512 display (i.e., the "zip512" rather than the "zip1024" option) also produces acceptable results. This change reduces the amount of image data by a factor of four.

Another important consideration is the availability of RF receive coils at 3.0T. For the intracranial exam, the 8-channel receive-only phased array head coil (MRI Devices, *http://www.mridevices.com*) performs very well in our experience. At this time, we do not have an optimal, commercially available neck coil or neurovascular coil. Consequently, we are currently using the cervical portion of an 8-channel CTL spine coil (USA Instruments, *http://www.usainstruments.com*) for this exam. As can be seen from Figs. A7.8.4 and A7.8.5, this coil tends to perform quite well near the carotid bifurcation, but then has signal drop-off nearer to the aortic arch. (We do have access to a prototype 4-channel receive-only neck array coil developed by GE Medical Systems, but since that coil is not commercially available, we did not use it for the neck protocol listed here.) We look forward to the commercially availability of a neurovascular RF coil, which will allow us to integrate the head and neck series into a single protocol.

The 3DTOF series (Sequence 3) uses parallel imaging (ASSET or SENSE). We have observed that at times SENSE can introduce artifacts. Since we are using an acceleration factor of 2, both the acquisition time and the acquired field of view are halved. Although the full field of view is restored during the ASSET reconstruction, we are vigilant for artifacts that appear at a distance of half of the field of view (i.e., 8.1 cm) in the phase-encoding direction from a bright structure, such as an ear. This signal could be artifactual, rather than some pathology such as an arterial-venous malformation. As the ASSET reconstruction continues to improve in future GE software releases, we expect that these artifacts might be reduced or eliminated.

Anticipated Results

The main anticipated result from Basic Protocol 1 is a relatively high-spatial-resolution 3-D image set of the intracranial circulation including the circle of Willis (Fig. A7.8.1). In addition to the transverse full-volume MIP,

three sets of targeted maximum intensity projections are obtained with post-processing. Sub-volume MIPs are obtained from the right, left, and posterior circulation. Generally we obtain 19 projections, i.e., a projection every 10 degrees. Figure A7.8.2 shows an example of a nearly lateral projection of the right internal carotid and associated arteries. The cranial-caudal coverage should extend from the PICA origins to the level where the anterior cerebral artery branches into the pericallosal and callosomarginal arteries.

The main anticipated result from Basic Protocol 2 is a high-spatial-resolution 3-D image set of the cervical arteries, including the two carotid, vertebral, and basilar arteries. The cranial-caudal coverage should extend from at least the vertebral origins to 2 cm superior to the petrous portion of the carotids. Figure A7.8.3 demonstrates the full-volume coronal MIP of the 2-D time of flight (sequence 5) used as a localizer for the gadolinium bolus acquisition (sequence 7). Figure A7.8.4 shows a full-volume coronal MIP, and Figure A7.85A-C show targeted MIPs of the right, posterior, and left circulation.

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