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Intracranial Contrast-Enhanced Magnetic Resonance Venography With 6.4-Fold Sensitivity Encoding at 1.5 and 3.0 Tesla

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Abstract

Purpose—To prospectively compare vessel conspicuity and diagnostic image quality between three-dimensional intracranial contrast-enhanced MR venography acquired at 1.5 Tesla (T) and 3.0T, with 6.4-fold sensitivity encoding.

Materials and Methods—Ten healthy volunteers were imaged on 1.5T and 3.0T MR scanners using eight-element head coil arrays. The intracranial venous vasculature was divided into five groups for evaluation based on vessel size and anatomical location. Two radiologists independently assessed vessel conspicuity, level of artifacts, and diagnostic image quality. Informed consent was obtained, and the study was approved by the institutional review board.

Results—With the exception of large cerebral sinuses where 1.5T and 3.0T results were rated as equivalent, 3.0T images demonstrated superior vessel continuity, sharpness, and signal contrast to background tissue than 1.5T for all other intracranial venous vasculature ($P < 0.01$). No statistical significance in overall image quality was found between 1.5T and 3.0T venograms, and all data sets were deemed sufficient for diagnostic interpretation.

Conclusion—Whole brain contrast-enhanced venography with 6.4-fold sensitivity encoding is robust and has the potential to become the method of choice for fast visualization of the intracranial venous vasculature. At 3.0T, demonstration of small cerebral vessels is superior to 1.5T.

Keywords

cerebral venography; contrast-enhanced MRA; parallel imaging; SENSE

THREE-DIMENSIONAL (3D) MR venography (MRV) is commonly used to image the dural venous sinuses and diagnose cerebral sinus thrombosis, and is usually performed using time-of-flight (TOF) and phase contrast (PC) techniques (1–4). Recently, contrast-enhanced (CE) MRV using intravenous gadolinium agents has been introduced into clinical practice (5–7), and is considered a valuable supplement, if not a superior alternative, to conventional TOF and PC methods (8–11). Imaging of the intracranial vasculature requires sub-millimeter spatial resolution to accurately depict the abundance of small cerebral vessels. The imaging volume typically encompasses the patient's entire brain, and the use of a large sampling matrix is necessary to achieve the desired spatial resolution. Acquisition of these large data sets is usually not practical with TOF or PC MRV because of prohibitively long scan times, and even for conventional 3D CE-MRV, the duration can exceed 4 min (7,12).

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The scan time of 3D CE-MRV can be significantly reduced with sensitivity encoding (SENSE; 13), and has been demonstrated at 1.5 Tesla (T; 14). SENSE can, however, suffer from a loss in signal-to-noise ratio (SNR) that is due to both the reduction in Fourier samples and the g -factors associated with the coil array used in data acquisition (13). In high spatial resolution MR angiography (MRA) at 1.5T, this SNR loss can lead to poor vascular detail in small vessels (15,16), and has limited 1D-SENSE accelerations to typically less than four in clinical applications. The purpose of this prospective study was to compare identical SENSE-accelerated 3D CE-MRV acquisitions at 1.5T and 3.0T on the basis of vessel conspicuity and diagnostic image quality. We show that a 2D-SENSE acceleration of 6.4 can be robustly achieved with an eight-element head coil. The acceleration was used to reduce acquisition time to 55 s and achieve a sampling voxel size of $0.8 \times 0.8 \times 1.0 \text{ mm}^3$. We hypothesize that, due to the higher SNR baseline at 3.0T, SENSE-accelerated CE-MRV at 3.0T will provide superior demonstration of the intracranial venous system, especially in small cerebral veins, than 1.5T.

Materials and Methods

Imaging Protocol

From May through October of 2006, 10 healthy volunteers (3 men, 7 women; age range, 33–61 years; mean age, 42 years) with no previous MR history participated in this prospective study. Informed consent and study approval were obtained from all participants and the institutional review board, respectively. Examinations were performed on 1.5T and 3.0T systems (Excite v.12, GE Healthcare, Milwaukee, WI). With the exception to their resonant frequency, two similar eight-element head coils (MRI Devices Corporation, Pewaukee, WI) were used for signal reception. Each exam consisted of 2D localizer scouts, a single slice, axial timing sequence located inferior to the skull base to monitor contrast uptake and passage, a gradient echo calibration sequence to calculate coil sensitivity profiles, and a 6.4-fold SENSE-accelerated CE-MRV acquisition with elliptical centric view order.

The CE-MRV sequence was a 3D fast spoiled gradient-echo pulse sequence with TR/TE = 6.2/2.3 ms, flip angle = 30° , bandwidth = $\pm 62.5 \text{ kHz}$, FOV = 25 cm, 320×320 sampling matrix, and 176 sagittal 1.0-mm-thick slices. The 6.4-fold acceleration was achieved using 2D SENSE with 3.2- and 2-fold acceleration along the phase (anterior, posterior) and slice (right, left) encoding axes, respectively. Imaging parameters for the calibration sequence were TR/TE = 10/3 ms, flip angle = 10° , bandwidth = $\pm 31.5 \text{ kHz}$, with a $160 \times 80 \times 44$ sampling matrix that encompassed the same imaging volume as the CE-MRV acquisition. Gadolinium contrast medium (Multihance; Bracco Diagnostics Inc., Princeton, NJ) was intravenously injected into each subject's antecubital vein by means of a power injector (Spectris; Medrad, Indianola, PA). The timing sequence used a 2 mL contrast bolus while the 3D CE-MRV acquisition used a larger 19 mL of contrast dose. Contrast medium was injected at 3 mL/s, and was followed each time by 25 mL of saline administered 2 mL/s. All examinations were performed by two of the authors with more than 8 years of combined experience in MRA research. Each volunteer was scanned at 1.5T and 3.0T on separate days to allow for complete clearing of contrast medium that was administered during the previous exam. The time between 1.5T and 3.0T exams varied between 3 and 8 weeks. There was no evidence for pathology in any of the volunteers that would have caused a difference in the appearance of the venogram between 1.5T and 3.0T studies during this interexamination interval.

Qualitative Image Evaluation

All data sets were reconstructed offline and transferred to a workstation (GE Advantage Windows, Version 4.1). Source images and maximum intensity projections (MIPs) were presented independently to two radiologists with 8 and 17 years of experience, respectively, in neurovascular MRI. Evaluation was divided into four categories (Table 1). Results from

1.5T and 3.0T were presented in a random order, and both radiologists were blinded to the magnetic field strength that generated each image set. Their raw scores were subsequently converted into those described in Table 1.

The intracranial venous system was divided into five vessel groups. For category A, radiologists determined whether specific veins could be identified at 1.5T and 3.0T, regardless of their appearance. Further assessment accounted for vessel-to-tissue signal contrast, vessel continuity, and vessel sharpness in category B. In category C, the presence of image artifacts was evaluated. When artifacts were observed, their impact on diagnostic image quality was determined. In category D, the radiologists assessed overall diagnostic value and image quality of the venograms, where a high score represents clear demonstration of all clinically relevant venous structures, allowing the radiologists to confidently assess the status (normal, hypoplastic, or pathologic) of the intracranial veins and sinuses.

SENSE *g*-Factors

Using the previously described calibration sequence, SENSE *g*-factors were computed for each in vivo data set during image reconstruction. Sensitivity profiles were calculated by dividing individual coil images by the root sum-of-squares image after Hanning apodizing windows were applied along all three axes of the raw *k*-space calibration data. In addition to the studied acceleration of 6.4, *g*-factors were also computed for acceleration rates of 4 and 5.2 for comparison.

Statistical Analysis

The Wilcoxon signed-rank test was applied to pooled scores in each of the five vessel groups in Categories A and B, as well as on the differences in scores between the two radiologists in Categories C and D. The Wilcoxon rank-sum test was applied to detect any differences in individual scoring between the two radiologists. The Student's *t*-test was used to compare *g*-factors. A *P* value of less than 0.05 was used to conclude statistical significance for all tests (17).

Results

Figure 1 summarizes scores from categories A and B. In category A, radiologist 1 believed that small deep (group 3), superficial (group 4), and extracerebral (group 5) veins were more identifiable at 3.0T than 1.5T (score 1). Radiologist 2 however, believed that vessels in all five groups were equally identifiable (score 0) between 1.5T and 3.0T. As a result, the superiority of 3.0T in vessel identification was statistically significant only for vessel group 3 ($P < 0.02$). Ratings between the two radiologists were statistically different only in vessel groups 3 ($P < 0.01$) and 4 ($P < 0.05$).

In category B, 3.0T results were rated superior to 1.5T results in vessel groups 2 through 5 ($P < 0.01$) on the basis of vessel-to-tissue signal contrast, vessel continuity, and vessel sharpness. This is evident in Figure 1b, where the mode and median scores from both radiologists are consistently positive and favor 3.0T. Ratings between the two radiologists were statistically different only in vessel group 1 ($P < 0.05$). Figures 2 and 3 show representative images from volunteer 1 and 7, where both radiologists believed that large and medium sinuses were equally demonstrated by 1.5T and 3.0T, while smaller veins (groups 3–5) were more conspicuous at 3.0T. These results prove our hypothesis.

Table 2 summarizes scores from categories C and D. No artifact ratings of 2 or 3 were assigned in category C, which corresponded to levels of artifacts that could have potentially affected diagnostic image quality. No statistically significant differences were detected in artifact levels

between 1.5T and 3.0T or between the ratings of the two radiologists. All instances where a score of 1 was given corresponded to negligible SENSE reconstruction artifacts that were easily “read through” by the radiologists.

For category D, radiologist 1 (17 years of experience) believed that the diagnostic quality of all 1.5T and 3.0T results was excellent, whereas radiologist 2 (8 years of experience) believed that 3.0T was superior in 8 of the 10 volunteers. Because the two radiologists performed image evaluations independently of one another and no training data were used to obtain a preliminary consensus in any of the four evaluation categories, this apparent interobserver disagreement in category D can likely be attributed to each radiologist's personal definition of acceptable diagnostic quality. Although the 1.5T scores from both radiologists are correlated with a Spearman's rank-correlation coefficient of 0.86 ($P < 0.01$), no statistical significance was found between the overall diagnostic quality of 1.5T and 3.0T results. Figure 4 illustrates MIPs from volunteer 3, a case where both 1.5T and 3.0T results were equally rated by both radiologists with excellent diagnostic quality.

Table 3 tabulates g -factors calculated from 1.5T and 3.0T in vivo data, showing the mean, 25th, 50th, 75th, and 90th percentiles for accelerations of 4, 5.2, and 6.4. No statistically significant differences were found between the distributions of g -factors at the two field strengths. Figure 5 illustrates g -factor maps of a representative sagittal slice at the two fields. Note the similarity between 1.5T and 3.0T results, as well as the relatively small increase in g -factors between accelerations of 4 and 6.4.

Discussion

We have shown in this prospective study that 6.4-fold 2D-SENSE accelerated CE-MRV acquisitions at 3.0T are superior in vessel demonstration, especially of small cerebral vessels, than 1.5T. The accelerated acquisition studied in this work took 55 s and achieved a sampling voxel size of $0.8 \times 0.8 \times 1.0 \text{ mm}^3$. All data from both 1.5T and 3.0T were deemed to have sufficient SNR and diagnostic value for clinical interpretation by both evaluating radiologists. However, some interobserver variation in scores was observed as a result of independent image evaluation between the two radiologists. This finding is potentially due to the difference in neurovascular experience between radiologist 1 and radiologist 2. In particular, scores in categories B and D reflect the more stringent evaluation criteria of radiologist 2.

The spatial resolution of $0.8 \times 0.8 \times 1.0 \text{ mm}^3$ obtained in this work was achieved without the use of volumetric interpolation or partial Fourier techniques. Combining these methods with parallel imaging can further reduce acquisition time (18). This finding was recently demonstrated in CE-MRV at 3.0T, where investigators used sixfold autocalibrating parallel imaging with 80% partial Fourier sampling along all three axes to achieve a sampling voxel size of $0.7 \times 0.7 \times 0.8 \text{ mm}^3$ (19). The resulting scan took 24 s and was performed with a 16-element coil array and a TR of 3 ms. The TR of 6.2 ms used in this work was the minimum that could be achieved by the MR systems at our institution for the given imaging protocol. Shorter repetition times and additional use of partial Fourier can further reduce our protocol's scan duration.

For this comparison study, the acceleration rate of 6.4 was selected because it seemed to be the limit beyond which excessive noise was introduced into the reconstructed images. No significant differences were observed in either g -factors (Table 3; Fig. 5) or artifact levels between 1.5T and 3.0T results. This finding is likely due to the fact that gains in parallel imaging performance in the human head can only be expected as the main magnetic field strength becomes greater than 5.0T, where the radiofrequency wavelength becomes significantly smaller than the size of the imaging object (20).

A limitation of this study is that the 2D-SENSE technique was not evaluated as a tool for the detection of venous thrombosis in a broader patient population. All 10 volunteers were healthy with no indications of cerebral vascular disease. At our institution, nonaccelerated 3D CE-MRV has been successfully used for clinical evaluation in more than 1000 patients. CE-MRV is considered superior to TOF and PC-based MRV by the neuroradiology practice, especially in the visualization of small deep cerebral veins, and is quickly becoming an alternative rather than a supplemental venography method. While TOF and PC MRV are performed at our institution primarily to detect venous occlusion and thrombosis of large dural venous sinuses, CE-MRV offers the additional capability to detect thrombosis in small cerebral vessels, as well as arteriovenous malformations and fistulas, venous angiomas, and cerebral infarctions. In addition, neurosurgeons at our institution use CE-MRV examinations with fiducial markers for stereotactic preoperative planning. During this study, all data reconstruction was performed offline. We are actively working to integrate the accelerated CE-MRV acquisition with online reconstruction capability into our institution's neurovascular protocols and daily workflow.

In addition to higher spatial resolution and shorter scan duration, parallel imaging accelerated CE-MRV also better exploits the rapid first-pass of the contrast bolus through the vasculature by allowing all data acquisition to be completed when the transient contrast-enhanced blood signal is the highest. Compared with nonaccelerated scans, the benefit of imaging more quickly during peak contrast-enhancement is a relative amplification in the signal contrast between blood and background tissue that directly leads to improved depiction of small vessels (21).

In conclusion, accelerated 3D CE-MRV with parallel imaging is a fast and robust technique for visualizing the intracranial venous vasculature. Furthermore, conspicuity of small cerebral vascular beds is significantly improved at 3.0T over 1.5T. The method represents a promising standard of care for MR venography.

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Figure 1.

a: Histogram of score distributions for categories A and B. Horizontal axis represents the five vessel groups outlined in Table 1. Vertical axis represents the total count of each numerical score in the five-point scale used for evaluation, where the maximum per vessel group is 10 (10 volunteers) for each radiologist. **b:** Mode, median, and mean scores are shown.

Figure 2.

Sagittal MIPs of 1.5T (a) and 3.0T (b) results from volunteer 1, a 34-year-old woman. Veins in vessel group 5 (arrows) are better depicted at 3.0T. Oblique projections at 1.5T (c) and 3.0T (d) depict a hypoplastic right transverse sinus (arrowhead) and a congenital variant dominant left transverse sinus (open arrowhead).

Figure 3.

Thin-volume (2-cm) sagittal MIPs from volunteer 1, demonstrating improved vessel continuity and sharpness at 3.0T (**b**) than 1.5T (**a**). Superior visualization and diagnostic quality of the basal vein of Rosenthal (white arrow), the internal cerebral vein (open arrow), the thalamostriate vein (white arrowhead), and the superficial middle cerebral vein (open arrowhead) are seen at 3.0T. Both images are displayed at the same window and level, thus making apparent the greater signal contrast between vessel and tissue background at 3.0T. **c,d:** MIPs from volunteer 7 show similar marked improvement with 3.0T (**d**) than 1.5T (**c**).

Figure 4. Sagittal (**a**) and coronal (**b**) MIPs of 1.5T results from volunteer 3 with corresponding 3.0T images (**c,d**), demonstrating the robustness of 6.4-fold accelerated 2D-SENSE using eight coils at both field strengths.

Figure 5.

Representative g -factor maps of a near-midbrain sagittal slice from volunteer 3. SENSE g -factors for accelerations of 4 (first column), 5.2 (second column), and 6.4 (third column), are shown from 1.5T (top row) and 3.0T (bottom row) data.

Table 1
Evaluation categories and scoring scales of 1.5T and 3.0T 3D CE-MRV for 10 volunteers.

Category A (Vessel Presence) for Five Vessel Groups*		
Score	Assessment	
-1	vessels present in 1.5T, not 3.0T	
0	vessels present in 1.5T and 3.0T	
1	vessels present in 3.0T, not 1.5T	
Category B (Vessel-to-Tissue Signal Contrast, Continuity, and Sharpness) for Five Vessel Groups*		
Score	Assessment	
-2	3.0T markedly inferior to 1.5T	
-1	3.0T moderately inferior to 1.5T	
0	3.0T equivalent to 1.5T	
1	3.0T moderately superior to 1.5T	
2	3.0T markedly superior to 1.5T	
Category C (Parallel Imaging and Motion Artifact)		
Score	Presence, Affect on Diagnosis	
0	none	
1	minor - does, or would not affect diagnosis	
2	moderate - could affect diagnosis	
3	severe - interferes with diagnosis, or non-diagnostic	
Category D (Diagnostic Image Quality)		
Score	Attribute	
0	nondiagnostic - < 50% vessels clearly visualized	
1	moderate - 50–70% of vessels clearly visualized	
2	good - 80–90% of vessels clearly visualized	
3	excellent - all vessels clearly visualized	

* Note - In category A and B, a single comparison score is assigned to each of the five vessel groups (VG) for each volunteer. In category C and D, a single score is assigned to each acquisition field strength (1.5T or 3.0T).

VG1 (Large Sinuses) - including the superior and inferior sagittal sinus, transverse sinus, and confluence of sinuses (torcular herophili).

VG2 (Medium Veins) - including the superior and inferior petrosal sinus, straight sinus, Rosenthal vein, great cerebral vein of Galen, and internal cerebral vein.

VG3 (Small Deep Veins) - including the septal vein, thalamostriate vein, and the superior and inferior vermian veins.

VG4 (Superficial Veins) - including the Labbe' vein, Trolard vein, and multiple cerebral venous beds.

VG5 (Extracerebral Veins) - including the opathalamic, paravertebral, and facial veins.

Table 2
Evaluation Scores for Category C (Parallel Imaging Artifact) and Category D (Diagnostic Image Quality)

Volunteer	Category C (artifact)				Category D (image quality)			
	Radiologist 1		Radiologist 2		Radiologist 1		Radiologist 2	
	1.5T	3.0T	1.5T	3.0T	1.5T	3.0T	1.5T	3.0T
1	0	0	1	1	3	3	2	3
2	0	0	0	0	3	3	2	3
3	0	0	0	0	3	3	3	3
4	0	0	0	1	3	3	2	3
5	0	0	0	1	3	3	2	3
6	0	0	0	0	3	3	2	3
7	1	1	1	0	3	3	2	3
8	0	0	0	1	3	3	2	3
9	1	1	1	1	3	3	2	2
10	1	1	0	0	3	3	2	3

Table 3

SENSE *g*-Factors for In Vivo Data Sets

Acceleration	1.5T			3.0T		
	4	5.2	6.4	4	5.2	6.4
mean (standard deviation)	1.38 (0.06)	1.71 (0.17)	2.32 (0.27)	1.46 (0.05)	1.96 (0.19)	2.57 (0.32)
25 th percentile	1.15	1.34	1.46	1.15	1.37	1.61
50 th percentile	1.29	1.60	2.08	1.30	1.63	2.06
75 th percentile	1.52	1.92	2.66	1.58	2.08	2.92
90 th percentile	1.88	2.59	3.73	2.04	3.04	4.31