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Intracranial CSF flow in pediatric hydrocephalus: evaluation with cine-MR imaging.

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Intracranial CSF Flow in Pediatric Hydrocephalus: Evaluation with Cine-MR Imaging

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Purpose: 1) To describe the pattern of normal intracranial CSF flow in children and 2) to demonstrate altered CSF flow patterns in pediatric hydrocephalus and ventriculomegaly with flow-sensitized cine-MR examinations. **Method:** Cardiac gated, multiframe, gradient echo sequences on a 1.5-T system were displayed on a closed loop cine format and compared to standard MR images. Areas of normal flow and areas of diminished flow were determined. **Results:** 1) In normal children, the CSF flow follows a consistent pattern with a to-and-fro movement of flow in the aqueduct, foramen of Magendie, and in the dorsal and ventral subarachnoid space at the cervicomedullary junction. 2) In patients with ventricular enlargement, the flow studies showed regional abnormalities of the CSF flow patterns: specifically, lack of flow and hyperdynamic flow. **Conclusion:** Cine-MR for CSF flow evaluation is a useful adjunct to routine MR in the evaluation of pediatric hydrocephalus because it can assist in determining the probable level of CSF obstruction.

Index terms: Hydrocephalus; Cerebrospinal fluid, flow dynamics; Pediatric neuroradiology

When confronted with a case of ventricular enlargement in the pediatric age group, a question often raised is whether the ventriculomegaly is atrophic or obstructive in nature. While oftentimes this can be answered on the basis of appropriate clinical data and initial imaging studies, frequently a more precise answer and localization of flow abnormalities is desirable. We have previously reported the use of a specialized magnetic resonance (MR) technique (cine-MR) in a wide range of intracranial and intraspinal abnormalities, predominately in the adult age group (1). This report seeks to demonstrate the usefulness of this technique in a particular subset of patients, specifically infants and children with hydrocephalus.

Patients and Methods

Following routine MR examinations in which hydrocephalus was found, cine-MR was performed on a 1.5-T MR system (Picker Vista, Highland Heights, OH), utilizing a cardiac gated, reduced flip angle (13°), gradient echo study in the midsagittal plane. The pulse sequence was (TR determined by the R-to-R interval)/18/(2–4) (TR/TE/excitations). Six-millimeter thick sections were acquired as a 128 or 192 × 256 matrix and displayed as 512 × 512 images. Eight to 14 frames were acquired during each cardiac cycle and displayed on a closed-loop cine format. All abnormal patients were studied with magnitude reconstruction (ie, phase maps were not obtained). To date, this technique has been applied to 30 children with suspected abnormalities of intracranial cerebrospinal fluid (CSF) flow. The study added approximately 10–15 minutes to total examination time when data were acquired in a single plane. In some patients, cine study was also performed in an orthogonal plane. The reader is referred to Reference 1 for further details concerning the technique and theoretical considerations in cine-MR of CSF flow.

Results

Figures 1–10 display only a few static frames (2 to 4 frames) out of the usual total of 8 to 14 frames per cine-MR study. The reader should recognize that such limited static material cannot compare with the often dramatic display of flowing CSF seen on cine-MR. Therefore, the value of the cine-CSF technique cannot be fully appreciated from these images alone.

Normal CSF Flow

As demonstrated in Figures 1–3, the flow of CSF through the foramen of Monro, aqueduct of Sylvius, and foramen of Magendie can be readily identified with midsagittal imaging. Occasionally, it may be necessary or helpful to repeat the study with the sagittal plane slightly off midline to visualize the foramen of Magendie. Close inspection of the images in the cine format shows early antegrade (ie, caudal) flow of CSF out of the fourth ventricle and into the cisterna magna. This is followed shortly after (1 frame) by similar caudal flow through the aqueduct. Later in the cardiac cycle during diastole, a reversal of this pattern is identified. When sensitized for flow along the axis of interest, phase-contrast imaging (Figure 3) is far more sensitive to areas of slower CSF flow than is magnitude imaging. As a result,

Fig. 1. A and B, Normal CSF flow. Variation in the normal CSF flow pattern throughout the cardiac cycle is seen here. Shortly after the peak of the R wave (A), marked hypointensity related to rapidly flowing CSF is seen starting at the level of the foramen of Monro (straight arrow), into the third ventricle (open arrow), and continuing throughout the length of the aqueduct of Sylvius (arrowheads). Later (B) in the cardiac cycle (during diastole), a greatly diminished flow void is identified in these regions indicating a lessened velocity of CSF flow. The small bent arrows in A and B indicate the posterior inferior cerebellar artery, not flow out of the fourth ventricle. Evaluation of the multiframe sequence in a cine format disclosed a normal "to-and-fro" movement of CSF through the aqueduct.
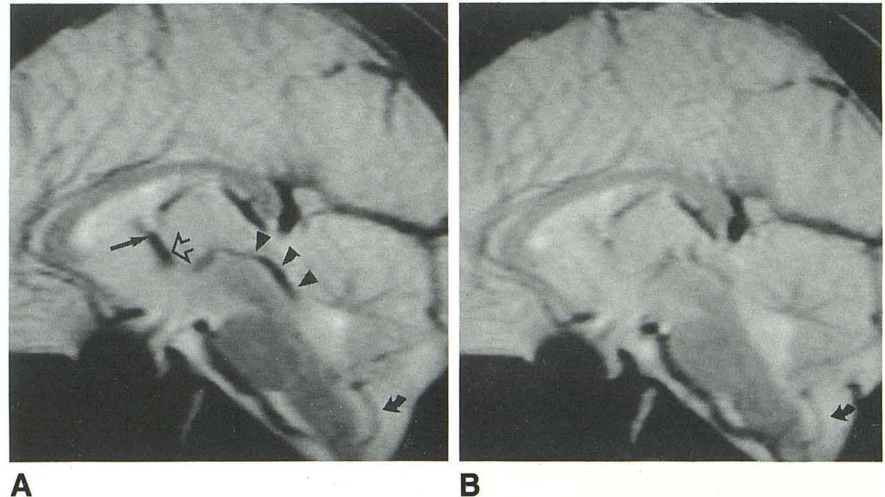

A   B

Fig. 2. A and B, Normal CSF flow. A shows flow through the foramen of Monro (straight arrow), the aqueduct (arrowheads), the foramen of Magendie (open arrow), and the fourth ventricle. The cine format documented that the flow void in B represented retrograde flow from the foramen magnum into the fourth ventricle.
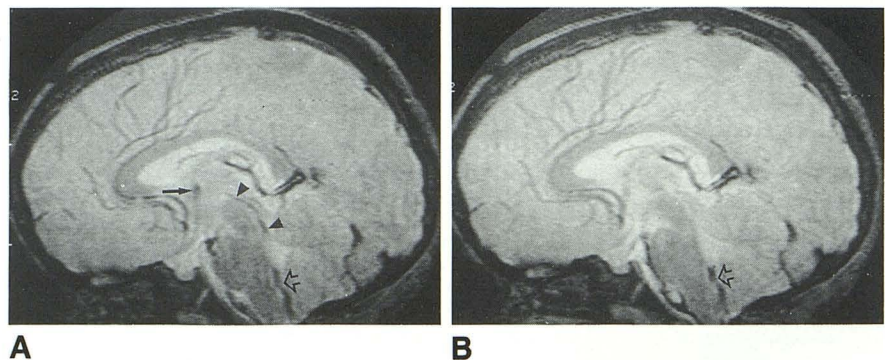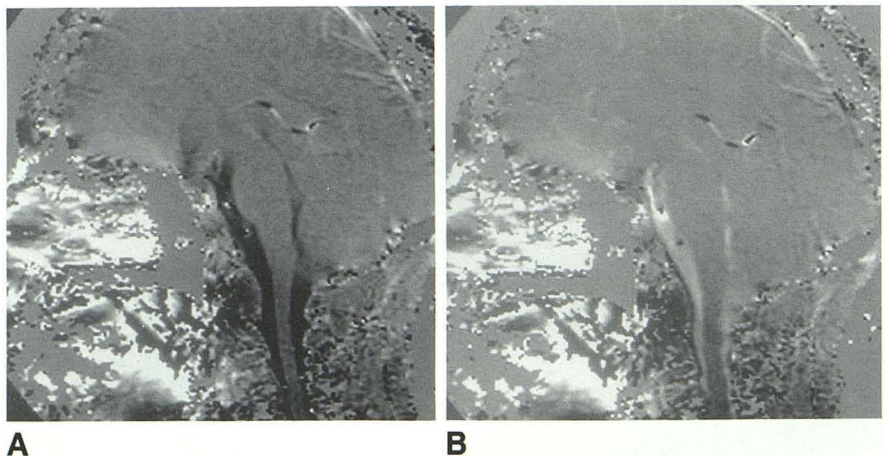

A   B

Fig. 3. Normal CSF-phase imaging. With flow sensitization along the cranial to caudal axis, phase imaging in systole is hypointense (A), indicating caudal flow of CSF within the cisterns, aqueduct, fourth ventricle, foramen of Magendie, and cervical subarachnoid space. This situation reverses in B, where cranial (retrograde) flow is identified as signal hyperintensity in those same structures. Whenever phase contrast imaging is performed and compared to magnitude imaging (eg, Figures 1 and 2), phase imaging is seen to have greater sensitivity to areas of slower flow.
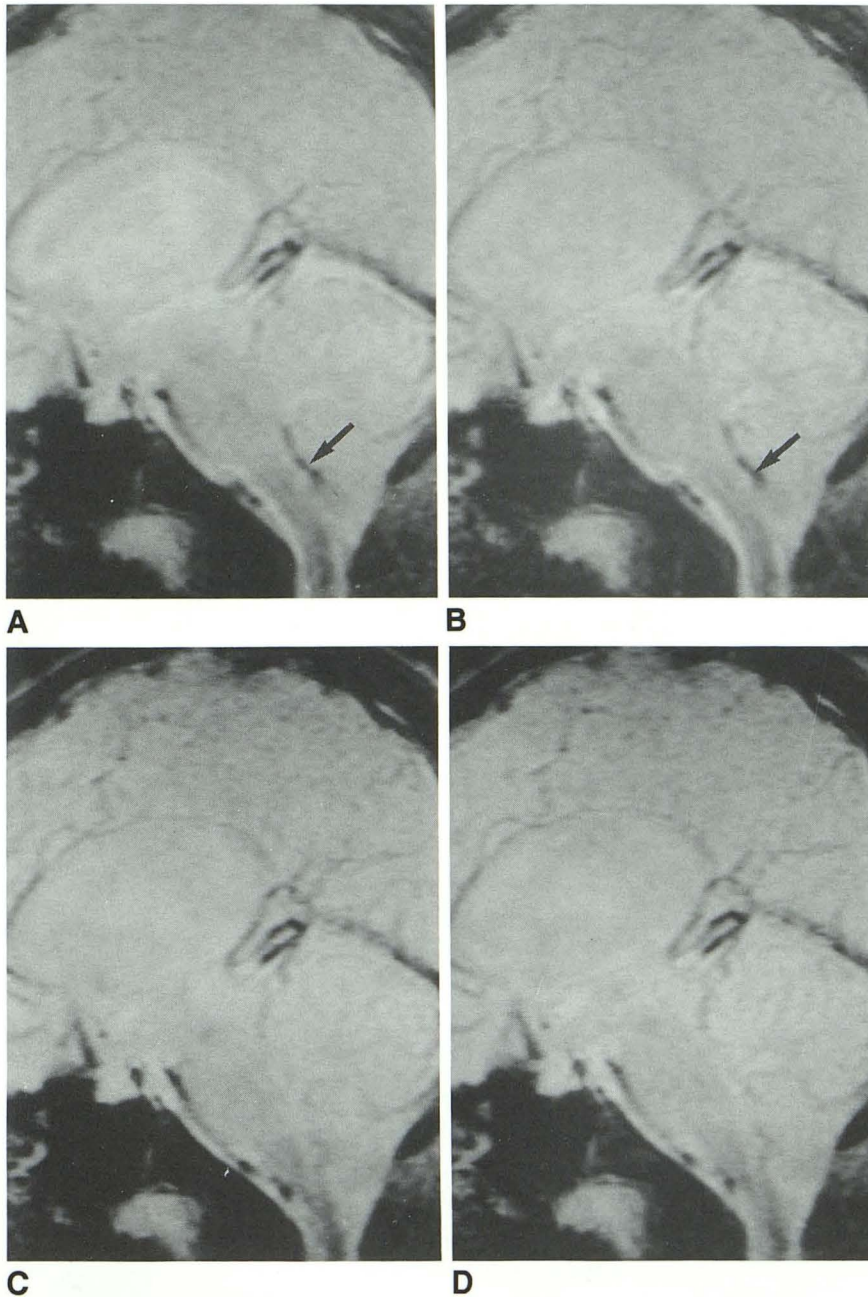

A   B

phase-contrast imaging can identify flow in the fourth ventricle and basal cisterns (Figure 3) when such flow is not apparent on magnitude imaging (Figures 1 and 2).

Suspected Intraventricular or Outlet Obstruction of CSF Flow

When obstruction to CSF flow is suspected, either within the ventricular system or at the outlets of the fourth ventricle, cine-MR can be used to define the probable site of flow abnormality. Examples of cine-MR in aqueductal stenosis (Fig. 4), a Dandy-Walker cyst/variant (Fig.

5) and a Chiari malformation with hindbrain herniation (Fig. 6) are illustrated. Of equal importance is the evaluation of patients clinically or radiologically suspected of having an obstruction to CSF flow but who, on subsequent cine-MR imaging, are shown to have intact CSF pathways (Figs. 7 and 8). Such a finding may obviate or postpone shunt placement for diversion of CSF.

Extraventricular (Communicating) Hydrocephalus and Atrophy

Cine-MR is useful to evaluate marked lateral, third, and fourth ventricular enlargement,
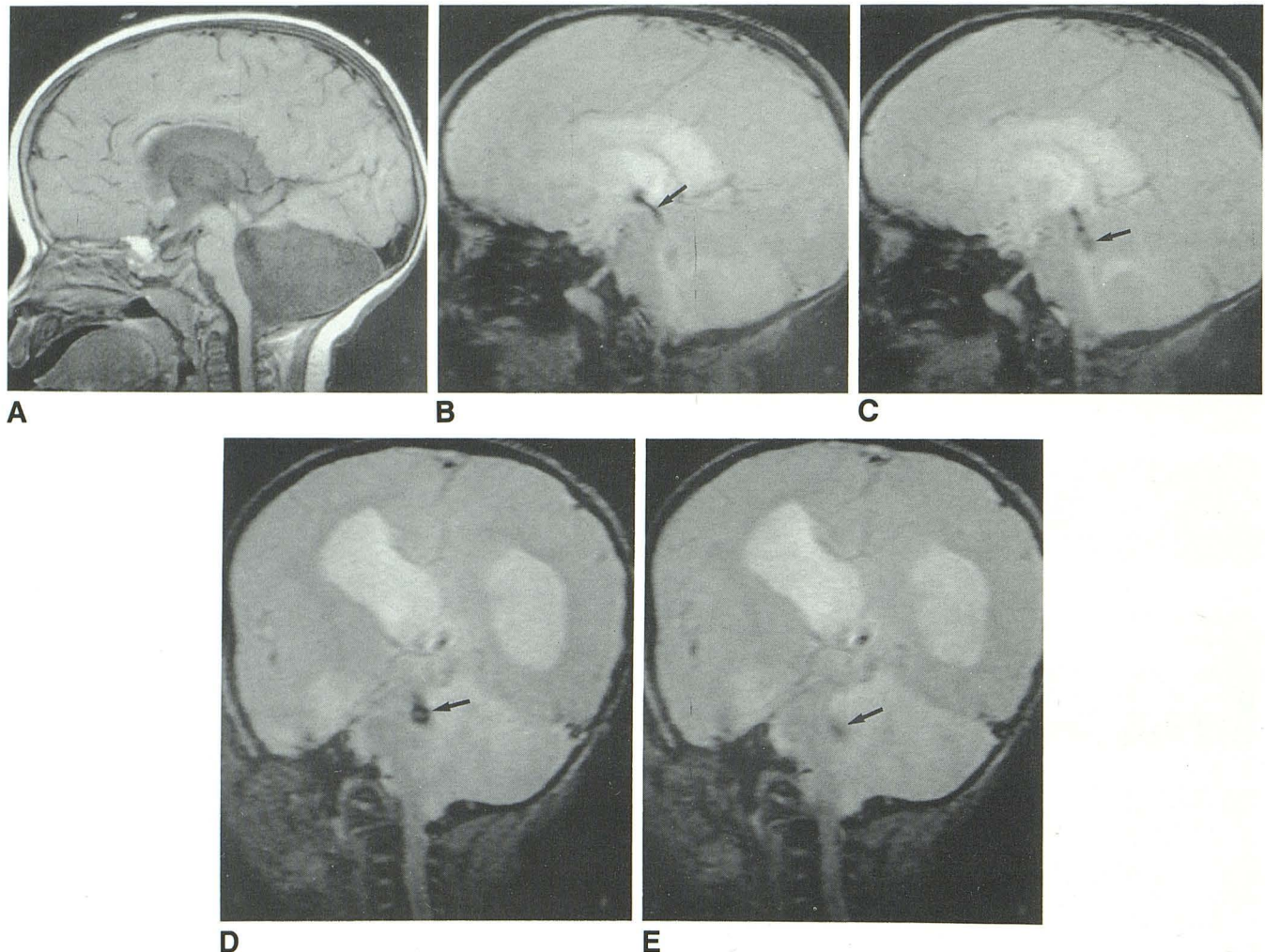
Fig. 5. A–E, Dandy Walker variant. A, Sagittal T1 MR shows a large posterior fossa cyst and partial absence of the corpus callosum. The cyst was asymmetric in the posterior fossa, not midline, and, therefore, was felt to represent a variation of the classic Dandy-Walker malformation. The marked hydrocephalus posed the question of possible associated aqueductal obstruction and/or obstruction of the outlet(s) of the cyst/fourth ventricle. Flow study in the sagittal plane (B and C) and the coronal plane (D and E) shows flow only in the aqueduct (arrow in B) and in the rostral fourth ventricle (arrow in C). Coronal cine-MR perpendicular to the aqueduct shows the marked CSF flow void in the aqueduct and rostral fourth ventricle (arrows in D and E). No flow out of the cyst was seen. Thus the CSF flow study documented that the aqueduct was patent, but the outlets of the cyst were obstructed.

whether the ventriculomegaly is associated with generalized cerebral atrophy or not. In the limited number of cases studied, the flow studies have shown remarkably similar increased fluid flow/turbulence in the fourth ventricle in both situations (Figs. 9C, 9D, 10C, and 10D). This pattern is clearly different from the normal appearance of the fourth ventricle (compare with Figures 1A, 1B, 2A, and 2B). When the CSF pathways show a flow void throughout, as in Figures 9 and 10, a complete or high-grade partial obstruction is unlikely.

Discussion

Routine brain MR imaging most commonly employs extra gradient pulses to suppress the artifacts associated with flowing blood (2, 3). While these flow-compensating techniques yield improved MR images, particularly at the skull base and inferomedial portions of the temporal lobes, a potential drawback is the dampening of the effects of CSF pulsations through the aqueductal and the fourth ventricular outlets. Therefore, valuable information concerning CSF flow can be lost. This information can be regained quickly by the use of the cine-MR technique described in this report.

T2 spin echo imaging without flow compensation (4) and single-slice gradient echo imaging (5) can also detect the presence of CSF flow within the aqueduct and within such other parts of the intracranial CSF pathways that have sig-
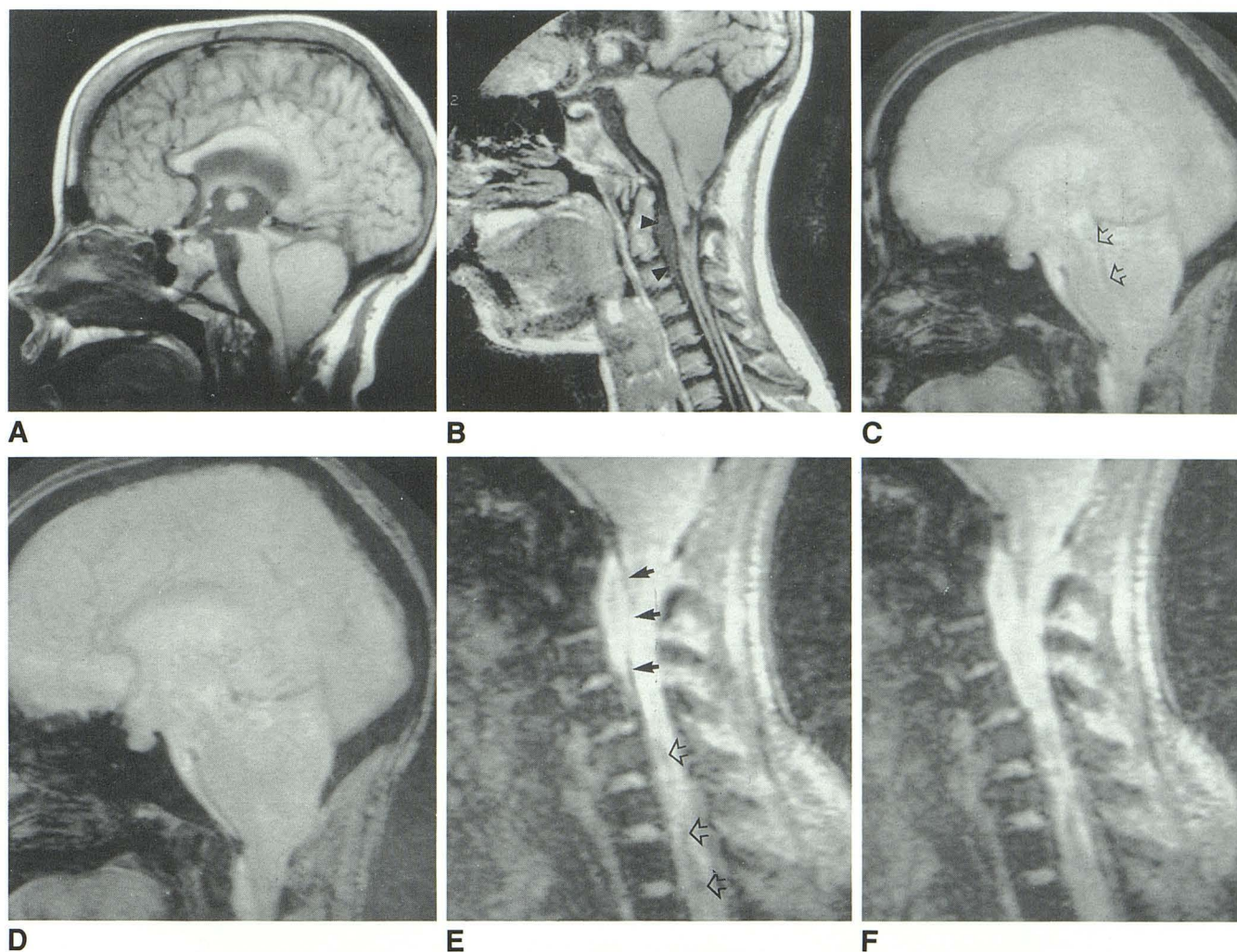
Fig. 6. *A–F*, Chiari II malformation with syringohydromyelia. The classic findings of the Chiari II malformation are shown in *A* and *B*: these include an elongated and inferiorly displaced fourth ventricle, a featureless and caudally displaced cerebellum, a beaked tectum, a kinked and displaced medulla, partial absence of the corpus callosum, and a syringohydromyelic cavity. The questions raised by this study were whether there was normal CSF flow in the aqueduct and out of the fourth ventricle, whether there was significant CSF flow in the syringohydromyelic cavity, and whether the CSF collection anterior to the cord at C2 (*arrowheads* in *B*) demonstrated fluid flow or was isolated from the adjacent subarachnoid space (SAS). In *C*, during systole, flow is noted within the aqueduct and elongated fourth ventricle (*open arrows*), indicating patency of this part of the CSF pathway. In neither *C* nor *D* was flow noted at the level of the foramen of Magendie or in the dorsal cervical SAS. The low-lying cerebellar tissue impacted at the foramen Magnum and C1 level and directed the bulk of CSF flow inferiorly in the anterior SAS (*solid arrows*). The anterior arachnoid cyst at C2 appeared isolated from the adjacent CSF flow. Significant flow is identified within the syringohydromyelic cavity in *E* (*open arrows*). In *F* (later in the cardiac cycle), flow in the anterior SAS at C2 and C3 is not seen (compare *E* with *F*) and there is a diminished flow void in the syrinx cavity. This was more convincingly demonstrated on the cine display where to-and-fro movement of CSF was clearly seen.

nificant flow velocity. However, cine-MR (1) displays the CSF flow in a dynamic, more easily appreciable, and more visually pleasing manner. In children with hydrocephalus or ventriculomegaly, cine-MR allows the determination of whether there is probable obstruction along those portions of the CSF pathways where obstruction is common (foramen of Monro, aqueduct, outlets of the fourth ventricle). The cine-MR study is usually performed in the sagittal plane because this plane displays the major CSF pathways in continuity. Reorienting the plane of acquisition to axial or

coronal plane (eg, Figs. 5D and 5E) however, may help to answer a specific question or to clarify equivocal findings in the sagittal plane.

The sensitivity to CSF flow may be increased by the use of phase imaging (eg, Figs. 3A and 3B). With this technique, areas of slower flow are visualized and the direction of flow can be readily appreciated. Within given ranges of velocities, therefore, areas that may show no flow on the magnitude imaging may manifest appreciable areas of CSF movement. The phase imaging technique has not been widely employed for a
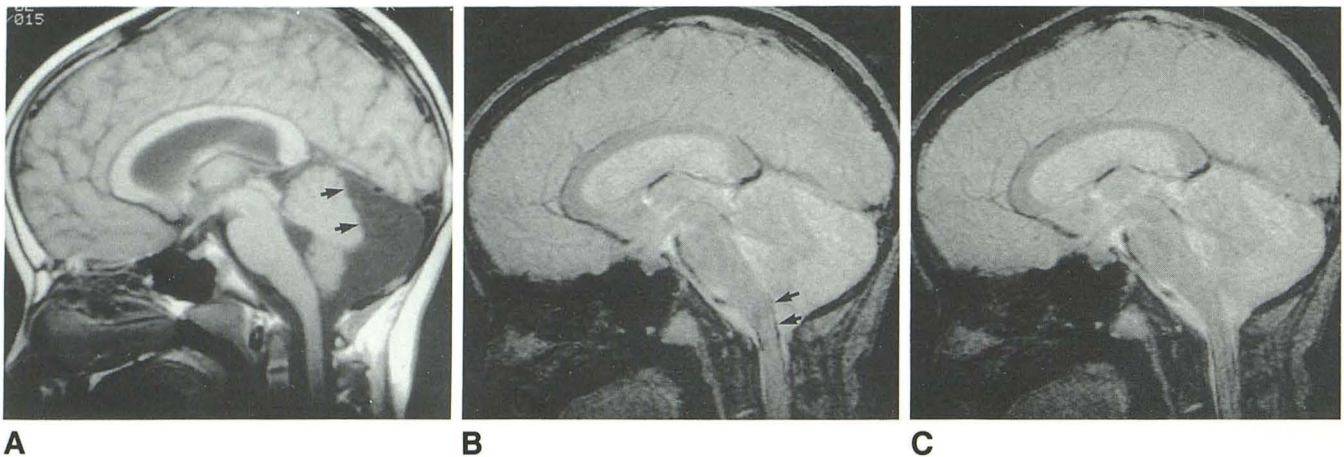
A   **B**   **C**

Fig. 7. A–C, Giant cisterna magna vs arachnoid cyst. Despite absence of mass effect on the fourth ventricle or brain stem, the flattening of the posterior surface of the cerebellum (*arrowheads* in A) suggested the presence of an arachnoid cyst and possible fourth ventricular outlet obstruction. Sagittal cine-MR (B and C) clearly shows flow out of the fourth ventricle into the cisterna magna (*arrows* in B).

Fig. 8. A–D, Intrathird ventricular cyst. A demonstrates hydrocephalus, a prominent CSF collection at the third ventricular level (enlarged third ventricle vs intraventricular cyst) and associated distortion and posterior displacement of the tectum (*arrow* in B). These findings suggested the presence of an intrathird ventricular cyst. Sagittal cine-MR, performed to determine whether the presumed cyst caused obstruction to CSF flow, showed flow (*arrow* in C) around the presumed cyst ("C" in C and D). CSF flow was unimpeded from the posterior third ventricle through the aqueduct into the fourth ventricle (*arrows* in D). On the basis of all these studies, a nonobstructing cyst was felt most likely.
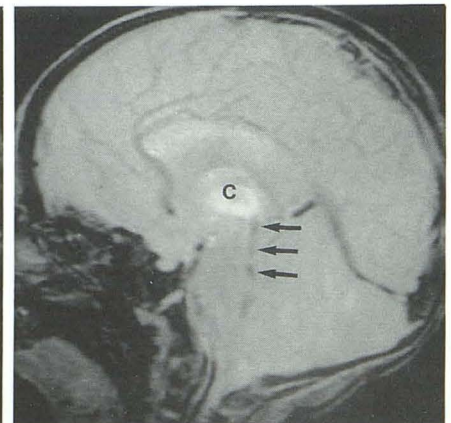

A

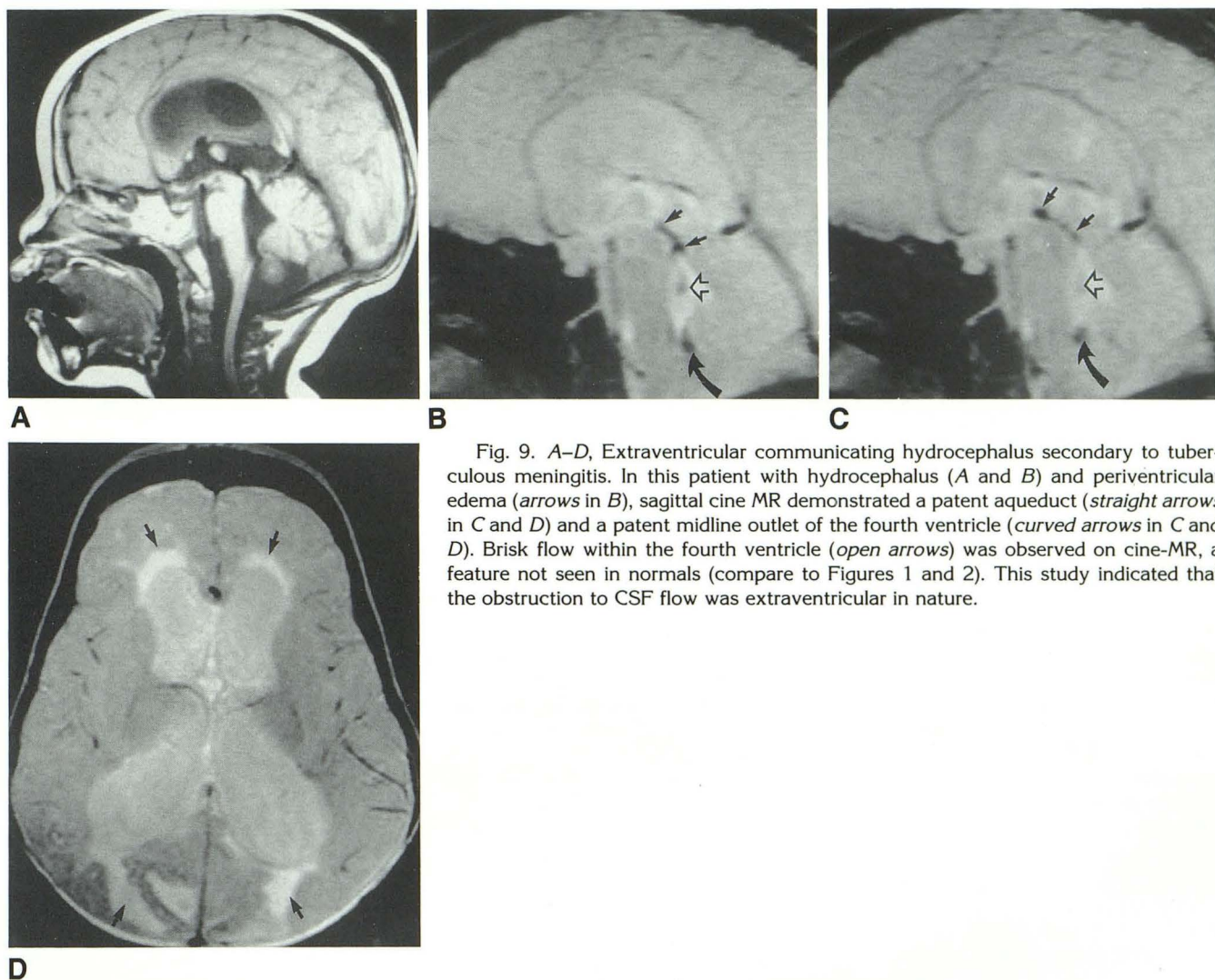

B   **C**   **D**
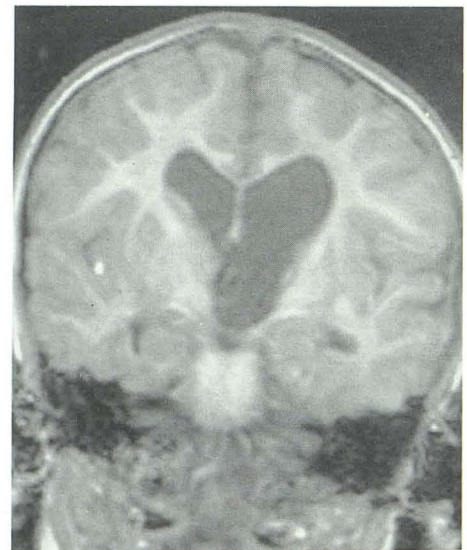
A

B
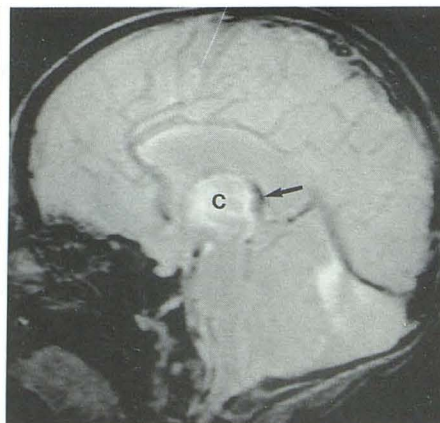
C

D

Fig. 9. A–D, Extraventricular communicating hydrocephalus secondary to tuberculous meningitis. In this patient with hydrocephalus (A and B) and periventricular edema (arrows in B), sagittal cine MR demonstrated a patent aqueduct (straight arrows in C and D) and a patent midline outlet of the fourth ventricle (curved arrows in C and D). Brisk flow within the fourth ventricle (open arrows) was observed on cine-MR, a feature not seen in normals (compare to Figures 1 and 2). This study indicated that the obstruction to CSF flow was extraventricular in nature.

number of reasons, including the fact that the anatomic details of the surrounding brain are not well defined. Nonetheless, the prospects for determination of actual CSF flow velocities in multiple regions of the ventricular system and in the surrounding cisterns are good and add to our understanding of CSF flow dynamics in healthy subjects and in patients with alterations in CSF dynamics due to a wide range of pathologic conditions.

The application of cine-MR CSF flow technique in hydrocephalic children holds great promise for improved diagnosis, particularly in those cases where the exact level or levels of CSF obstruction need to be determined. In the normal patient, consistent flow patterns are observed (Figs. 1–3) and are quite different from those patterns that are seen in hydrocephalus. The information obtained with cine-MR often is not readily apparent

on routinely acquired MR images and may help to answer the question of whether the ventriculomegaly observed on routine MR is associated with patent CSF pathways (Figs. 8 and 10), whether the obstruction to flow is probably extraventricular (Fig. 9), or whether the obstruction is intraventricular (Figs. 4 and 5). When patients are evaluated clinically for possible CSF diversionary procedure or cyst decompression, a cine-MR may provide valuable evidence that such surgery is not indicated (Figs. 7 and 8). In instances where the differential diagnoses include the possibility of a trapped cyst with poor flow into and out of the cyst (eg, Fig. 5), proper surgical care could require lateral ventricular shunting combined with cyst shunting. In such a circumstance, cine-MR can provide information that may alter the surgical approach to the patient. In the case shown in Figure 5, a single shunt placed into the cyst
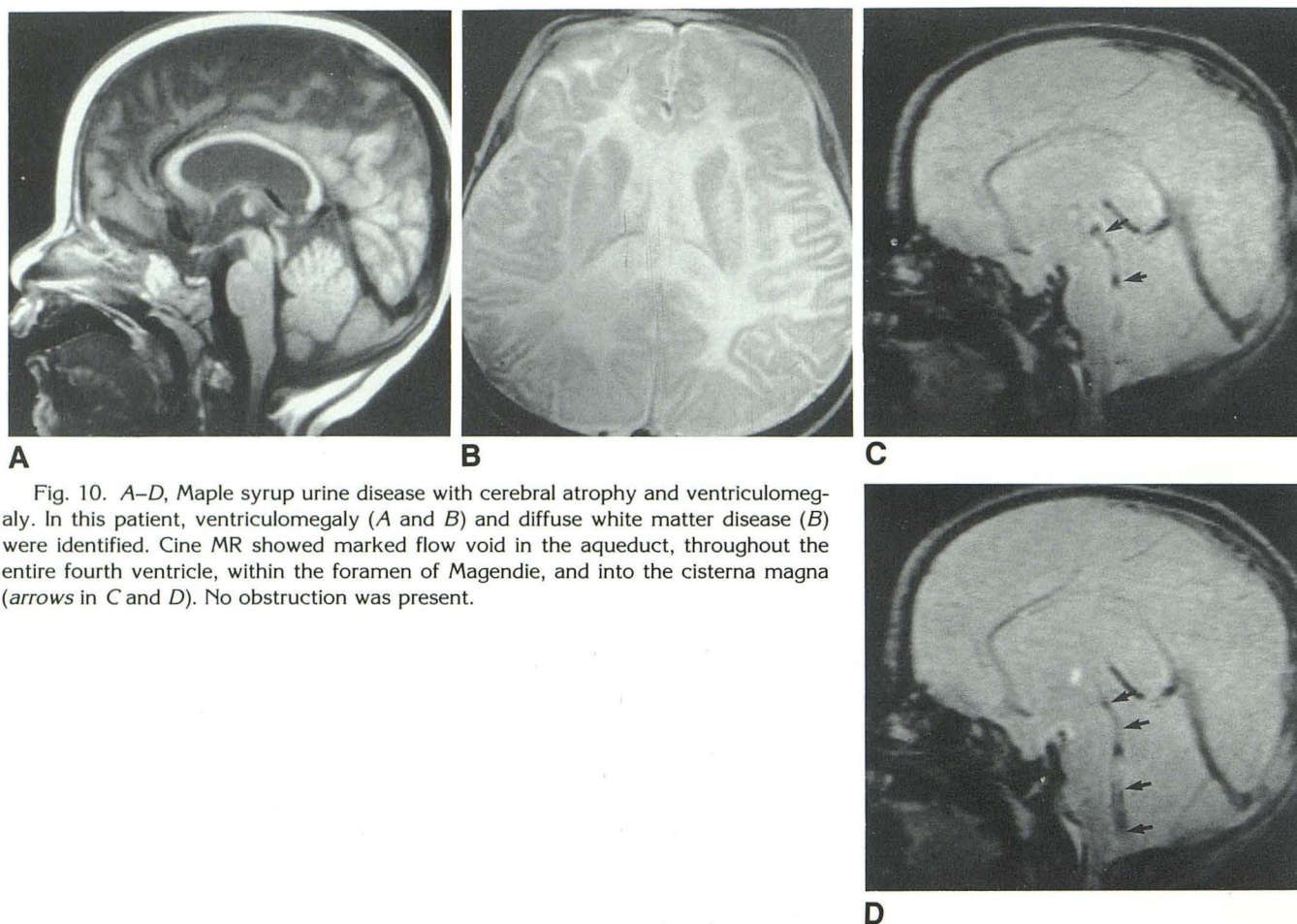
Fig. 10. *A–D*, Maple syrup urine disease with cerebral atrophy and ventriculomegaly. In this patient, ventriculomegaly (*A* and *B*) and diffuse white matter disease (*B*) were identified. Cine MR showed marked flow void in the aqueduct, throughout the entire fourth ventricle, within the foramen of Magendie, and into the cisterna magna (*arrows* in *C* and *D*). No obstruction was present.

would be adequate to decompress the cyst and the entire ventricular system.

Hyperdynamic CSF flow, encompassing the entire fourth ventricle (Fig. 10) has been observed in children with ventriculomegaly. This is similar to the flow pattern observed in adult patients with generalized cerebral atrophy (1). In patients in whom routine MR strongly *suggests* atrophy, the simple addition of a cine-MR study can confirm this impression within a few minutes.

Cine-MR can also be used to evaluate patients with tumors and inflammatory lesions that cause obstruction to CSF flow directly (by contiguous mass effect) or indirectly (by aqueductal kinking or distorting the fourth ventricular outlets). While this may not carry the same importance as determining areas of impaired CSF flow in congenital hydrocephalus, the information so derived might be useful in determining whether a CSF diversionary procedure would be justified.

In conclusion, qualitative assessments of CSF flow as described and illustrated in this report indicate the potential usefulness of cine-MR in pediatric hydrocephalus. It is clear that the potential of this technique has not been fully explored. With the knowledge that phase imaging is capable of generating actual velocity measurement, CSF flow studies will probably assume a greater role in MR imaging.

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