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## Dural Sinus Occlusion: Evaluation with Phase-Sensitive Gradient-Echo MR Imaging

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The purpose of this study was to evaluate the usefulness of limited-flip-angle, phase-sensitive velocity imaging with gradient-recalled-echo (VIGRE) MR when combined with spin-echo MR in the diagnosis of dural sinus thrombosis. The VIGRE sequence consists of a rapid single-slice acquisition, 50/15/2 (TR/TE/excitations), and 30° flip angle. At each slice position, a total of four images were reconstructed; these consisted of one magnitude image and three images sensitive to proton motion in each orthogonal direction. The flow direction and flow velocity (cm/sec) were obtained from each of the phase images, and results were correlated with data obtained from a phantom experiment. In normal controls, dural sinus velocities ranged from a mean of 9.9 to 14.4 cm/sec for the transverse and superior sagittal sinuses, respectively. Three patients with proved dural sinus occlusion were studied with spin-echo images at 1.5 T. Three-dimensional time-of-flight MR angiography was also performed in one patient. The presence of dural sinus occlusion was determined by the lack of flow void on the spin-echo images, the absence of phase shift on the VIGRE study, and the presence of retrograde flow on the phase image in the sinus proximal to the occluded segment. Time-of-flight angiography overestimated the extent of the thrombosis caused by spin saturation. Follow-up VIGRE studies detected the formation of collateral flow in one patient and recanalization with the establishment of normal antegrade sinus flow in the other.

We conclude that phase-sensitive MR imaging is helpful in establishing the diagnosis and extent of dural sinus occlusion. Because of the short acquisition time, selected images can be obtained whenever the flow within the dural sinus is in question on a routine spin-echo study. Retrograde sinus flow appears to be a sensitive indicator of distal sinus occlusion or high-grade obstruction.

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Dural venous sinus thrombosis has been associated with several pathologic conditions [1]. Its clinical diagnosis may be difficult because of the wide variety of nonspecific findings [2]. Early recognition of this condition may be necessary in order to institute prompt therapy [3]. In the past, cerebral angiography or venography was required to establish this diagnosis. Less invasive techniques such as CT may indicate the presence of dural sinus occlusion with the findings of the cord and delta signs, congested deep subcortical veins, or increased tentorial or gyral enhancement [4, 5]. These CT signs may be subtle and easily overlooked. In one clinical series on septic lateral sinus thrombosis, the majority of CT examinations were completely normal [6].

MR imaging has become the method of choice in the noninvasive diagnosis of dural sinus thrombosis and may be positive when the CT findings are nondiagnostic [5]. Sinus thrombosis may be suggested on the basis of spin-echo (SE) or gradient-echo MR imaging alone [4, 5, 7-9]; however, unequivocal distinction between venous stasis and physiologic slow flow may be difficult [10]. The interpretation of high-intensity signal as flow-related enhancement, and thus as sinus patency, may be incorrect in the presence of methemoglobin within thrombus, or with gadopentetate dimeglumine enhancement.

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Because of these potential pitfalls, the use of phase-shift imaging with SE techniques [10–15], which yields direct measurements of blood velocity as well as flow direction, may contribute additional MR specificity. More recently, preliminary experience with rapid phase-sensitive, limited-flip-angle gradient-recalled-echo pulse sequences has been described as a method for evaluating portal hypertension, discriminating arterial from venous flow as well as clot from slow flow, and quantifying blood flow within the carotid arteries [16, 17]. Our experience with the use of this method in proved cases of dural sinus occlusion is described.

### Materials, Subjects, and Methods

A velocity-sensitive technique based on phase contrast and gradient-recalled echoes, VIGRE (velocity imaging with gradient-recalled echoes, General Electric Medical Systems), was initially tested with a flow phantom. The theory behind phase-shift velocity imaging and methods of image reconstruction using this technique are described in greater detail elsewhere [17]. Briefly, in the most basic mode, VIGRE requires two separate gradient schemes resulting in two views that are acquired for each phase-encoding increment. The first view is a flow-compensated sequence that results in zero phase shift for both stationary spins and spins moving with constant velocity during TE. This first view is the equivalent of a conventional GRASS study, and the data can be used to reconstruct a magnitude image (Fig. 1A). The second view is a flow-encoded sequence that uses a slightly altered gradient waveform such that the constant-velocity spins accumulate a phase shift related to that component of the flow vector that lies along the flow-encoding gradient axis. Again, the stationary spins do not accumulate any phase shifts. The TR and TE are kept constant for both views. From the data acquired with both views, a single-phase image is constructed such that the degree of phase shift is directly related to the flow velocity at each voxel (Fig. 1B). The flow sensitivity for this single-phase image is limited to the vector component parallel to the flow-encoded gradient, which can be selected to lie along any one of the three orthogonal directions. Stationary voxels in the phase image correspond to the special case of zero velocity and appear as intermediate (gray) intensity, representing 1024-magnitude units. Spatial resolution of the phase-reconstructed image is similar to that of a standard MR image.

In our clinical examples, the basic VIGRE acquisition described above is modified such that the flow-compensated and flow-encoded view is repeated three times in an interleaved fashion during each phase-encoding increment as a single data set. The purpose for this more complex set is to acquire flow information along all three orthogonal directions corresponding to the frequency, phase, and slice-select axes. As a result, the imaging time is increased by a factor of three. The rationale for obtaining separate velocity measurements in all three axes during a single imaging session is to ensure that velocities in vessels that are obliquely oriented to the plane of section can be analyzed. The sequences are interleaved to minimize motion between flow encodings. The resulting data are then combined to produce four separate images: a conventional-magnitude or GRASS image, a flow image in which pixel intensity is related to the flow velocity along the frequency-encoding direction, a flow image in which pixel intensity is related to the flow velocity in the phase-encoded direction, and a flow image in which pixel intensity is related to flow velocity along the slice-select direction. The imaging parameters include 35/15/2 (TR/TE/excitations), 30° flip angle, 4-mm slice thickness, 24-cm field of view (FOV), and 192 × 256 matrix. Two excitations are performed in order to improve the signal-to-noise ratio. Because of the short TR, data acquisition for a complete single slice study is 55 sec. Multiple single-slice images can also be prescribed depending on the area of coverage required.

Phase-sensitive techniques are sensitive to aliasing artifact if the actual velocity within the vessel is greater than the expected velocity range. This artifact results in a misrepresentation of flow such that the flow direction and actual velocity are displayed incorrectly. To avoid this problem, one can specify a peak velocity that controls the flow-encoding gradient lobes. In the flow-encoded experiment, the gradient lobes are designed so that a spin moving at the specified peak velocity accumulates a phase shift of  $+\pi$ . A spin moving in the opposite direction at the specified peak velocity would accumulate a phase shift of  $-\pi$ . This peak velocity specifies the maximum velocity that can be resolved without aliasing. On the basis of preliminary work (Mattle H, et al. Presented at the annual meeting of the Radiological Society of North America, November 1989), the peak velocity for our patients was set at 50 cm/sec for the analysis of dural sinus velocity. Because the sign of the phase shift is recorded, flow directionality is displayed by either relative hypointensity or hyperintensity with respect to the background stationary spins set at 1024-intensity units, which is midscale on the phase-reconstructed image. The magnitude of the difference between the intensity of the moving

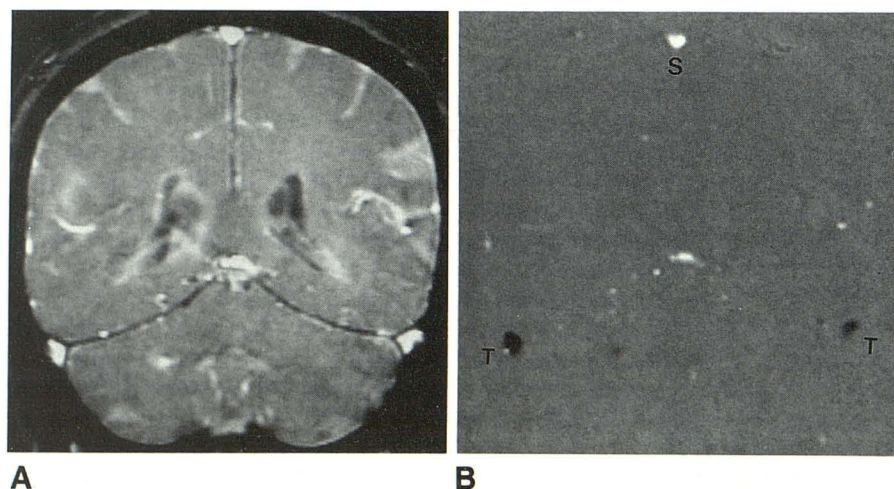


Fig. 1.—Example of VIGRE images of a normal volunteer with acquisition parameters as described in the text.

A, Conventional-magnitude or GRASS image through posterior aspect of cranium in coronal plane. Hyperintensity within superior sagittal and transverse sinuses is due in part to flow-related enhancement.

B, Phase-reconstructed image with flow-sensitive axis oriented in slice-select (anteroposterior) direction. Blood moving anteriorly is depicted as a region of hypointensity, such as in transverse sinuses (T), whereas blood moving posteriorly, such as in superior sagittal sinus (S), is hyperintense relative to background stationary spins, which are of intermediate intensity.



and stationary spins will allow a direct calculation of the velocity within the dural sinus.

#### VIGRE Calibration and Normal Controls

An in vitro phantom was constructed with two parallel Plexiglas tubes with 3- and 7-mm inner diameters placed in a water bath filled with tap water. Tap water circulated through the two tubes by means of a nonpulsatile gravity-fed device with mean and peak velocities calculated from a timed collection in a graduated cylinder. Actual velocities ranged from 2.3 to 122 cm/sec. An assumption was made that laminar flow was present in the phantom. Appropriate adjustments in the peak velocity settings were made for the in vitro VIGRE studies. VIGRE imaging was performed with the long axis of the tube oriented perpendicular to the imaging plane. A mean velocity was calculated from the phase image by specifying a region of interest across the entire cross section of the tube and measuring the mean voxel intensity. A peak velocity was also obtained by measuring the central voxel with the greatest deviation from 1024.

Direct coronal images were obtained perpendicular to the superior and transverse sinuses in normal volunteers ( $n = 5$ ; mean age, 30). On the phase image, a region of interest was drawn to include the entire cross section of the dural sinus, and a mean intensity and velocity were obtained.

#### Studies in Patients

Over a 6-month period, we had the opportunity to use the VIGRE technique with a 1.5-T imager (General Electric Signa Performance Plus, Milwaukee, WI) to examine three inpatients proved to have dural sinus occlusion. All patients were initially imaged with a multislice T1-weighted sagittal sequence, SE 600/20/2, with 5-mm-thick slices, a 1-mm interslice gap, a 22-cm FOV, and a  $192 \times 256$  matrix. This was followed by a multislice, multiecho T2-weighted sequence, 2800/30,80/1, with 5-mm-thick slices, a 2.5-mm interslice gap, a 20-cm FOV, and a  $192 \times 256$  matrix. Gradient-moment nulling (Flow Compensation, General Electric Medical Systems) was used on the long TR images. Additional coronal and axial T1-weighted images were obtained in selected cases for further anatomic detail.

After completion of the SE acquisitions, the major dural sinuses were viewed on the monitor for the possible use of VIGRE images. The criteria for their use in these patients included atypical flow features in the dural sinus, such as the lack of flow void; the presence of subacute thrombus; replacement or compression of the dural sinus; the lack of normal rephasing with the application of gradient-moment nulling; and poor visualization of the dural sinus. A midline sagittal plane for the VIGRE study was selected to evaluate the entire course of the superior sagittal sinus, straight sinus, and torcular Herophili. The coronal plane through the posterior fossa was selected to evaluate the transverse and superior sagittal sinuses. An axial VIGRE image was used to evaluate the distal superior sagittal sinus, torcular Herophili, jugular bulb, and occasionally the transverse sinus if this vessel was parallel to the axial plane of section. Usually, one to four single-slice VIGRE images were obtained during a total acquisition time ranging from 55 sec to 3:40 min.

One patient was also studied with time-of-flight MR angiography [18]. This sequence consisted of a flow-compensated, three-dimensional, spoiled gradient-echo sequence (50/7/1/15° flip angle) consisting of 64 0.9-mm-thick partitions, a 23-cm FOV, and a  $256 \times 256$  matrix. IV gadopentetate dimeglumine was not administered. The partitions were oriented in the axial plane. Selective maximum-intensity-projection reconstructions were performed through the dural sinuses.

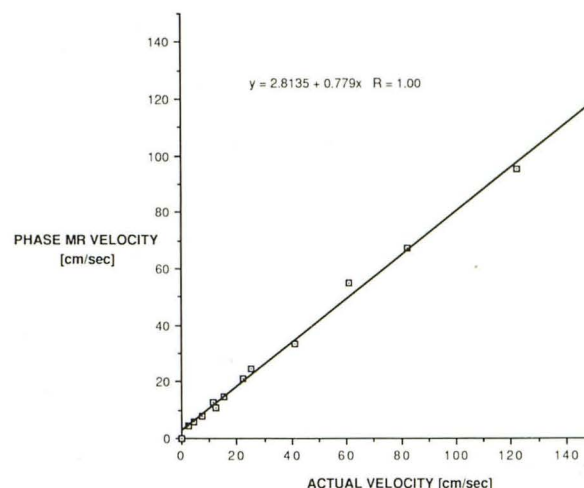


Fig. 2.—In vitro comparison between actual and observed flow velocities with VIGRE sequence. Because of velocity range tested, peak velocity was set higher than velocity range used in clinical imaging.

## Results

### Phantom Experiments and Normal Controls

The MR velocity data obtained from the phantom experiment was compared with the actual flow velocities (Fig. 2). A nearly linear relationship was noted between actual and measured velocities. In the normal controls, the calculated mean velocity was 14.4 cm/sec (range, 10.6–17.5 cm/sec) in the superior sagittal sinus and 9.9 cm/sec (range, 2.7–14.2 cm/sec) in the transverse sinus. The greater range of velocities in the transverse sinuses was due to developmental asymmetry in one patient. In all normal controls, anterior to posterior flow was demonstrated in the superior sagittal sinus and posterior to anterior flow in the transverse sinus.

### Studies in Patients

The clinical information and imaging findings in the three patients are summarized in Table 1. Representative SE and VIGRE images from the three patients are depicted in Figures 3–5.

## Discussion

MR imaging has become the noninvasive method of choice in the evaluation of dural sinus occlusion. Characteristically, direct visualization of thrombus within the sinus and loss of normal flow void on SE imaging have been reported in clinical examples [1, 5, 8, 9, 19, 20]. Initially, acute thrombosis may appear as a region of isointensity relative to normal brain parenchyma on T1-weighted images (Fig. 4B), becoming progressively hyperintense corresponding to the formation of methemoglobin (Fig. 3E) [20]. In acute thrombosis, the use of T2-weighted images alone may be potentially misleading since magnetic susceptibility effects, accentuated when im-



**TABLE 1: Summary of Patients with Dural Sinus Occlusions Studied by Velocity Imaging with Gradient-Recalled Echoes (VIGRE)**

Variable	Case 1	Case 2	Case 3
Age (years)	79	2	40
Sex	F	M	F
History	New onset of seizures and left-sided weakness 7 days after partial resection of posterior fossa meningioma	Ear pain, poor appetite, increased irritability with fevers and retroauricular swelling	"Pounding" sensations in the back of the head with findings of papilledema
Pathogenesis	Postoperative complication	Epidural abscess with septic thrombosis	Meningioma
Occluded sinus	Superior sagittal	Left sigmoid and transverse	Left sigmoid and transverse
Method of confirmation	Clinical course and imaging findings	Surgical	Surgical
Spin-echo findings at site of sinus obstruction	Loss of normal flow void and acute hemorrhagic venous infarcts	Loss of normal flow void and dilated venous collaterals	Loss of normal flow void and flow-related enhancement on MR angiogram
VIGRE findings			
Loss of phase shift	Yes	Yes	Yes
Retrograde flow	Yes	Yes	Yes
Therapy	Hypervolemic therapy	Debridement and antibiotics	Meningioma resection
Outcome	Slow improvement of hemiparesis	Reestablishment of normal antegrade flow in sinus	Improved

aging at high field strengths, can produce hypointense signal mimicking flow void [20, 21]. The absence of flow void on SE imaging may not necessarily represent thrombosis, since the lack of flow void may be confused with flow-related enhancement or rephasing of spins caused by even-echo rephasing and/or gradient-moment nulling [5, 15]. As a result, the suspected area should be evaluated in multiple planes with both long and short TR SE techniques [1].

The potential pitfalls of SE imaging can be partially overcome by the use of enhancement with gadopentetate dimeglumine, which may show nonenhancing thrombus within enhancing dural sinus as well as improved delineation of venous collaterals [1]. One should also be aware that contrast enhancement in the presence of slow-flow states may lead to some pitfalls in interpretation (Boyko O. Presented at the annual meeting of the Radiological Society of North America, November 1990). RF presaturation pulses [22] also may aid in identifying flow voids without the presence of flow-related enhancement, which on occasion may mimic thrombus. More recently, single-slice gradient-recalled-echo MR has proved to be valuable in the assessment of sinus patency [7]. Reliance on gradient-echo techniques alone may be misleading, since hyperintense thrombus may mimic flow [23, 24]. In addition, the presence of paradoxical enhancement is not a quantitative measurement of flow, and the minimum flow rate required to yield hyperintensity on either SE or gradient-echo images needs further clinical evaluation [7, 10].

Phase-contrast MR angiography has been anecdotally shown to be helpful in detecting dural sinus occlusion [25]. However, the authors in this report did not specify the velocity sensitivity with their technique. In addition, their study did not supply any information about flow directionality. In one of our cases, three-dimensional time-of-flight MR angiography confirmed sinus occlusion by a meningioma. However, the MR angiography results were somewhat misleading in that the proximal left transverse sinus appeared to be completely occluded. This contradicted the finding on both the VIGRE and conventional angiographic studies, which showed a pat-

ent proximal transverse sinus and retrograde filling toward the contralateral side. This misleading finding on MR angiography is due to the saturation of spins in this dural sinus secondary to the relatively long dwell time within the imaging volume. A similar saturation effect was noted in the right lateral sinus distal to partial obstruction by an arachnoid granulation, in which faint flow-related enhancement of the right sigmoid sinus and jugular bulb was noted on MR angiography (Fig. 5B). The VIGRE study (Fig. 5D), however, showed high flow velocities in this saturated region. The use of IV gadopentetate dimeglumine may improve MR time-of-flight venoangiography (Okumura R, et al. Paper presented at the annual meeting of the Radiological Society of North America, November 1990), and if it had been used in this patient, the dural sinuses with poor flow-related enhancement would have been visualized better. However, we elected not to use gadopentetate dimeglumine because of the concern that the densely enhancing portions of a meningioma within the occluded sinus may simulate flow-related enhancement on time-of-flight angiography, especially when the results are viewed with the use of a maximum-intensity-projection reconstruction algorithm [26].

A strong argument could be made that the parameters we used for our time-of-flight MR angiography are sensitive only for fast flow in arteries and major dural sinuses. In our experience, the major dural sinuses in normal subjects are adequately visualized with these parameters. This sequence, however, is very sensitive to reduced flow states, and therefore is a sensitive indicator of altered flow patterns such as in this patient. Multislice two-dimensional time-of-flight MR angiography is more immune to saturation effects. Unfortunately, this sequence was not available to us when this patient (case 3) was studied. However, the VIGRE technique does produce a single-slice two-dimensional magnitude image that can be used to evaluate the presence of flow-related enhancement.

MR velocity imaging based on phase shift is a well-known process in which a relationship is established between the



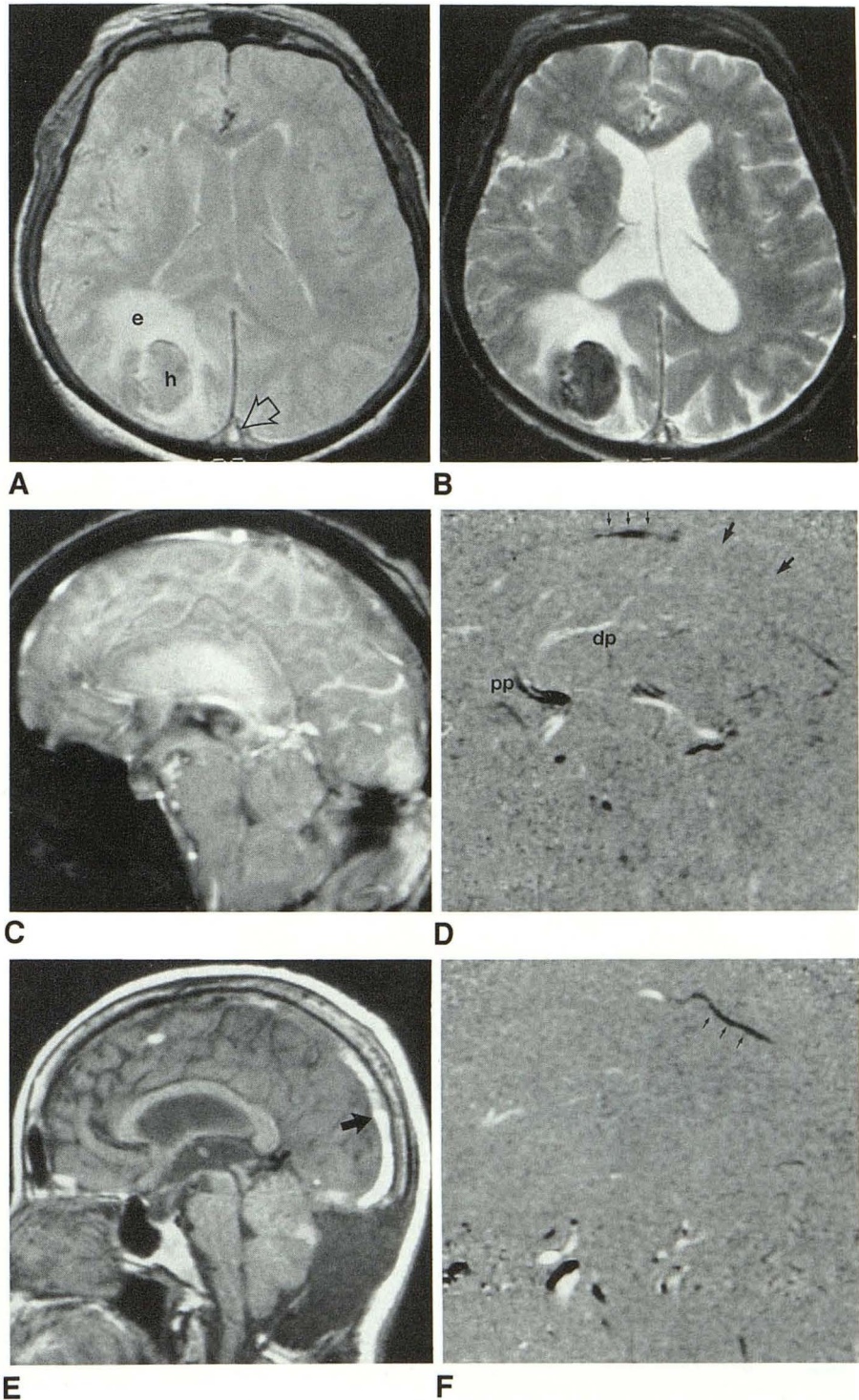
Fig. 3.—Case 1: Postoperative superior sagittal sinus occlusion.

A and B, SE 2800/30 (A) and SE 2800/80 (B) images. Loss of normal flow void (arrow) within posterior aspect of sinus represents either occlusion or slow flow with rephasing due to presence of gradient-moment nulling. Portions of acute hemorrhagic infarct (h) with T2 shortening, surrounding edema (e), and mass effect are noted.

C and D, Conventional (C) and midline VIGRE image with flow-sensitive axis in anteroposterior direction (D). VIGRE image shows lack of expected high signal within distal aspect of sinus on magnitude image and corresponding absent flow on phase reconstruction (large arrows). Proximal aspect of sinus is patent (small arrows); however, retrograde or anterior flow is seen owing to its hypointensity. For reference, note that anterior flow direction of normal proximal pericallosal (pp) arteries is similarly represented by hypointensity, whereas posterior flow direction of normal distal pericallosal arteries (dp) is represented by hyperintensity.

E, Follow-up SE 600/20 sagittal midline section shows evolution of subacute thrombus with corresponding hyperintensity (arrow) within sinus.

F, Follow-up VIGRE phase image obtained at a parasagittal location depicts a developing venous collateral (arrows) with flow directed anteriorly (flow-sensitive axis in anteroposterior direction). Focus of high signal intensity is noted directly anterior to collateral vessel, which represents another cortical vein sectioned obliquely that has a velocity vector directed posteriorly just before it enters proximal superior sagittal sinus.



relative phase of the transverse magnetization and the flow velocity in the direction of the magnetic field gradient [11–13]. One method of extracting this information is to introduce bipolar (dephasing and rephasing) gradient pulses during an imaging sequence [10]. If the protons are stationary, there is no net change in phase. If there is net motion of protons, there will not be complete rephasing resulting in a net phase shift proportional to velocity. If the applied field gradient is known, a direct velocity measurement can be estimated [14].

The VIGRE technique used in this study is based on these principles [17]. Because of the use of a short TR and gradient-recalled echoes, data acquisition is reasonably fast and can be added to a normal imaging sequence if the SE study is equivocal, as was described in the Materials, Subjects, and Methods section. In our clinical examples, only a limited number of VIGRE images were required to evaluate the sinus in question without appreciably increasing the imaging time. Flow-sensitive images can be obtained in an interleaved fash-



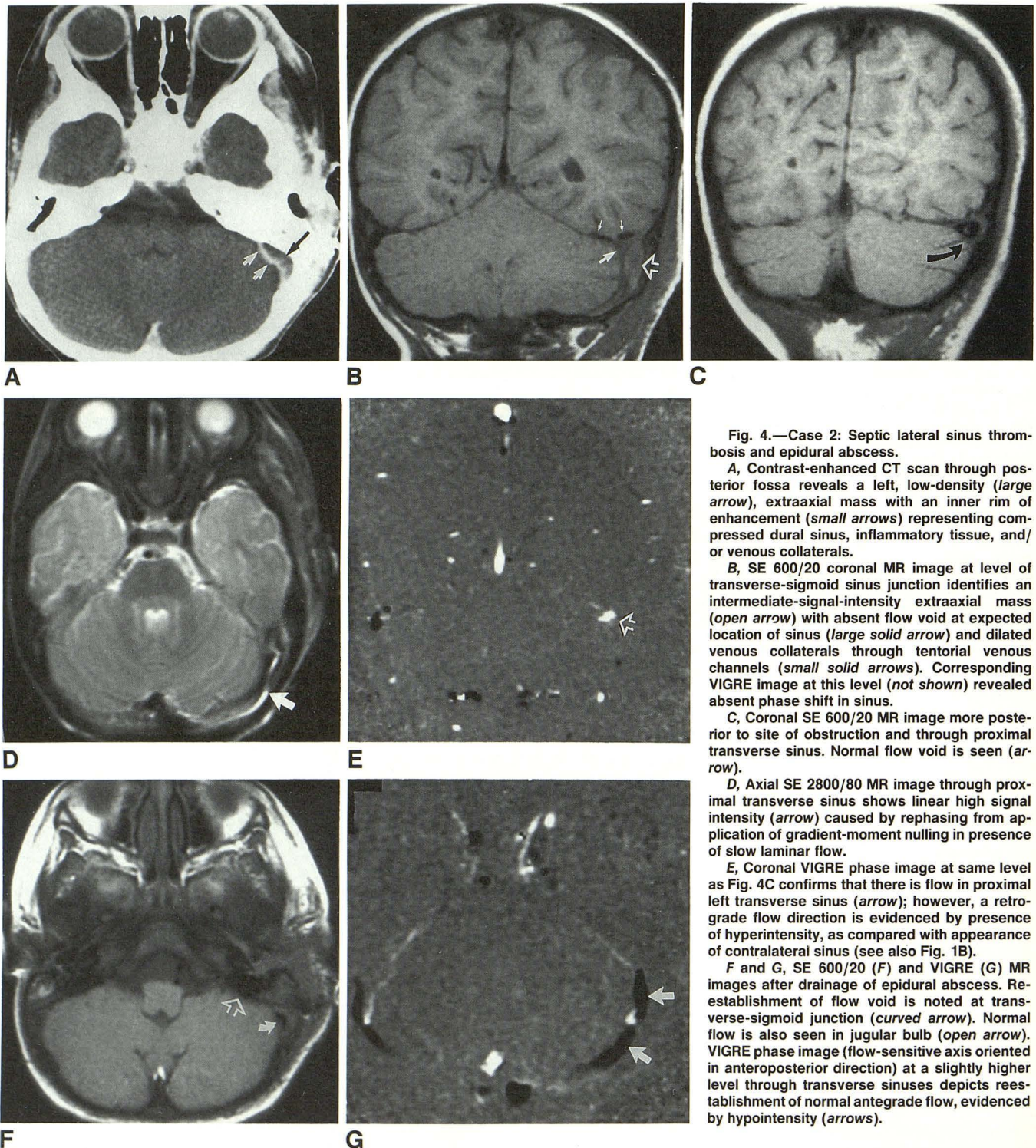


Fig. 4.—Case 2: Septic lateral sinus thrombosis and epidural abscess.

A, Contrast-enhanced CT scan through posterior fossa reveals a left, low-density (large arrow), extraaxial mass with an inner rim of enhancement (small arrows) representing compressed dural sinus, inflammatory tissue, and/or venous collaterals.

B, SE 600/20 coronal MR image at level of transverse-sigmoid sinus junction identifies an intermediate-signal-intensity extraaxial mass (open arrow) with absent flow void at expected location of sinus (large solid arrow) and dilated venous collaterals through tentorial venous channels (small solid arrows). Corresponding VIGRE image at this level (not shown) revealed absent phase shift in sinus.

C, Coronal SE 600/20 MR image more posterior to site of obstruction and through proximal transverse sinus. Normal flow void is seen (arrow).

D, Axial SE 2800/80 MR image through proximal transverse sinus shows linear high signal intensity (arrow) caused by rephasing from application of gradient-moment nulling in presence of slow laminar flow.

E, Coronal VIGRE phase image at same level as Fig. 4C confirms that there is flow in proximal left transverse sinus (arrow); however, a retrograde flow direction is evidenced by presence of hyperintensity, as compared with appearance of contralateral sinus (see also Fig. 1B).

F and G, SE 600/20 (F) and VIGRE (G) MR images after drainage of epidural abscess. Reestablishment of flow void is noted at transverse-sigmoid junction (curved arrow). Normal flow is also seen in jugular bulb (open arrow). VIGRE phase image (flow-sensitive axis oriented in anteroposterior direction) at a slightly higher level through transverse sinuses depicts reestablishment of normal antegrade flow, evidenced by hypointensity (arrows).

ion along all three orthogonal imaging planes, which we found helpful in analyzing obliquely oriented vessels. If necessary, velocity analysis in these obliquely oriented vessels can be performed by vector addition [12]. Overall, the VIGRE images allowed high contrast and conspicuity in identifying flowing spins on the clinical studies.

The phantom study showed reasonable correspondence between measured and actual velocities in the useful diag-

nostic range for dural sinuses. The known limitations of VIGRE, including gradient imperfections, eddy currents, sensitivity as a function of the peak velocity settings, resolution, and the distribution of velocities within the imaging voxel, may account for the slight discrepancies between the actual vs measured velocities [17]. Similar calibration curves using phase mapping have been shown by other investigators [16]. The results obtained in the normal controls are interesting in



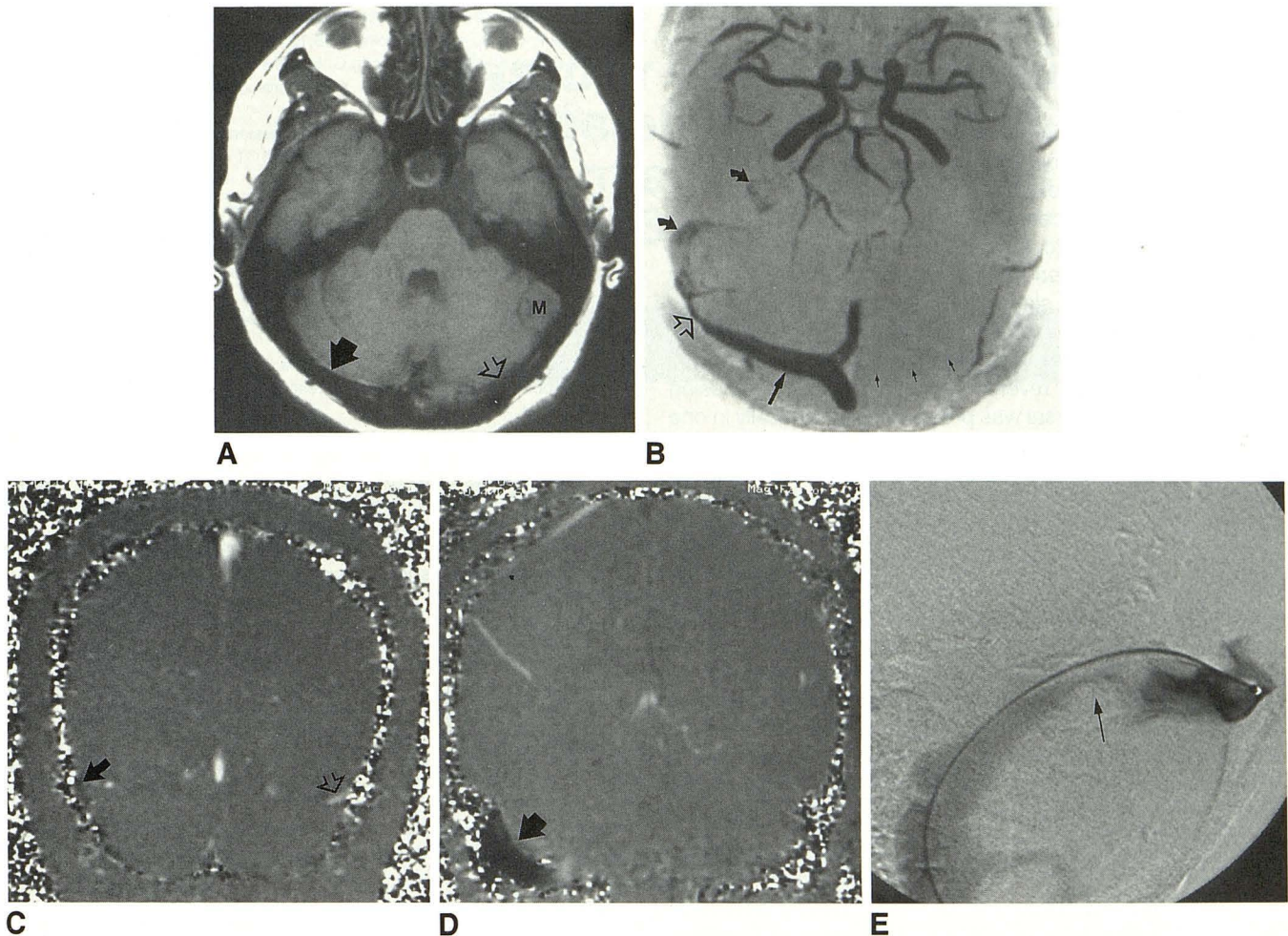


Fig. 5.—Case 3: Left posterior fossa meningioma with sinus occlusion.

A, Axial SE 600/20 MR image shows isointense mass (M) involving left transverse-sigmoid sinus junction. There is definite flow void in right transverse sinus (solid arrow) and possible flow void in left proximal transverse sinus (open arrow).

B, MR angiogram, from an axially oriented maximum-intensity projection, shows complete absence of left transverse sinus (small straight solid arrows). Unexpected findings are noted on right. A patent right proximal transverse sinus (large straight solid arrow) is seen, along with marked narrowing (open arrow) and incomplete flow-related enhancement distally in sigmoid sinus and jugular bulb (curved arrows).

C, Coronal VIGRE study through mid transverse sinuses shows retrograde flow (hyperintense signal) in left transverse sinus (open arrow) proximal to occlusion and faint antegrade flow (hypointense signal) at level of right transverse sinus stricture (solid arrow).

D, Coronal VIGRE image at level of sigmoid sinus, with flow-encoding axis in superoinferior direction, depicts normal inferior flow (hypointense signal) on right (arrow). A similar finding is expected normally on left; however, in this case there is proximal obstruction by tumor. Venous phase from a posterior fossa arteriogram (not shown) revealed identical flow patterns in dural sinuses.

E, Lateral projection, retrograde right transverse sinus venogram, confirms a segmental narrowing and filling defect (arrow) seen initially on MR angiography and presumably caused by arachnoid granulation. Pressure measurement across this stricture indicated a moderate gradient of 10 mm Hg. It was postulated that complete occlusion of left transverse sinus by a meningioma as well as partial obstruction on the right resulted in venous hypertension leading to the finding of papilledema.

that a range of velocities can be seen within the sinuses, particularly in cases of developmental asymmetry. Because of this range, any single measurement of the absolute velocity of a dural sinus in a given patient may be difficult to interpret. Measurement of the actual flow through the sinuses has been proposed as an estimate of cerebral perfusion (Mattle et al. RSNA, November 1989). More work in this area needs to be performed.

In our series, the presence of dural sinus occlusion was determined on the basis of several imaging criteria. First, in all instances the normal flow void was not seen on the SE images. Second, both the magnitude and phase-reconstruction VIGRE images demonstrated diminished or absent flow

at the point of obstruction owing to the lack of flow-related enhancement or phase shift, respectively. Third, if patency is seen in the proximal segment of the distally obstructed sinus, retrograde flow was noted. This latter finding makes physiologic sense, since normal blood flow is expected to be shunted to other collaterals in the case of distal obstruction. With further clinical experience, this retrograde sign may prove to be quite specific in the diagnosis of sinus occlusion or high-grade obstruction.

Several assumptions are required for VIGRE imaging to be applicable in dural sinus thrombosis. First, the absence of phase shift alone is insufficient evidence for complete occlusion since its sensitivity to very slow states (less than 1 cm/



sec) has not been tested by us or others [17]. The finding of proximal retrograde flow, therefore, is used as an indirect indicator of a hemodynamically significant lesion due to either high-grade stenosis or obstruction. Second, an assumption was made that dural sinus velocity is nonpulsatile, and therefore a gated acquisition was not obtained. We based this assumption on other experimental results with a bolus-tagging technique, which demonstrated no evidence of significant pulsatile motion due to the lack of dispersion of the bolus boundaries (unpublished results) when imaging the superior sagittal sinus. Even if significant pulsations exist within the sinus, VIGRE velocity measurements remain reasonably accurate [17]. Third, the retrograde flow seen in the proximal sinus represents true reversal of flow and not an aliasing artifact. This flow reversal was proved angiographically in one patient. If an aliasing artifact were present in the other two patients, the flow velocities would have been uniformly greater than the peak velocity of 50 cm/sec. It would be difficult to explain this on a physiological basis. Also, in our experience, an aliasing artifact is usually depicted as nonuniform and variable signal intensity within the vessel. This was not the case in the sinuses demonstrating retrograde flow.

Overall, owing to its quantitative nature, phase imaging adds improved diagnostic confidence in the diagnosis of dural sinus occlusion, since the potential pitfalls encountered in trying to distinguish between the loss of flow void due to physiological MR phenomena and/or slow flow from actual occlusion can be reduced. An improvement in study specificity leading to an earlier diagnosis may affect patient management, such as with the institution of heparin or urokinase therapy [3] or prompt surgical treatment including mastoidectomy, exposure of the sinus, or incision and drainage in the case of septic lateral sinus thrombosis [27].

In summary, phase-sensitive limited-flip-angle gradient-recalled imaging is an accurate and useful adjunct to SE MR imaging and three-dimensional time-of-flight MR angiography in the noninvasive diagnosis of dural sinus thrombosis, confirming the development of collateral flow, and determining the results of therapy. Retrograde flow in the proximal sinus caused by distal obstruction can be readily detected and appears to be a specific indicator of sinus occlusion or significant obstruction to antegrade flow. Further work needs to be performed to determine the sensitivity of VIGRE imaging in states of very slow flow. Quantitative phase imaging allows insight into the pathophysiological changes of venoocclusive disease and shows promise in the further evaluation of normal and abnormal flow conditions of both intracranial arteries and veins.

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