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Time-of-Flight Intracranial MR Venography: Evaluation of the Sequential Oblique Section Technique

Jonathan S. Lewin, Thomas J. Masaryk, Alison S. Smith, Paul M. Ruggieri, and Jeffrey S. Ross

PURPOSE: To implement a time-of-flight MR angiographic technique using the oblique acquisition of thin gradient-echo sections to evaluate the intracranial venous system, and to assess the feasibility of application of this technique in a routine clinical setting. **METHODS:** The MR angiographic technique consisted of a two-dimensional gradient-echo technique with sequential overlapped sections obtained with an oblique orientation, angled from the sagittal toward the coronal plane. Parameters were evaluated during 41 measurements in 21 healthy volunteers with the section orientation varying from direct sagittal to direct coronal, followed by 64 examinations in 53 patients with an angle of obliquity of 15° to 20° from the sagittal toward the coronal plane. Confirmation of MR venographic findings was through correlation with clinical data and imaging studies. **RESULTS:** The volunteer data demonstrated optimal visibility of the smaller midline structures with an angle of obliquity of 15° or greater. Patient examinations with this angle demonstrated sinus obstruction or thrombosis (n = 11), sinus compression (n = 2), and apparent sinus stenosis (n = 1). **CONCLUSIONS:** Oblique-acquisition time-of-flight MR venography seems to provide a rapid, robust technique for intracranial venous examination and can be applied as a useful adjunct to parenchymal MR in the evaluation of suspected venoocclusive disease. This oblique technique demonstrated improved vessel contrast over direct sagittal acquisition, required significantly fewer sections and thus a shorter acquisition time than direct coronal acquisition, and was applied without difficulty in the vast majority of patients in the clinical setting.

Index terms: Angiography, technique; Magnetic resonance, technique; Magnetic resonance angiography (MRA); Veins, magnetic resonance

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Dural sinus occlusion typically presents with symptoms of headache, seizure, nausea, and vomiting, or with focal neurologic deficits, and is most often observed in patients with histories of middle ear or mastoid infections, hypercoagulability, malignancy, or trauma (1, 2). Diagnosis of this condition traditionally has been through conventional intraarterial contrast angiography, intravenous contrast digital subtraction angiography, or with computed tomographic scanning by the direct identification of thrombosed veins or the "empty delta," "sinus rectus," or "falx" signs (3–5). Magnetic resonance (MR) imaging has provided improved noninvasive diagnosis of this entity by showing veins in the middle and posterior fossae. However, subacute thrombus occasionally may be confused with normal high signal from entry section phenomenon on routine T1-weighted images at higher field strengths, or deoxyhemoglobin of acute thrombus may mimic flow void on T2-weighted images (6–10). Early investigations using both time-of-flight and phase-contrast MR angiographic techniques to evaluate the dural sinuses and intracranial veins have been promising (11–15). The purpose of this study was to implement a new time-of-flight MR angiographic technique using the oblique acquisition of thin gradient-echo sections and to

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assess the feasibility of application of this technique in a routine clinical setting.

Subjects and Methods

Subjects

The MR angiographic technique was performed in 21 healthy volunteers ranging from 19 to 29 years of age, followed by 53 patients 3 weeks to 73 years of age, with informed consent obtained from each after the nature of the examination was fully explained.

Presenting diagnoses in the patient population included 16 patients with suspected pseudotumor cerebri, 15 patients with hypercoagulability and headache, with or without imaging evidence of venous infarctions, 7 patients with meningioma (5 preoperatively, 1 postoperatively, and 1 imaged both preoperatively and postoperatively), 3 patients with skull base or intracranial infection, 3 patients with neonatal intracranial hemorrhage, 2 patients with skull metastasis, 1 patient each with skull plasmacytoma, an intracranial mass of uncertain cause, sphenoid sinus mucocele, sickle cell disease, and dehydration and lethargy, 1 patient after aneurysm clipping, and 1 patient after skull lesion resection.

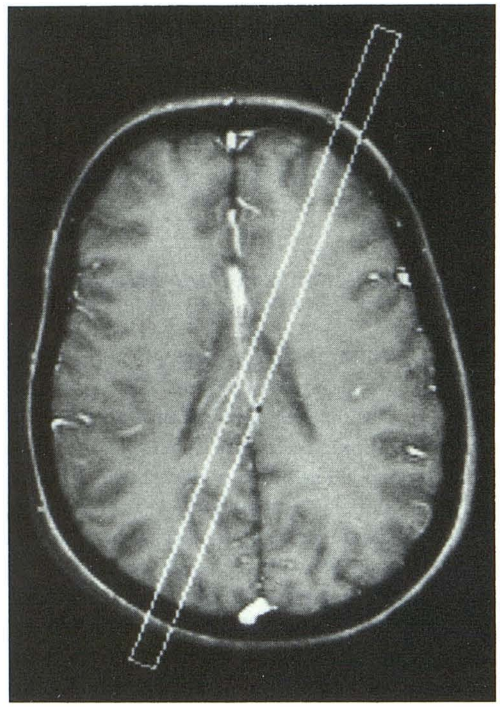


Fig 1. Scout view demonstrating an angle of obliquity of 25° from the sagittal toward the coronal plane. For illustrative purposes, the section depicted is thicker than that actually used.

MR Imaging Technique

All studies were performed on a clinical 1.5-T whole-body imaging system with a 10-mT/m gradient capability and a transmit-and-receive circularly polarized head coil. The pulse sequence used was a fast low-angle shot two-dimensional Fourier transform gradient-echo sequence with first-order flow-compensation gradients in the read-out and section-select directions. Parameters included 25-32/10/1 (repetition time [TR]/echo time [TE]/excitations), 30° to 60° flip angle, 256 × 256 or 192 × 256 matrix with a 21-cm field of view, and 3-mm section thickness with a 1- to 1.5-mm overlap. The total examination time ranged from 5 to 9 minutes. Sequential sections were obtained to cover the region of interest, with an oblique section orientation angled from the sagittal toward the coronal plane (Fig 1) (Lewin JS, Laub G. Evaluation of the intracranial venous system with the thin-slice oblique acquisition sequential technique. Presented at the Eighth Annual Meeting of the Society for Magnetic Resonance Imaging; February 1990; Washington, DC). The frequency sampling was asymmetric with 64 points collected before the echo. An axially oriented spatial presaturation pulse was placed inferior to the imaging volume to suppress signal from inflowing arterial spins. Postprocessing was performed with a maximum-intensity projection ray-tracing algorithm (16) (Rossnick S, Kennedy D, Laub G, et al, Three-dimensional Display of Blood Vessels in MRI, Proceedings of the Institute of Electrical and Electronic Engineers Computers in Cardiology Congress, Piscataway, NJ, 1986:193–196) to provide an angiographic projectional display from any desired viewing angle.

Imaging parameters were evaluated during 41 measurements in the 21 healthy volunteers with the section orientation varying from direct sagittal to direct coronal. Sixty-four examinations were performed in the 53 patients with angles of obliquity of 15° to 20° from the sagittal toward the coronal plane. Routine spin-echo short-TR/TE images in the coronal and sagittal planes and long-TR/long- and short-TE axial images were also acquired, with phase reconstruction of the resultant data for at least one of these sequences in 31 patients (17).

The patient data were evaluated through examination of the postprocessed images of multiple projectional views of each measurement, with qualitative assessment of vascular signal intensity and continuity of the superior and inferior sagittal sinuses, straight sinus, vein of Galen, internal cerebral veins, thalamostriate veins, and basal veins of Rosenthal. In addition, the site and size of areas of artifactual flow void were recorded. When findings on the maximum-intensity projection reconstructed images were equivocal, the individual 2-D Fourier transform fast low-angle shot images were evaluated for the presence or absence of inflow enhancement in the dural sinus or vein with suspected abnormality. Conventional spin-echo short-TR/TE and long-TR/long- and short-TE images of the brain from the spin-echo data were also evaluated in each patient examination. Phase-reconstructed images were examined in the 31 patients in whom they were available. Conventional contrast angiography was not performed in this patient population, with confirmation of MR venographic findings limited to correlation with clinical

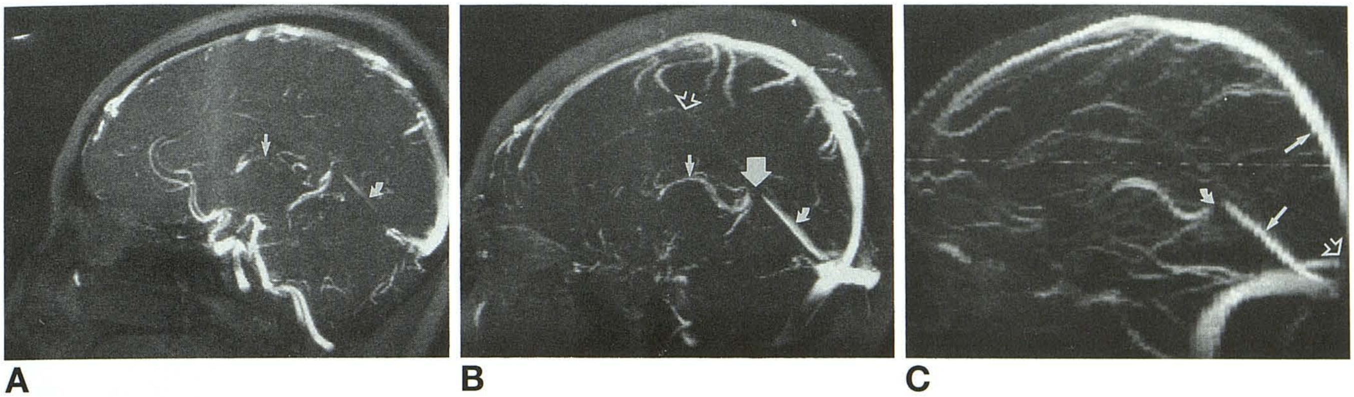


Fig 2. *A,* Lateral maximum-intensity projection of an MR venogram from a data set acquired with a direct sagittal imaging plane (a 0° angle of obliquity), a 60° radio frequency pulse flip angle, and parameters of 32/10. Note that the internal cerebral veins (*straight arrow*) and straight sinus (*curved arrow*) are poorly seen, and the superior sagittal sinus demonstrates loss of signal with increasing distance from inflowing cortical veins because of the effects of spin saturation.

B, Lateral maximum-intensity projection of an MR venogram obtained with a 20° angle of obliquity and other parameters unchanged. Note improvement in visibility of midline structures such as the internal cerebral veins (*straight arrow*) and straight sinus (*curved arrow*), as well as increased homogeneity of the superior sagittal sinus. Slowly flowing structures such as the inferior sagittal sinus (*open arrow*) also can be noted with the increased inflow resulting from the 20° angle of obliquity. A prominent residual flow void is noted at the junction of the vein of Galen and straight sinus (*large arrow*).

C, Lateral maximum-intensity projection of an MR venogram obtained with a direct coronal plane of acquisition (a 90° angle of obliquity) and other parameters unchanged. Homogeneity of the superior sagittal sinus is excellent, as is visibility of the internal cerebral veins and straight sinus. The examination required 110 sequential 3-mm sections with a 1-mm overlap, with limitation in spatial resolution evident as steplike artifacts in the obliquely flowing structures such as the posterior segment of the superior sagittal sinus and the straight sinus (*straight arrows*). Persistent flow void is noted at the level of the junction of the vein of Galen and straight sinus (*curved arrow*) and is also noted at the level of the torcular herophili, where flow is in plane with the direct coronal plane of acquisition (*open arrow*).

data, spin-echo images, and phase reconstructions when available.

Results

Volunteer Examinations

The larger and presumably faster-flowing vessels were adequately seen with an angle of obliquity of 10° or greater. An angle of 15° to 20° represented the minimum angle for consistent visualization of the smaller midline veins and sinuses and was used for the subsequent patient examinations (Fig 2).

Patient Examinations

Patient examinations demonstrated 11 studies in 9 patients with sinus obstruction or thrombosis (Figs 3 and 4), 2 patients with sinus compression (Fig 5), 1 patient with apparent sinus stenosis, 48 patients with normal examination results, and 2 patients whose studies were uninterpretable because of motion artifact. The sizes and locations of residual areas of signal void in the 48 normal examinations are presented in the Table. Spin-echo images in the patients with sinus obstructions demonstrated signal within the involved segments of the sinuses on T1-weighted images that was hyperintense to brain parenchyma in 4 cases and isointense in the remainder. Luminal signal intensity was variable on T2-weighted images.

Discussion

The evaluation of cerebral venous occlusive disease has greatly benefited from MR imaging

Persistent flow voids in patients with normal findings on oblique-acquisition time-of-flight MR venography

	Vein of Galen–Straight Sinus Junction	Transverse–Sigmoid Junction	Torcular Herophili	Posterior Superior Sagittal Sinus
0–1 mm	14	9	21	34
2–5 mm	24	7	9	6
6–10 mm	8	5	9	2
>10 mm	2	21	9	6
Not Applicable[a]		6		
Total Patient Examinations	48	48	48	48

[a] Transverse–sigmoid sinus junction was not included because of the restricted number of imaging sections.

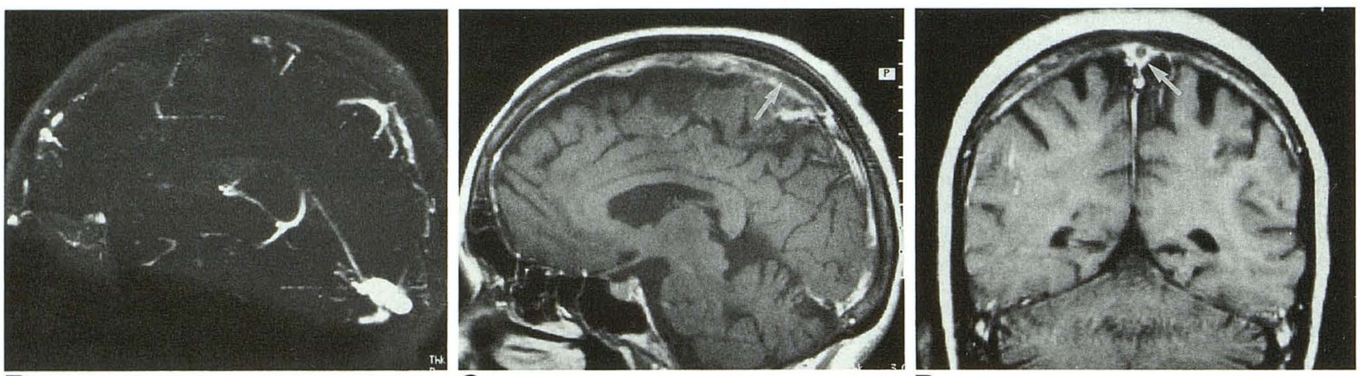
Fig 3. Sixty-year-old patient with paroxysmal nocturnal hemoglobinuria and acute onset of headache and confusion.

A, T2-weighted (2000/90) spin-echo image demonstrates focal areas of hyperintensity within the parasagittal frontal lobes bilaterally, consistent with venous infarction (*straight arrows*). Low signal intensity simulating flow void is present within the superior sagittal sinus, which represents paramagnetic deoxyhemoglobin within the thrombus (*curved arrow*).

B, Lateral maximum-intensity projection from an MR venogram obtained with an angle of obliquity of 20° demonstrates normal flow within subependymal veins and the straight sinus but lack of flow throughout almost the entire superior sagittal sinus. Residual signal is noted within cortical veins.

C and *D*, T1-weighted sagittal and coronal (520/15) spin-echo examinations after intravenous administration of gadopentatate dimeglumine demonstrate gadolinium outlining thrombus that is isointense to the adjacent brain parenchyma (*arrows*).

A

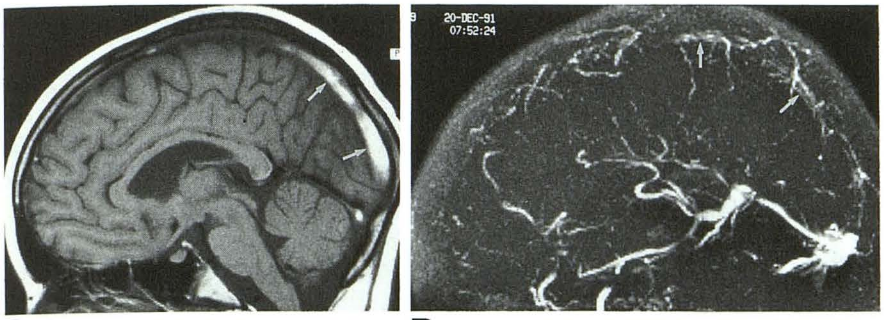


B C D

techniques. However, spin-echo MR imaging may be misleading, with a false impression of intravascular clot resulting from flow-related enhancement or even-echo rephasing, or with the false impression of vessel patency resulting from deoxyhemoglobin or intracellular methemoglobin mimicking flow void on T2-weighted images. Spin-echo imaging in multiple imaging planes often can circumvent these pitfalls when carefully applied (7, 8). However, the use of time-of-flight MR venography can serve as a helpful adjunct, because the diagnosis of intracranial venous occlusion with MR venography is usually straightforward.

The slow-flow sensitivity of the 2-D time-of-flight MR angiography technique and its application in the evaluation of the intracranial venous system was initially described by Edelman et al (18). A more critical look at this technique was subsequently reported by Mattle et al (14), using a combination of direct coronal, direct sagittal, and direct axial imaging planes. These authors describe good correlation of MR venographic results in all 14 patients in whom contrast angiograms were obtained.

The rationale for an oblique plane of acquisition for evaluation of the intracranial venous system as used in this study is relatively simple. The degree of flow-related enhancement depends on several variables, including TR, flip angle, section thickness, and velocity of inflowing blood (19). In addition, flow-related enhancement is maximized when the vessel of interest is perpendicular to the imaging section (19) (Fig 6A). Inflow enhancement is poorest when the plane is parallel to the vessel of interest, resulting in saturation of the inplane flowing blood. As the plane of acquisition is rotated from parallel to perpendicular relative to the vessel of interest, the magnitude of unsaturated inflow is increased, proportional to the sine of the angle of obliquity (Fig 6B). This theoretical situation can be observed in the images of the volunteers (Fig 2). With a sagittal plane of ac-

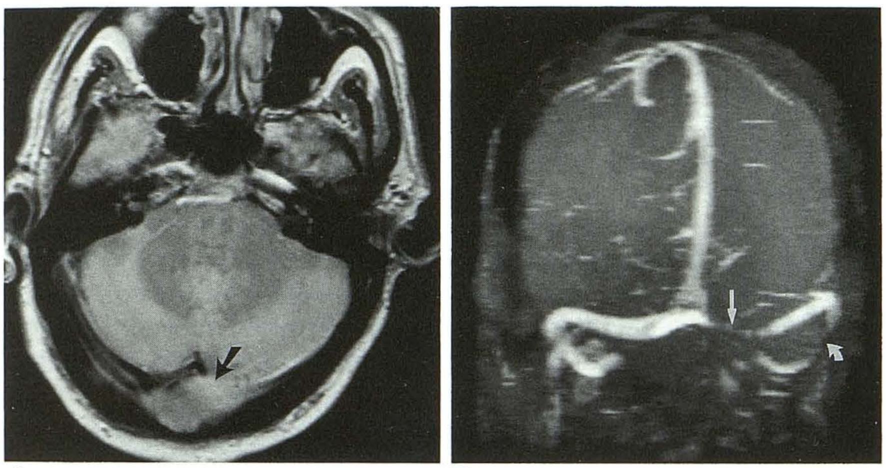


A B

Fig 4. Ten-year-old patient with acute lymphocytic leukemia on asparaginase therapy, with mental status changes and headache.

A, T1-weighted (520/15) spin-echo sagittal images demonstrate hyperintense thrombus within the superior sagittal sinus (*arrows*).

B, Lateral maximum-intensity projection of an MR venogram obtained with an angle of obliquity of 20° demonstrates marked reduction of signal within the superior sagittal sinus throughout almost its entire course, relative to high signal within the subependymal veins, the straight sinus, and torcular herophili. Faint signal within the sinus likely represents methemoglobin within the thrombus detected by the maximum-intensity projection algorithm (*straight arrows*). The intensity of this signal is easily distinguished from normal flow within the sinus.



A B

Fig 5. Sixty-three-year-old patient with metastatic squamous cell carcinoma of the lung to the occipital bone.

A, Intermediate-weighted (2500/22) spin-echo image demonstrates a metastatic lesion within the occipital bone (*arrow*).

B, Anteroposterior maximum-intensity projection of an MR venogram obtained with an angle of obliquity of 15° demonstrates focal compression of the medial aspect of the left transverse sinus (*arrow*). Although the transverse sinuses are well seen with the oblique MR venographic technique, the flow void commonly seen within the sigmoid sinus is well demonstrated in this examination (*curved arrow*).

quisition, parallel to the primary direction of blood flow, inflow enhancement is significantly limited. As opposed to the theoretical case, the midline, sagittally oriented venous structures are visible because unsaturated blood flows into the venous structures from veins off the midline, such as cortical and thalamostriate veins and the basal veins of Rosenthal. The improvement in inflow with relatively small degrees of obliquity is readily apparent within the smaller midline veins (Fig 2B). Although the difference is less visible within the normal, larger, more rapidly flowing veins, such as the superior sagittal sinus, slow-flow sensitivity may become more important in pathologically slowed flow states, as might be seen in cases of sinus compression or partial recanalization. The use of direct coronal imaging (Fig 2C) provides the greatest inflow of unsaturated spins for the midline veins but requires a much larger number of sections to evaluate the entire sagittal sinus and subependymal veins, resulting in a greatly increased examination time. In addition, signal loss may be seen in the posterior aspect of the superior sagittal sinus with direct coronal imaging because of spin saturation in this region (Fig 2C).

Several MR angiographic methods other than sequential 2-D time-of-flight techniques have been described for the evaluation of the intracranial venous system. Both 3-D and 2-D phase-contrast angiographic techniques have been reported in the evaluation of dural sinus occlusion (12, 20, 21). These techniques are unaffected by intracranial methemoglobin or other sources of high signal intensity on T1-weighted images that can lead to artifact on time-of-flight MR angiograms, which may be advantageous in some instances.

Three-dimensional time-of-flight techniques also have been evaluated; however, spin saturation limits evaluation of slowly flowing blood within thicker volumes (11, 22). Slow-flow sensitivity of the 3-D techniques may be improved

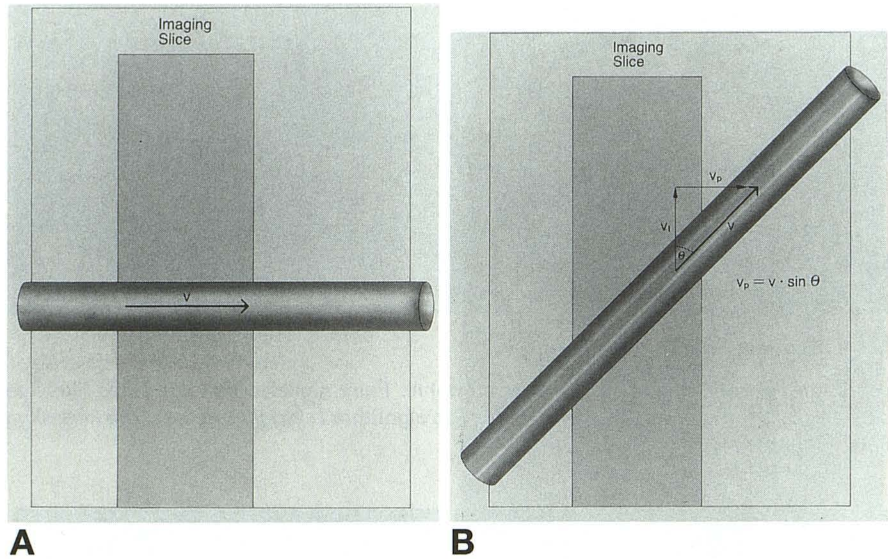


Fig 6. *A,* Diagrammatic representation of perpendicular inflow, as would be seen with a coronal imaging plane for the midline venous structures. The degree of inflow is directly proportional to the mean blood velocity (*V*).

B, With an oblique imaging plane, as used in this investigation, the degree of inflow is directly proportional to the component of blood velocity perpendicular to the imaging section (V_p). There is no contribution to inflow from the inplane component of velocity (V_i). The velocity component contributing to inflow thus is related to the overall mean velocity (*V*) by a factor of the sine of the angle between the imaging section and vessel of interest (Θ).

through the application of multiple overlapping thin volumes or through gadopentatate dimeglumine administration. However, evaluation of intracranial veins and sinuses remains inferior to that with sequential 2-D time-of-flight techniques with the multiple thin-volume method (22). Gadopentatate dimeglumine–enhanced 3-D time-of-flight MR angiography may yield false-negative results in patients with enhancing intracranial lesions, such as neoplasms adjacent to dural sinuses or veins, or enhancing inflamed dura adjacent to thrombosed sinuses.

The use of MR phase-image reconstruction of conventional spin-echo data, described for intracranial vascular abnormalities by Nadel and colleagues (17), provides a simple method that can be applied without cost in imaging time and may answer the clinical question. In our investigation, this technique was used as an adjunct to MR venography in 31 cases (Fig 7).

Several potential pitfalls exist with the oblique 2-D time-of-flight technique. The presence of methemoglobin within a thrombus can lead to increased intravascular signal mimicking flow on gradient-echo MR images and may yield false-negative results (23). To avoid this potential pitfall, T1-weighted spin-echo images were obtained along with all MR angiograms. Although areas of hyperintense intravascular thrombus were detected on T1-weighted spin-echo sequences in four examinations in this investigation, the signal intensity was only sufficiently high to project into the maximum-intensity projection angiogram in two cases, in which thrombus was easily differentiated from flow (Fig 4). Hyperintense signal from methemoglobin within a subdural hematoma was also evident on a postprocessed MR venogram in one study. A more significant limitation results from persistent areas of flow void, most notable in regions of vessel confluence such as the vein of Galen and torcular herophili, as well as at the junction of the sigmoid sinus and transverse

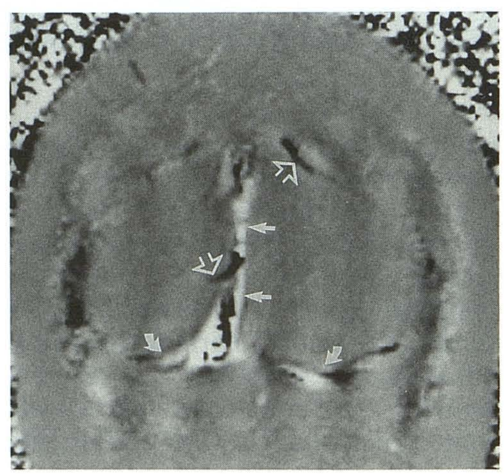


Fig 7. Phase reconstruction of spin-echo data: normal examination. The data from a routine T1-weighted spin-echo coronal image were reconstructed with pixel intensity based on the phase of the signal rather than magnitude (17). Flow within the posterior aspect of the superior sagittal sinus (*straight arrows*), a frequent site of artifact in the MR venographic technique, along with the transverse sinuses (*curved arrows*) and several cortical veins (*open arrows*), results in bright and dark pixel intensity from flow-related phase change compared with the intermediate gray of adjacent stationary tissue. These reconstructions are automatically calculated online with no additional imaging time. Unlike phase-contrast MR angiographic techniques, the pixel intensity from flow does not reflect flow direction or velocity.

sinus (Table and Fig 2). The presence of persistent signal void at these sites despite first-order flow compensation techniques likely arises from nonuniform flow resulting in persistent phase dispersion combined with persistent inplane flow from orientation of portions of the venous system within the oblique imaging plane. This disadvantage may be reduced in part through use of shorter TEs (24). Although these areas occur in characteristic locations and are not likely to be misinterpreted for thrombus, reliable detection of true abnormalities in these areas is significantly limited with the TE used in this investigation. In this study, thrombus was excluded in these areas of artifactual signal void through careful examination of the individual 2-D Fourier transform sections of the MR angiogram along with the spin-echo images through the area of suspected artifact. In addition, phase-reconstruction images of the spin-echo data were examined for the presence of flow when available and were helpful to confirm artifact (Fig 7). When abnormality in a vessel parallel to the oblique imaging plane is suspected before imaging, such as within the sigmoid sinus, an alternate imaging plane perpendicular to the segment of interest likely would yield superior flow-related enhancement and should be used.

The direction in which the imaging section is angled from the sagittal toward the coronal plane was varied in the volunteers but kept constant (toward the left as in Fig 1) in the patient population. The side to which the section was angled had no effect on visibility of the midline sinuses or veins but affected on which side the transverse and sigmoid sinus junction was inplane and thus more prone to artifact. Therefore, with the imaging plane angled toward the left in the patient examinations, the left transverse and sigmoid sinus junction was the most common site of the larger artifactual signal voids.

An additional potential limitation may arise in evaluation of the postprocessed projections of the data, in which clots too small to fill the vascular lumen completely may not be appreciated. This pitfall can be avoided through careful evaluation of the individual 2-D Fourier transform sections of the data set or through multiplanar reconstruction of the data, rather than relying entirely on the postprocessed projection images. Finally, limitations of spatial resolution, compared with plain-film or digital-subtraction contrast x-ray angiography, may not allow appreciation of slight irregularity of a venous sinus as may be seen after recanalization. This possibility awaits further clinical experience.

In summary, oblique acquisition 2-D Fourier transform time-of-flight MR venography seems to provide a rapid, robust technique for intracranial venous examination and can be applied as a useful adjunct to parenchymal MR in the evaluation of suspected venoocclusive disease. This oblique technique demonstrated improved vessel contrast over direct sagittal acquisition, required significantly fewer sections and thus a shorter acquisition time than direct coronal acquisition, and was applied without difficulty in the vast majority of patients in the clinical setting.

In our institution, this technique is routinely applied clinically and seems useful in the evaluation of patients with suspected venous sinus thrombosis, pseudotumor cerebri, and intracranial infection, as well as for preoperative and postoperative evaluation of tumor adjacent to or within a dural sinus. These preliminary data are promising, but this investigation did not attempt to evaluate the sensitivity or specificity of the oblique 2-D Fourier transform time-of-flight technique, and further investigation with correlation to a standard of reference such as contrast x-ray angiography is necessary.

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