Imaging of Meningitis and Ventriculitis

Suyash Mohan, MD, PDCC[a,*], Krishan K. Jain, MD, PDCC[b], Mohammad Arabi, MD[c], Gaurang V. Shah, MD[c]

KEYWORDS

• Central nervous system • Infection • Magnetic resonance imaging • Meningitis • Ventriculitis • Complications

KEY POINTS

- Meningeal enhancement is nonspecific and can be seen in meningitis of any cause, including noninfectious processes.
- Imaging helps in noninvasive differentiation of infective from the noninfective conditions and helps in better clinical decision making.
- In acute meningitis, meningeal enhancement is located over the cerebral convexity, whereas in chronic meningitis it is most prominent in the basal cisterns.
- The role of neuroimaging is to confirm suspected meningitis, rule out meningitis mimics, evaluate for complications, and rule out increased intracranial pressure before lumbar puncture.
- Magnetic resonance imaging is critical in evaluating complications of meningitis (eg, ventriculitis, extra-axial collections, cerebritis and abscess, herniations, cranial neuropathy, and vasculopathy).

INTRODUCTION

Central nervous system (CNS) infections account for 1% of primary hospital admissions and 2% of nosocomial infections[1,2] and when encountered, require prompt diagnosis and initiation of specific treatment. The brain has some unique peculiarities like absence of lymphatics, lack of capillaries in the subarachnoid space, and presence of cerebrospinal fluid (CSF), which is an excellent culture medium for dissemination of infectious processes, in the subarachnoid space and into the ventricular system. The normal brain responds to these insults in a limited and stereotypical fashion, and in most cases there is concomitant abnormality of the blood-brain barrier, with associated enhancement. Therefore, the imaging findings are mostly nonspecific with respect to the causative pathogen. However, imaging techniques are sensitive for detecting an abnormality, localizing it, and in many cases categorizing the lesion into infectious or inflammatory disease versus neoplastic. Contrast enhancement is generally useful, and in the light of clinical history and examination findings the radiologist can provide a probable differential diagnosis. Whereas analysis of CSF remains the gold standard to identify the infectious agent, neuroimaging plays a pivotal role not only in diagnosis but also in monitoring therapeutic response. This article begins by briefly describing the anatomy of cranial meninges and extra-axial spaces of the brain. Characteristic findings and recent advances in neuroimaging of meningitis and its complications and ventriculitis are then summarized, and certain noninfectious causes of meningitis and meningitis mimics are described.

[a] Division of Neuroradiology, Department of Radiology, University of Pennsylvania School of Medicine, 219 Dulles Building, 3400 Spruce Street, Philadelphia, PA 19104, USA; [b] Department of Neuroradiology, National Neuroscience Institute, 11 Jalan Tan Tock Seng, Singapore 308433; [c] Department of Radiology, University of Michigan Health System, 1500 East Med Center Dr, Ann Arbor, MI 48109, USA
* Corresponding author.
E-mail addresses: drsuyash@gmail.com; suyash.mohan@uphs.upenn.edu

Neuroimag Clin N Am 22 (2012) 557–583
doi:10.1016/j.nic.2012.04.003

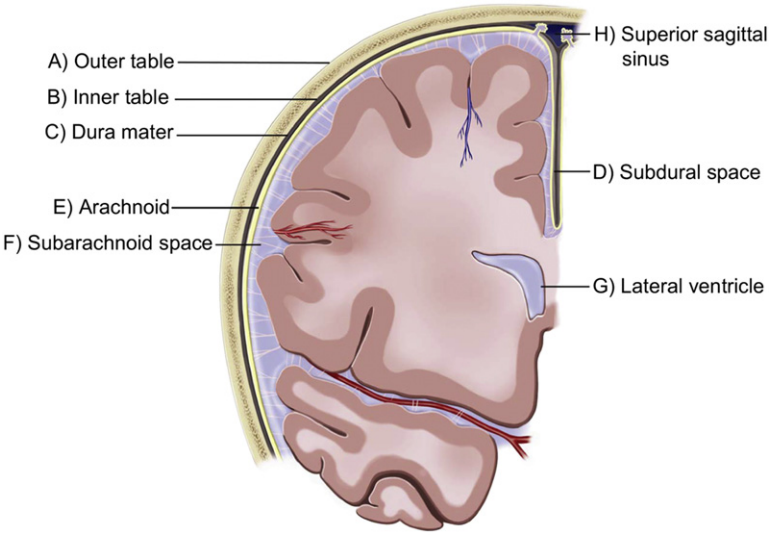

Fig. 1. Coronal section through the brain shows the meningeal layers and spaces. (A) Outer table, (B) inner table, (C) dura mater, (D) subdural space, (E) arachnoid, (F) subarachnoid space, (H) superior sagittal sinus, (G) lateral ventricle.

CRANIAL MENINGES AND EXTRA-AXIAL SPACES: NORMAL ANATOMY

Three membranes of connective tissue cover the brain, which are collectively called the meninges. They are named, from the outermost layer inward, the dura mater (also called pachymeninx [literally, "tough mother"]), arachnoid mater, and pia mater, which together constitute the leptomeninges. The space between the inner table of the skull and the dura mater is the epidural space. The space between the dural covering and the arachnoid is the subdural space (Fig. 1), which is a potential space containing bridging veins and arachnoid villi. The arachnoid is a delicate outer layer that parallels the dura and is separated from the pia by the subarachnoid space, which contains the CSF (Fig. 2). The pia is closely applied to the brain surface and carries a vast network of blood vessels.

NORMAL AND ABNORMAL MENINGEAL ENHANCEMENT

In normal meninges, enhancement is visualized as a thin, markedly discontinuous rim covering the surface of the brain, which is typically most prominent parasagittally. The enhancement is primarily in the dura and venous structures, along the inner table, falx, and tentorium, related to absent blood-brain barrier (Fig. 3). The arachnoid is thin and avascular. However, vascular enhancement of the normal, delicate pia is too subtle to visualize.[3] Thin, linear, well-demarcated and symmetric enhancement may sometimes be seen in the sulci, because of enhancing veins. Abnormal meningeal enhancement is usually not symmetric and is usually not so sharply demarcated and more importantly it extends deep into the base of the sulci (Fig. 4).[4] Quint and colleagues[5] reported that when meningeal enhancement was present

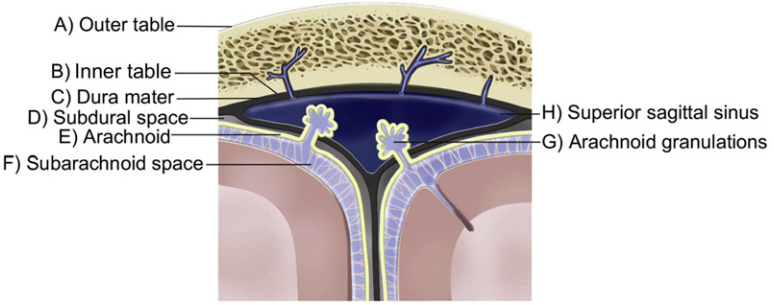

Fig. 2. The brain at the level of the superior sagittal sinus shows the meningeal layers and spaces and the relationship to the dural venous sinus. (A) Outer table, (B) inner table, (C) dura mater, (D) subdural space, (E) arachnoid, (F) subarachnoid space, (H) superior sagittal sinus, (G) arachnoid granulation.

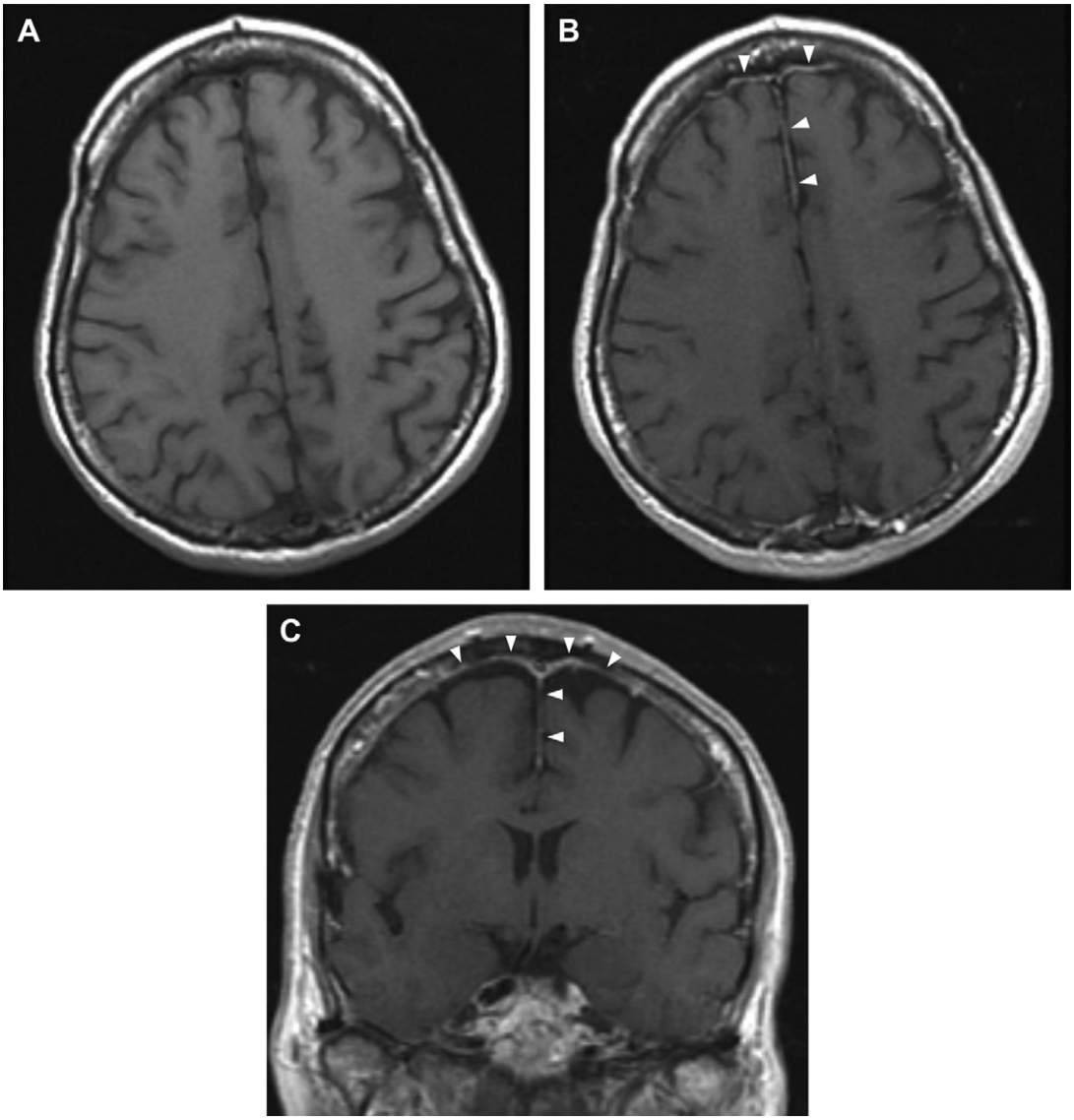

Fig. 3. Axial T1WI before (*A*) and after (*B*) contrast administration show normal, mild, thin, parasagittal dural enhancement (*arrowheads*). The enhancement is primarily in the dura and venous structures along the inner table and anterior falx. (*C*) Coronal T1WI after contrast shows the smooth, nonnodular, parasagittal dural enhancement.

on more than 3 contiguous 1.5-T spin-echo (SE) magnetic resonance (MR) images, it was highly correlated with substantial intracranial abnormality. Thicker, longer, or more intensely enhancing segments, as well as nodular meningeal enhancement, are abnormal (**Box 1**).

PATTERNS OF MENINGEAL ENHANCEMENT

Extra-axial meningeal enhancement may be classified as either pachymeningeal or leptomeningeal (**Box 2** and **Fig. 5**). Because the normal, thin arachnoid membrane is attached to the inner surface of the dura mater, the pachymeningeal pattern of enhancement is also described as dura-arachnoid enhancement, whereas enhancement on the surface of the brain is called pial or pia-arachnoid enhancement, often referred to as leptomeningeal enhancement and usually described as having a gyriform or serpentine appearance.[6] The enhancement follows along the pial surface of the brain and fills the subarachnoid spaces of the sulci and cisterns. Combined dura-arachnoid and pia-arachnoid enhancement may coexist, typically focal in location and in association with vascularized extra-axial tumor, including metastases,

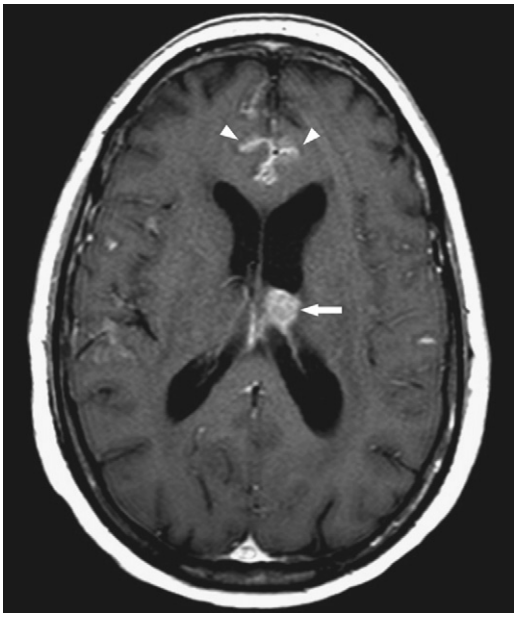

Fig. 4. Leptomeningeal metastasis in a patient with melanoma. Axial T1WI of the brain after contrast administration shows abnormal anterior frontal parasagittal leptomeningeal enhancement extending deep into the cerebral sulci (*arrowheads*). A subependymal enhancing nodule is seen in the lateral ventricle (*arrow*).

Box 1
Differentiation between normal meningeal vessels/cortical veins and abnormal leptomeningeal enhancement

Normal Meningeal Vessels/Cortical Veins	Abnormal Leptomeningeal Enhancement
• Thin	• Thick
• Smooth	• Nodular/irregular
• Short and discontinuous	• Longer and continuous
• Well-demarcated	• Poorly demarcated
• Symmetric	• Asymmetrical
• Superficial, and most prominent parasagittally	• Extends deep into the base of the sulci
• Short-segment convexity meningeal enhancement	• Long-segment (>3 cm) or diffuse convexity meningeal enhancement
• Isolated fine linear falcine and tentorial meningeal enhancement	• If meningeal enhancement was present on more than 3 contiguous 1.5-T SE MR images
• No enhancement of suprasellar cistern and ventricular walls	

Box 2
Conditions that produce pachymeningeal and leptomeningeal enhancement

Pachymeningeal	Leptomeningeal
• Intracranial hypotension	• Acute stroke
• Idiopathic	• Infection
• Infection	• Inflammatory diseases (eg, sarcoidosis)
• Inflammatory diseases (eg, sarcoidosis)	• Metastases
• Metastases	
• Shunting	
• SAH	

lymphoma, focal tuberculous meningitis (TBM), and sarcoidosis (**Figs. 6** and **7**).[7]

Leptomeningeal enhancement is usually associated with meningitis, which may be bacterial, viral, or fungal. Bacterial (**Figs. 8** and **9**) and viral (**Figs. 10** and **11**) meningitis exhibit typically thin and linear enhancement, whereas fungal meningitis usually produces thicker, lumpy, or nodular enhancement.[8] Neoplasms may spread into the subarachnoid space and produce enhancement of the brain surface and subarachnoid space, a pathologic process that is often called carcinomatous meningitis (**Fig. 12**). Both primary tumors (medulloblastoma, ependymoma, glioblastoma, and oligodendroglioma) and secondary tumors (eg, lymphoma and breast cancer) may spread through the subarachnoid space. Neoplastic disease in the subarachnoid space may produce thicker, lumpy, or nodular enhancement, similar to that of fungal disease. Viral encephalitis (as well as sarcoidosis) may also produce enhancement along the cranial nerves, in addition to the brain surface. Normal cranial nerves never enhance within the subarachnoid space, and such enhancement is always abnormal (**Fig. 13**).[6]

Pachymeningeal enhancement may arise from various benign or malignant processes, including transient postoperative changes, intracranial hypotension (**Figs. 14** and **15**), neoplasms such as meningioma, metastatic disease (from breast and prostate cancer), secondary CNS lymphoma, and granulomatous disease. Postoperative meningeal enhancement occurs in most patients and may be dura-arachnoid or pia-arachnoid (**Fig. 16**).[9] In patients who have not undergone surgery, other causes of this enhancement pattern should be considered. Although such enhancement has been reported after uncomplicated lumbar puncture, this observation is rare, occurring in less than 5% of patients (see **Fig. 14**).[10]

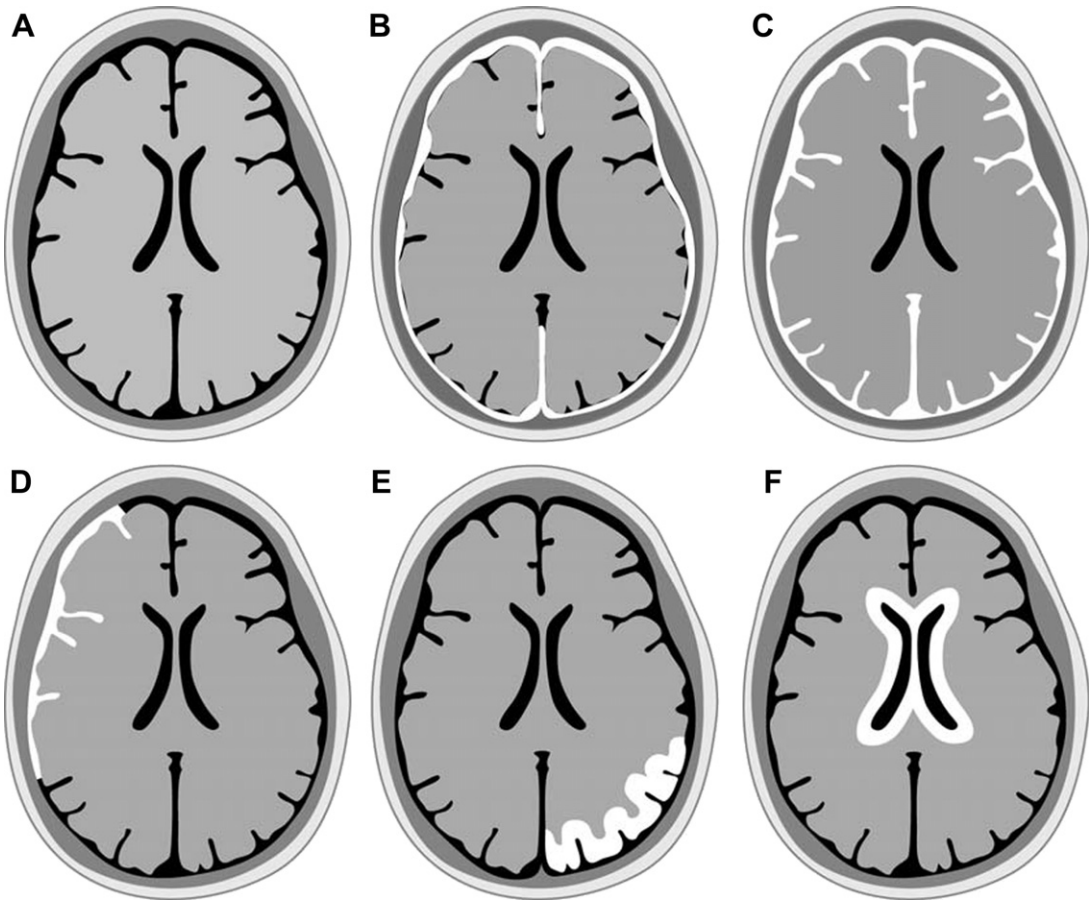

Fig. 5. The patterns of meningeal enhancement. (*A*) Normal meninges, (*B*) diffuse pachymeningeal enhancement, (*C*) diffuse leptomeningeal enhancement, (*D*) localized leptomeningeal enhancement, (*E*) gyriform cortical enhancement, and (*F*) ependymal enhancement.

SUMMARY OF CAUSES OF MENINGEAL THICKENING AND ENHANCEMENT

- Infectious: meningitis (bacterial, fungal, tuberculous, viral, or parasitic)
- Neoplastic meningitis: carcinoma, lymphoma, leukemia, primary CNS neoplasia
- Sarcoidosis: most common form is leptomeningitis; however, it also can present as a pachymeningitic process affecting predominantly the dura mater. Sarcoidosis is the most common cause of chronic meningitis in the Western world, whereas tuberculosis is the most common cause in the developing world
- Chemical meningitis: subarachnoid hemorrhage (SAH), dermoid cyst rupture, methotrexate instillation, and other neurotoxic substances
- Drug-induced aseptic meningitis: many antimicrobials, xanthine oxidase inhibitor allopurinol, nonsteroidal antiinflammatory drugs, ranitidine, carbamazepine, vaccines against hepatitis B and mumps, immunoglobulins, OKT3 monoclonal antibodies, cotrimoxazole, radiographic agents, and muromonab-CD3 have also been associated. A high index of suspicion is needed to make an accurate diagnosis of drug-induced meningitis. Diagnostic accuracy in clinical care depends on a complete history and physical examination
- Collagen vascular disorders: pachymeningitis is occasionally seen in Wegener granulomatosis and rheumatoid arthritis. Aseptic meningitis is occasionally seen in systemic lupus erythematosus and Behçet disease
- Intracranial hypotension

CLINICAL FEATURES

Clinical features are related to patient's age (**Boxes 3** and **4**). In adults, meningitis presents with the classic triad of fever, neck stiffness, and

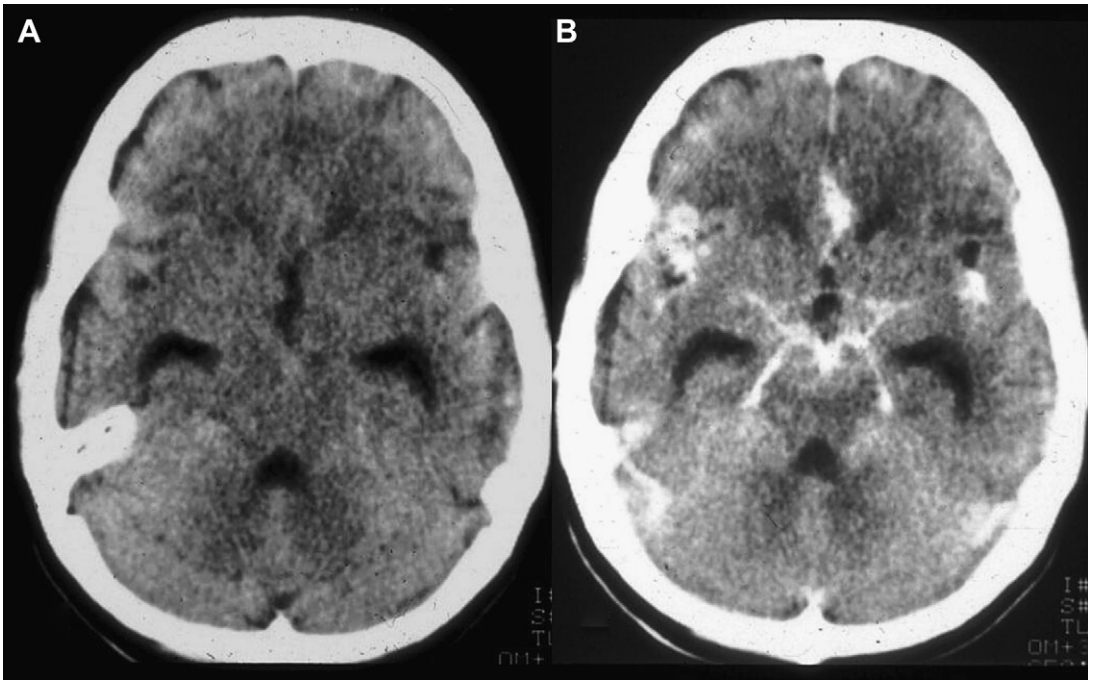

Fig. 6. Tubercular meningitis in a 45-year-old man who presented with seizures and fever. Axial plain CT image (*A*) shows dilated bilateral lateral ventricles with diffusely swollen gyri and obliteration of basal cisterns. Axial postcontrast CT (*B*) shows thick meningeal enhancement in basal cistern regions. (*From* Shah GV. Central nervous system tuberculosis: imaging manifestations. Neuroimaging Clin N Am 2000;10(2):355–74; with permission.)

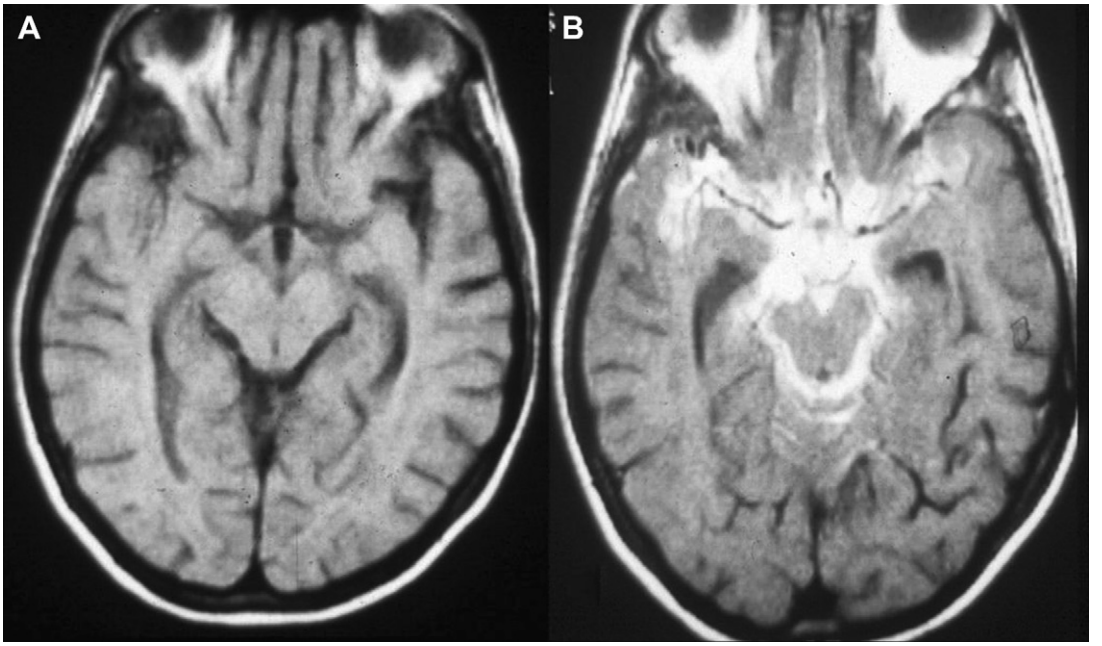

Fig. 7. Tubercular meningitis in a 45-year-old man who presented with seizures and fever. Axial plain T1WI (*A*) shows obliteration of basal cisterns with thick meningeal enhancement on contrast study (*B*). (*From* Shah GV. Central nervous system tuberculosis: imaging manifestations. Neuroimaging Clin N Am 2000;10(2):355–74; with permission.)

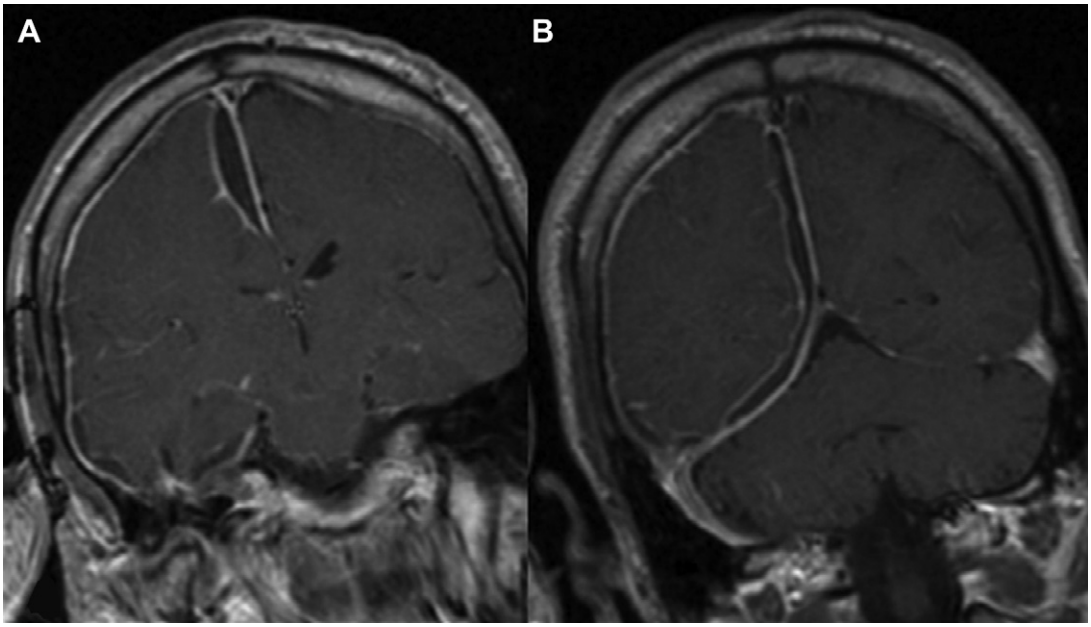

Fig. 8. Subdural empyema in a 34-year-old woman. Postcontrast T1WI (*A*, *B*) shows subdural collection abutting interhemispheric fissure and along the right tentorial leaf with peripheral enhancement.

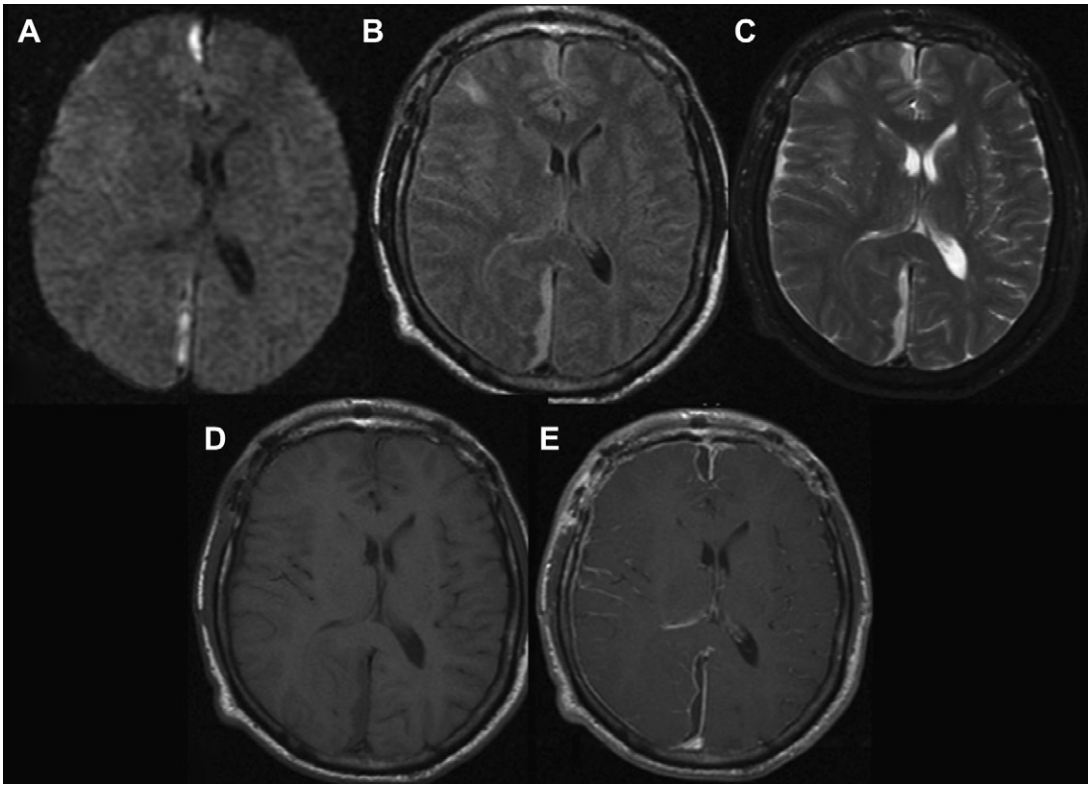

Fig. 9. Subdural empyema in a 34-year-old woman. Axial T2WI (*B*) and FLAIR imaging (*C*) shows concavo-convex hyperintense collection abutting anterior and posterior interhemispheric fissure, with presence of focal cortical hyperintensity in right frontal lobe. Collection is hypointense on T1WI (*D*) and showing restriction on axial DWI (*A*). Peripheral enhancement is seen on axial postcontrast T1WI (*E*), along with the presence of increased leptomeningeal enhancement.

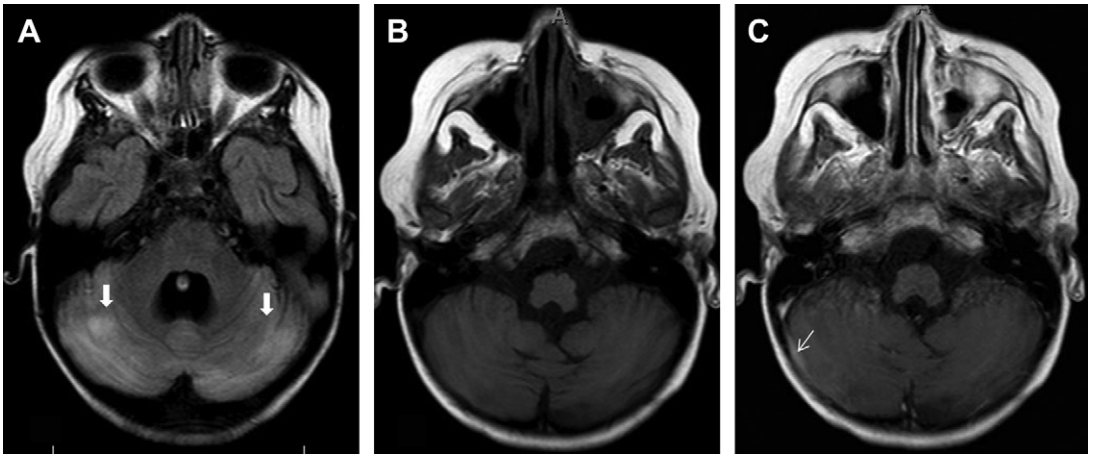

Fig. 10. Acute cerebellitis in a 9-year-old boy. Axial FLAIR imaging (*A*), plain axial T1WI (*B*) and contrast-enhanced axial T1WI (*C*) show diffuse hyperintense signal in bilateral cerebellar hemispheres (*white block arrows*), with some volume loss and increased leptomeningeal enhancement (*white arrow*), especially overlying the right cerebellar hemisphere.

an altered mental status.[11] However, it has been noted that the prevalence of this classic triad is low among adults with community-acquired bacterial meningitis. However, almost all patients (95%) present with at least 2 of the 4 symptoms of headache, fever, neck stiffness, and an altered mental status, and a high percentage of patients (33%) present with focal neurologic deficits at admission.[11]

ROUTES OF SPREAD AND PATHOPHYSIOLOGY

There are 4 common routes of entry infectious agents into the CNS.[1]

1. Hematogenous dissemination from a distant infectious focus is most common.
2. Direct implantation is usually traumatic and rarely iatrogenic when microbes are introduced

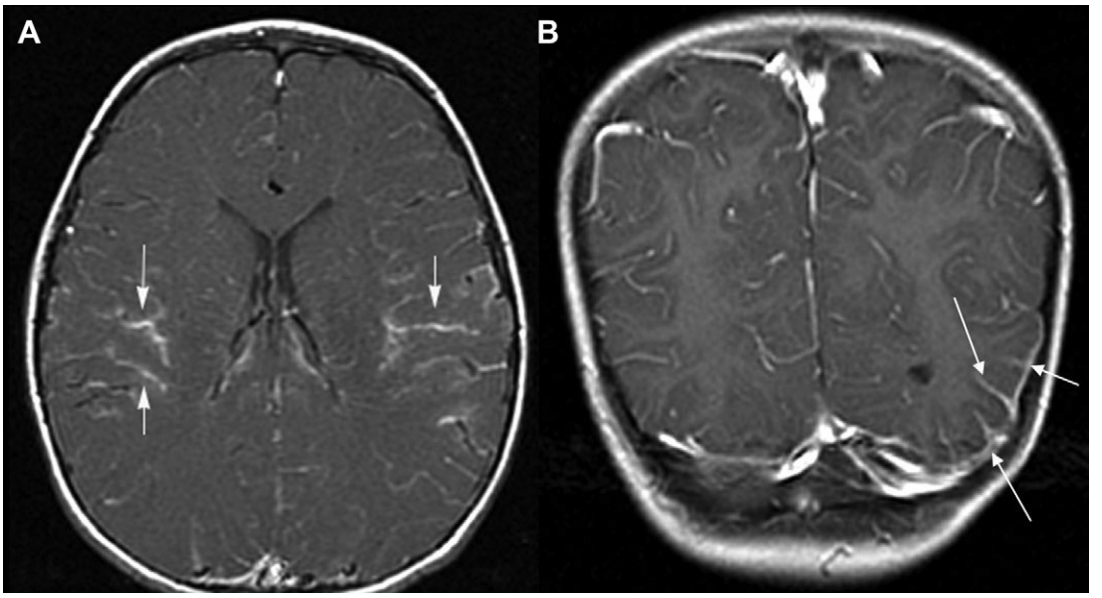

Fig. 11. Axial and coronal postcontrast T1WI (*A*, *B*) shows diffuse smooth increased meningeal enhancement along the cerebral sulci (*arrows*).

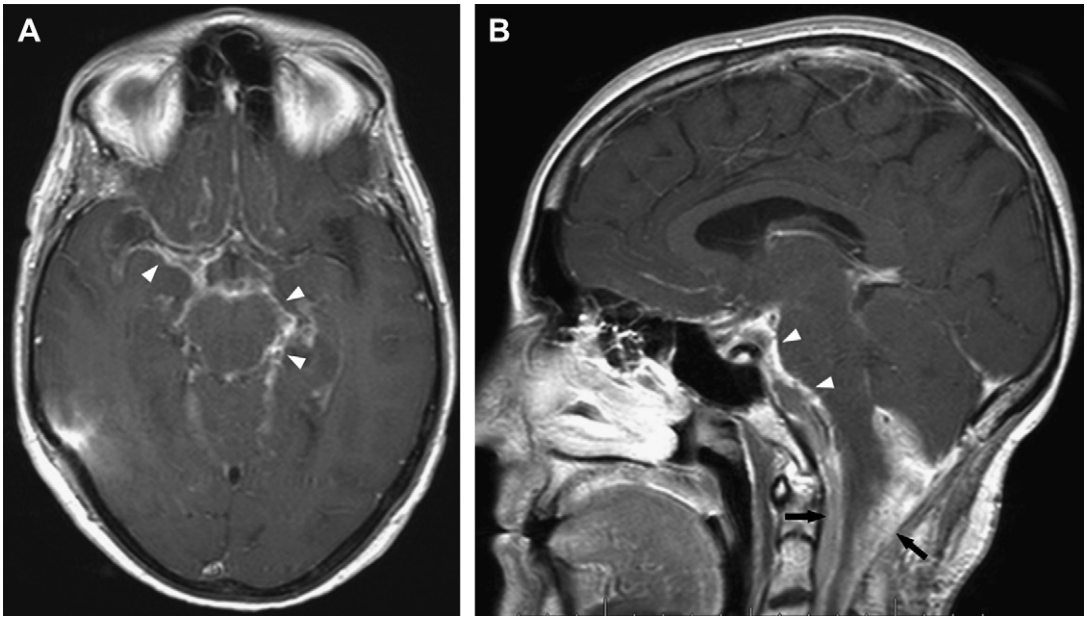

Fig. 12. Axial sagittal postcontrast T1WI (*A*, *B*) show diffuse meningeal thickening and enhancement along the basilar cisterns (*arrowheads*) and foramen magnum (*black arrows*), consistent with leptomeningeal metastasis from glioblastoma multiforme.

with a lumbar puncture needle or during surgery.

3. Local extension from sinusitis (Fig. 17), orbital cellulitis, mastoiditis (Fig. 18), otitis media, or an infected tooth is less common.
4. Spread of infection along the peripheral nervous system has also been described for certain viruses such as rabies and herpes simplex.

Other uncommon routes include inhalation, or rarely secondary to abscesses or infections in the epidural or subdural spaces. It is presumed that the infection enters the brain via the choroid plexus. Thereafter, the subarachnoid space is distended by purulent exudates that also extend into the perivascular spaces. Bacteria then stimulate the production of cytokines and other inflammatory compounds, which cause breakdown of the blood-brain barrier and allow contrast material to leak from vessels into the CSF, leading to meningeal enhancement, as seen on imaging studies.[12–15]

WHAT COMES FIRST: LUMBAR PUNCTURE OR COMPUTED TOMOGRAPHY?

Most patients who present with moderate or severe impairment of consciousness, neurologic deficits (not including cranial nerve abnormalities), or both, which are contraindications to performing lumbar puncture, should undergo computed tomography (CT) before lumbar puncture. Patients without these red flags can directly proceed to lumbar puncture if there is no clinical evidence to suggest raised intracranial pressure.[11,16]

ROLE OF IMAGING

Imaging studies are not used for the initial diagnosis of meningitis. Only 50% of patients with meningitis show subarachnoid space enhancement. Therefore, the role of neuroimaging is to confirm suspected meningitis, to rule out meningitis mimics and increased intracranial pressure before lumbar puncture, and to evaluate for complications. In cases of uncomplicated meningitis, cranial CT seems to be sufficient for clinical management to exclude acute brain edema, hydrocephalus, and disease of the base of the skull.[17] The most common signs of complicated meningitis are an enlarging head (in children) and increased intracranial pressure (persistent headache, nausea, vomiting, papilledema, and focal deficits).[12] These patients need imaging, preferably using MR imaging.

Although contrast-enhanced MR imaging has been used for many years in the evaluation of patients with complicated meningitis, during the last 5 years the introduction and widespread use of new imaging techniques have contributed significantly to the rapid and more specific diagnosis

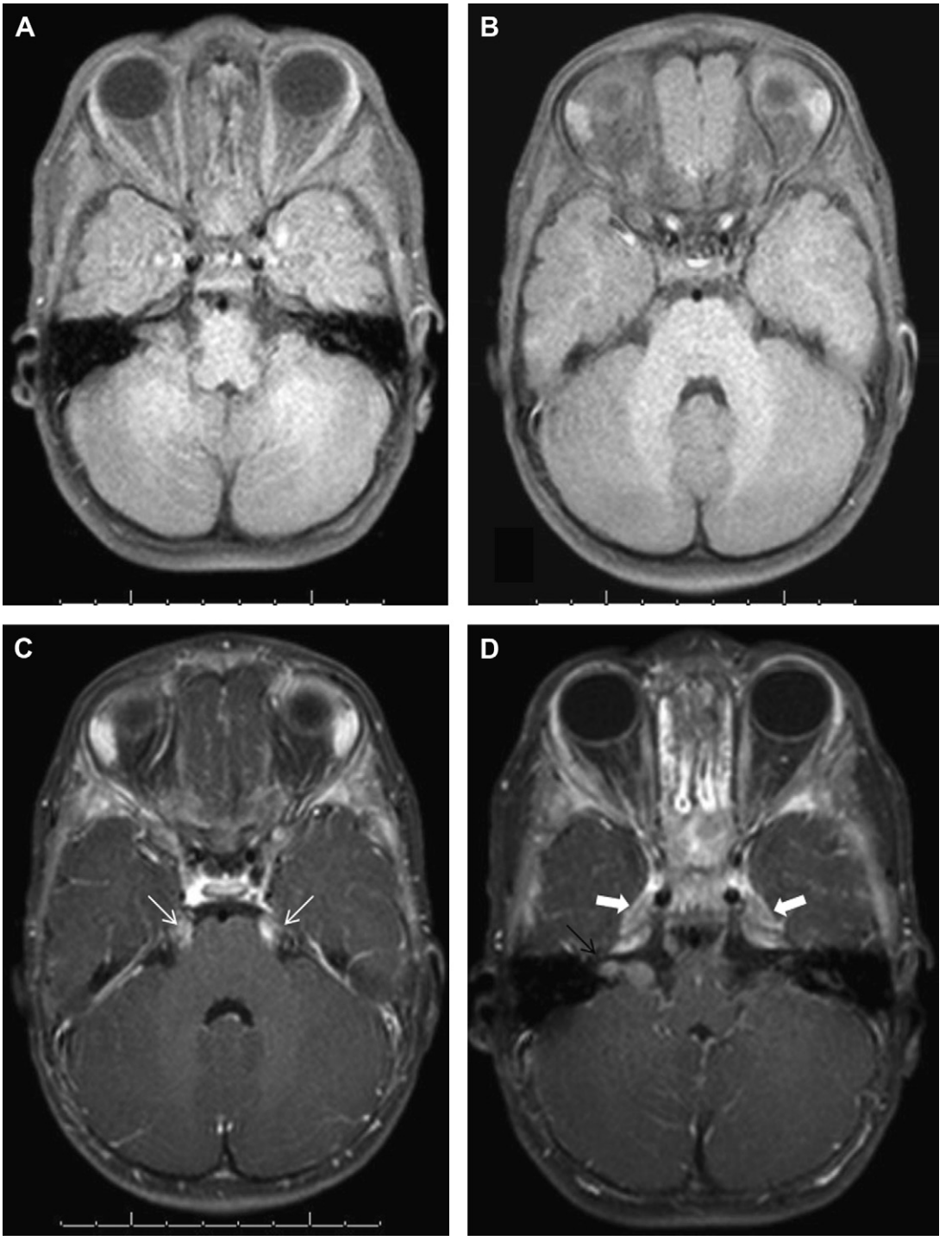

Fig. 13. Multiple cranial nerve involvement in a 1-year-old boy with acute lymphoblastic leukemia. Plain axial T1WI (*A*, *B*) and contrast-enhanced (*C*, *D*) images show enlarged, thickened and enhancing bilateral fifth (*white arrows*) and right ninth, 10th, and 11th nerve complex (*black arrow*), with expansion and enhancement of the bilateral cavernous sinus (*white block arrows*).

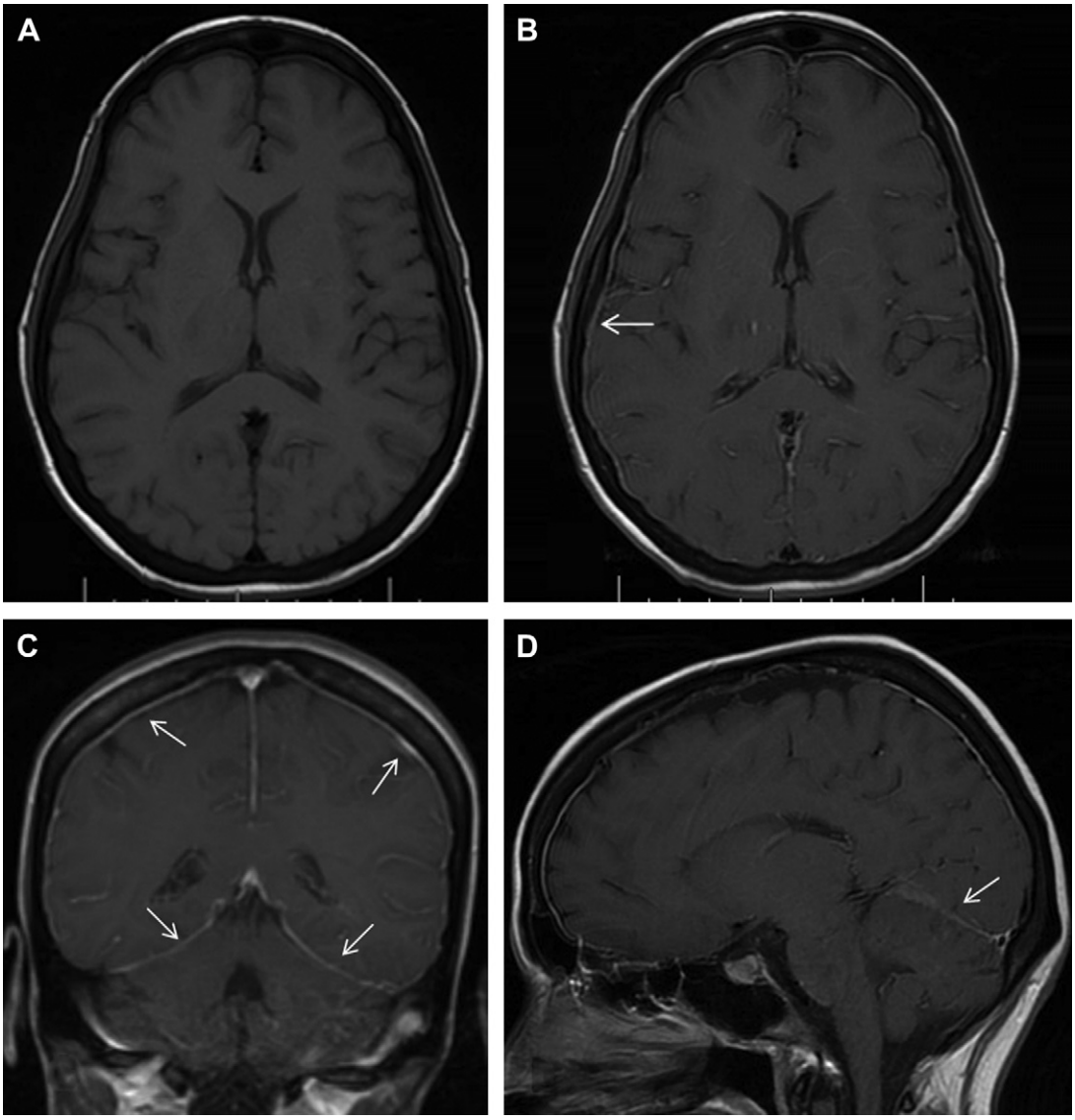

Fig. 14. Pachymeningeal enhancement in a 43-year-old man, 3 days after lumbar puncture. Pain axial T1WI (*A*) appears grossly normal; however, mildly increased pachymeningeal enhancement (*white arrows*) is seen on post-contrast axial, sagittal, and coronal T1WI (*B–D*). This enhancement resolved completely on the follow-up scan (*not shown*).

of the complications of meningitis and have helped in patient management.

INFECTIOUS MENINGITIS

Infectious meningitis is divided into the following general categories[14,15]:

1. Acute pyogenic meningitis
2. Acute lymphocytic meningitis
3. Chronic meningitis

Acute Pyogenic Meningitis

Acute pyogenic meningitis is a diffuse inflammation of the pia mater and arachnoid and is more common in children. The estimated incidence is 2.6 to 6 per 100,000 adults per year in developed countries and is up to 10 times higher in less-developed countries.[11] The diagnosis of meningitis is based on clinical and CSF analysis. CSF analysis shows neutrophilic pleocytosis and increased protein and low glucose levels. These

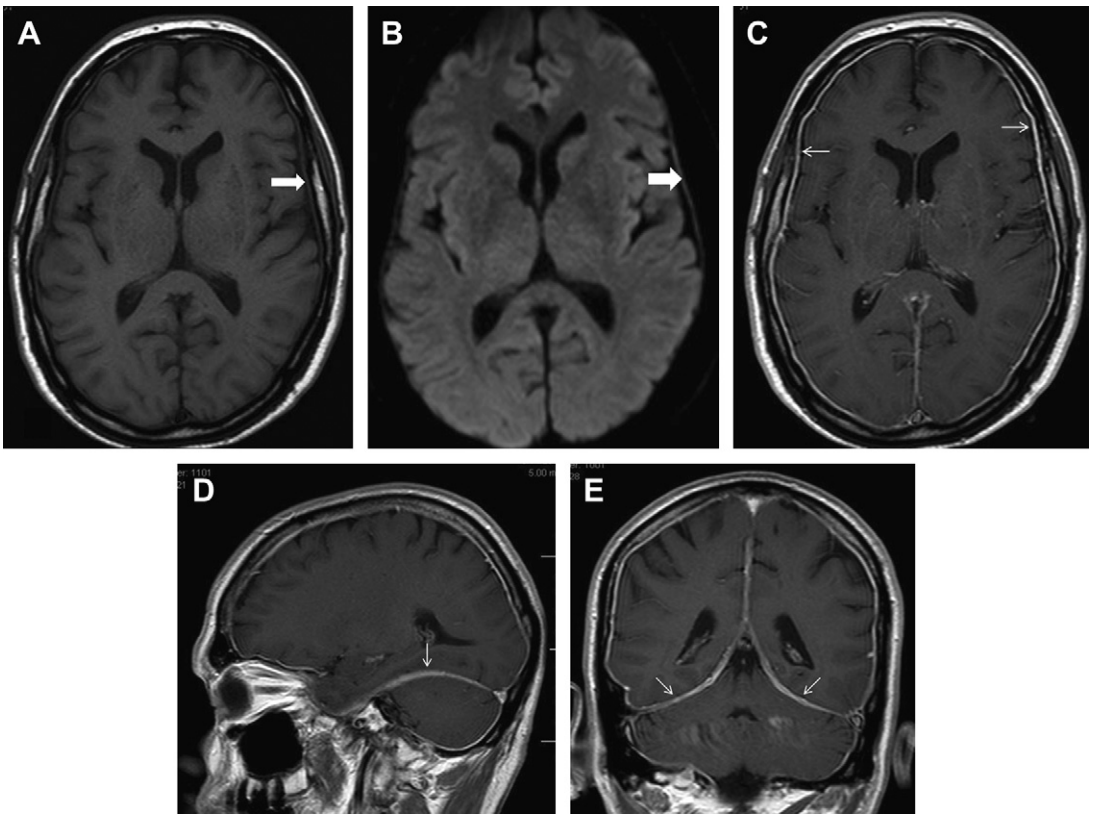

Fig. 15. Idiopathic pachymeningitis in a 46-year-old man. Axial T1WI (*A*) and DWI (*B*) show minimal dural thickening (*white block arrows*), with intense diffuse enhancement (*white arrows*) on postcontrast axial, sagittal, and coronal T1WI (*C*–*E*).

features suggest a pyogenic cause. The cause of meningitis varies according to the age of the patient and the status of their immune system. Common causative organisms of meningitis include group B streptococcus, and *Escherichia coli* (newborns), *Haemophilus influenzae* (children younger than 7 years), *Neisseria meningitidis* (older children and adolescents), and *Streptococcus*

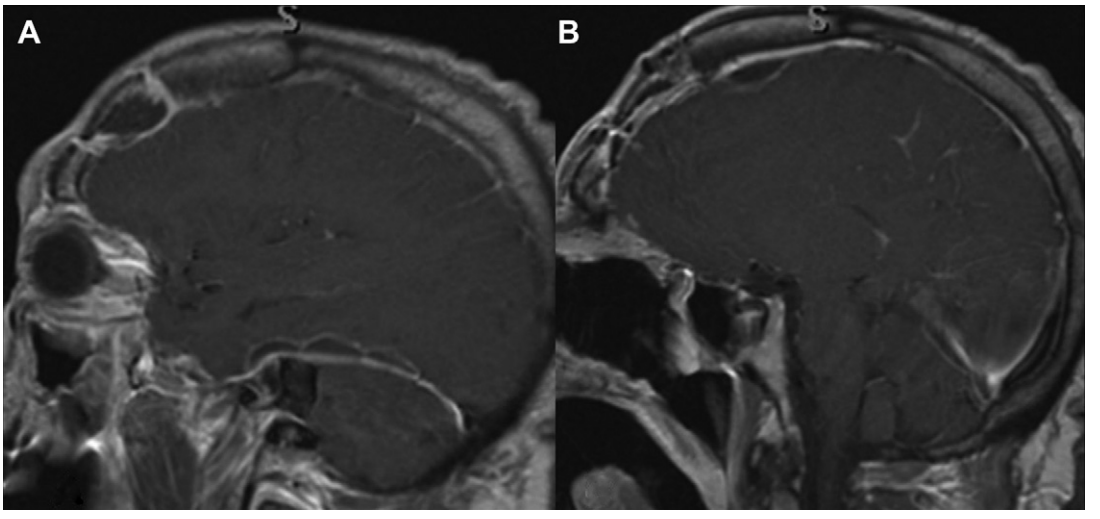

Fig. 16. Epidural and subdural empyemas in a 54-year-old woman. Postcontrast T1WI (*A*, *B*) shows epidural collection abutting frontal convexity and subdural collection along the tentorial leaf with peripheral enhancement. Increased leptomeningeal enhancement is also evident.

Box 3
Clinical features of leptomeningitis

Infants	Adults
• Altered state of consciousness	• Fever
• Anorexia	• Kernig sign
• Bulging fontanelle	• Headache
• Constipation	• Meningismus
• Failure to thrive	• Photophobia
• Fever	
• Irritability	
• Kernig sign	
• Seizures	
• Vomiting	

pneumoniae (leading cause of bacterial meningitis in adults) (see **Fig. 9**). Immunocompromised patients are prone to infections caused by *E coli*, *Klebsiella, Pseudomona*s, and fungi. Iatrogenic infections are usually the result of gram-negative microorganisms. The epidemiology of bacterial meningitis has changed. Meningitis caused by *H influenzae* type b has been nearly eliminated in the Western world since vaccination against *H influenzae* type b was initiated, and the introduction of conjugate vaccines against *Streptococcus pneumoniae* is expected to reduce the burden of childhood pneumococcal meningitis significantly.[11] Pyogenic meningitis still remains a serious disease, with high potential for permanent neurologic impairment and high overall mortality (even with treatment) of up to 20%.[11,12]

Acute Lymphocytic Meningitis

Acute lymphocytic meningitis is usually a benign and self-limited condition. It is rare in adults and is most commonly viral in origin. Common pathogens are enteroviruses and mumps viruses. Other agents include herpes simplex virus I and II, and human immunodeficiency virus (HIV).[15] Signs and symptoms such as headache, fever, and meningismus are similar to those of bacterial meningitis, but are often less severe. CSF studies show lymphocytic pleocytosis, moderate protein increase, and normal glucose.[14] Viral meningitis causes severe headache, but is usually self-limited. Imaging findings are usually normal unless coexisting encephalitis occurs (see **Fig. 10**).[14,15]

Box 4
Imaging findings in leptomeningitis

- Normal scan
- Enlargement of CSF spaces
- Poor visualization of basal cisterns
- Generalized cerebral swelling
- Diffuse meningeal enhancement
- ± Virchow-Robin spaces
- Communicating hydrocephalus
- Subdural effusion
- Focal high-signal parenchymal abnormalities secondary to infarction

Chronic Meningitis

Chronic meningitis is a smoldering process usually caused by *Mycobacterium tuberculosis* and some fungi causing an indolent infection. Infection reaches the meninges generally by hematogenous spread.[15,18] It involves predominantly basal subarachnoid spaces, which are filled with thick, gelatinous exudates containing chronic inflammatory cells, fibrin, and hemorrhage. Chronic meningitis may also have more generalized disease.[19] Most children with TBM also have concomitant miliary brain infection, and 11% of all patients have combined parenchymal/meningeal lesions.[19,20] The clinical diagnosis of TBM may be difficult. Diagnosis is dependent on CSF cytology and biochemistry, detection of acid-fast bacilli in smear and culture; however, only 8% to 30% of cases show a positive result on smear and culture. CSF studies are also nonspecific and show moderate pleocytosis with monocytosis and neutrophils and increased protein and low glucose levels.[14] Moreover, because of the low sensitivity of laboratory tests, noninvasive imaging plays an important role in diagnosis (see **Figs. 6** and **7**). Sequelae of chronic meningitis include hydrocephalus, pachymeningitis, and infarctions caused by basal vascular occlusions, cranial nerve palsies, atrophy, and calcifications.[15,20]

IMAGING IN MENINGITIS

CT and MR imaging are normal in the early disease process in most cases of acute bacterial meningitis (see **Boxes 3** and **4**). Once the infection progresses, an unenhanced CT scan shows mild dilatation of the ventricular system and subarachnoid space with diffuse cerebral swelling. Obliteration of the basal or convexity cisterns by inflammatory exudates may be seen in some cases (see **Fig. 6** and **7**). Contrast-enhanced MR imaging has been shown to be more sensitive than contrast-enhanced CT in detection of abnormal meningeal enhancement in basal cistern, sylvian fissure region, and deep within the cortical sulci.[15,21,22]

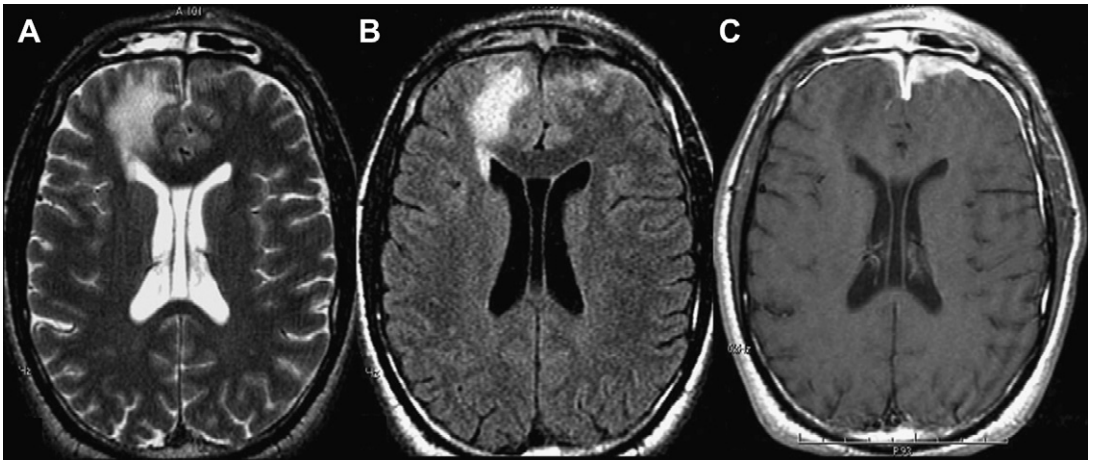

Fig. 17. Early cerebritis in a 34-year-old woman with meningitis. Axial T2WI (*A*) and FLAIR (*B*) images show focal area of hyperintensity in the right frontal lobe white matter along with the presence of mucosal hypertrophy of bilateral frontal sinuses. Axial postcontrast T1WI (*C*) shows increased pachymeningeal enhancement in bilateral frontal region, with enhancing mucosal thickening in bilateral frontal sinuses; no abnormal intraparenchymal enhancement was seen.

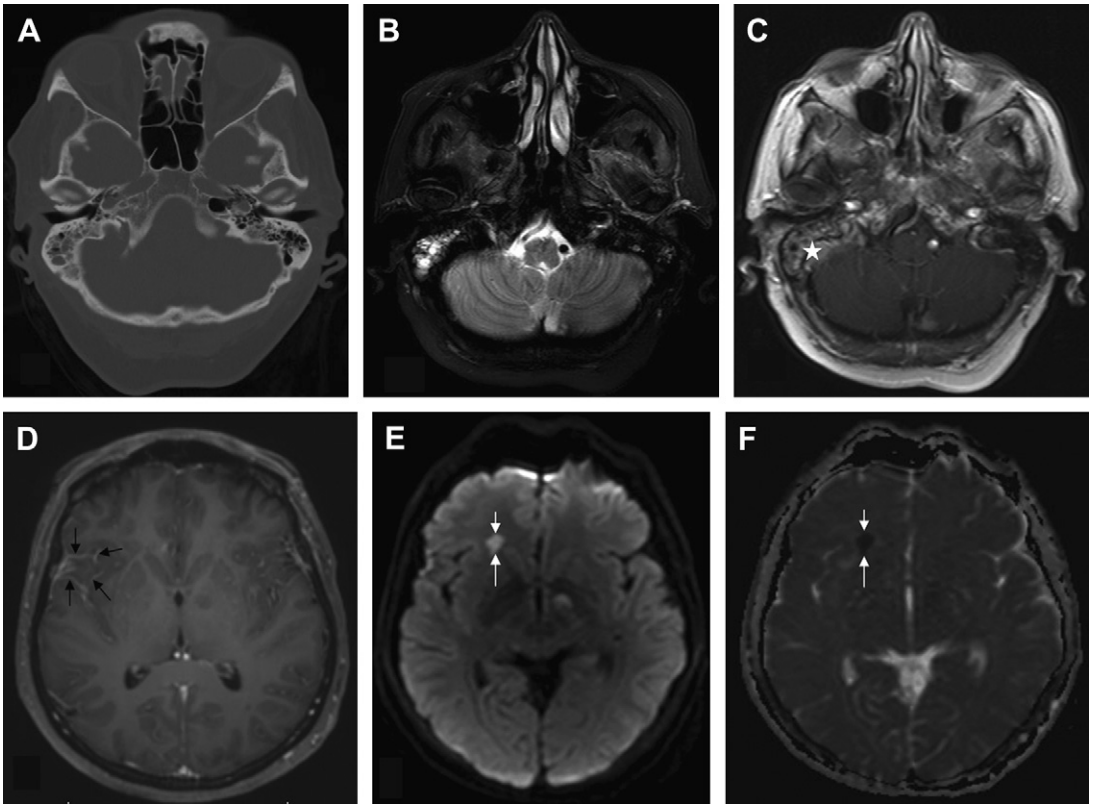

Fig. 18. Right-side mastoiditis in a 25-year-old man with meningitis and cerebritis. Axial CT (*A*), T2-weighted MR imaging (*B*) and postcontrast T1WI (*C*, *D*) showing right mastoiditis (*white asterisk*), with focal leptomeningitis in the right sylvian cistern region (*black arrows*). Focal area of cerebritis (*white arrows*) is seen in the right frontal lobe, with restricted diffusion on DWI (*E*) and ADC map (*F*); no obvious enhancement is seen on postcontrast image (*D*).

Enhancement can also be seen along the tentorium, falx, and the convexities.[22] MR imaging is superior to CT, not only in the evaluation of suspected meningitis, where precontrast T1-weighted imaging (T1WI) may show obliterated basal cisterns, but also in depicting complications such as subdural/epidural empyema and vasculitic complications, notably on fluid-attenuated inversion recovery (FLAIR) images.[17] FLAIR imaging shows leptomeningeal enhancement and CSF hyperintensity presumably caused by increased protein content (**Fig. 19**).[23] Sulcal hyperintensity on the FLAIR sequence has other differential diagnostic considerations, as listed in **Box 5**.[24]

In chronic meningitis, abnormal enhancement may be seen even years after the initial infection, and en plaque dural thickening and even popcorn-like dural calcification can be seen in some cases around the basilar cistern.[20] Sequelae of chronic meningitis include ischemic changes and atrophy, which in some cases may be striking.[21]

In acute meningitis, meningeal enhancement is preferentially located over the cerebral convexity, whereas in chronic meningitis enhancement is most prominent in the basal cisterns (**Figs. 6,7,11**).[1,25] Meningeal enhancement is a nonspecific finding, because it may be seen in meningitis of any cause, including noninfectious processes, such as carcinomatosis and chemical meningitis; however, carcinomatous meningitis typically presents with dural enhancement and thus may usually be differentiated from infectious cause.[15,26]

RECENT ADVANCES IN NEUROIMAGING OF MENINGITIS

Magnetization Transfer

The magnetization transfer (MT) technique has recently received attention as an additional sequence to differentiate TBM from meningitis with a nontuberculous cause. MT is reported to be superior to conventional SE sequences for imaging the abnormal meninges, which are seen as hyperintense on precontrast T1-weighted MT images and enhance further on postcontrast T1-weighted MT images.[27] In addition, quantification of MT ratio (MTR) helps in predicting the cause of meningitis. The MTR of these hyperintense meninges in TBM remains significantly higher than in viral meningitis. Fungal and pyogenic meningitis shows higher MTR compared with TBM.[27,28] It has also been reported that visibility of the inflamed meninges on precontrast T1-weighted MT images with low MTR is specific of TBM and differentiates it from other nontuberculous chronic meningitis.[28] The tuberculous bacteria remain laden with high lipid content, which is probably responsible for the low MTR in tubercular meningitis.

Diffusion-weighted Imaging

The newer technique of diffusion-weighted imaging (DWI) shows early parenchymal and certain extra-axial complications of meningitis earlier and with more clarity and is of help in differentiation

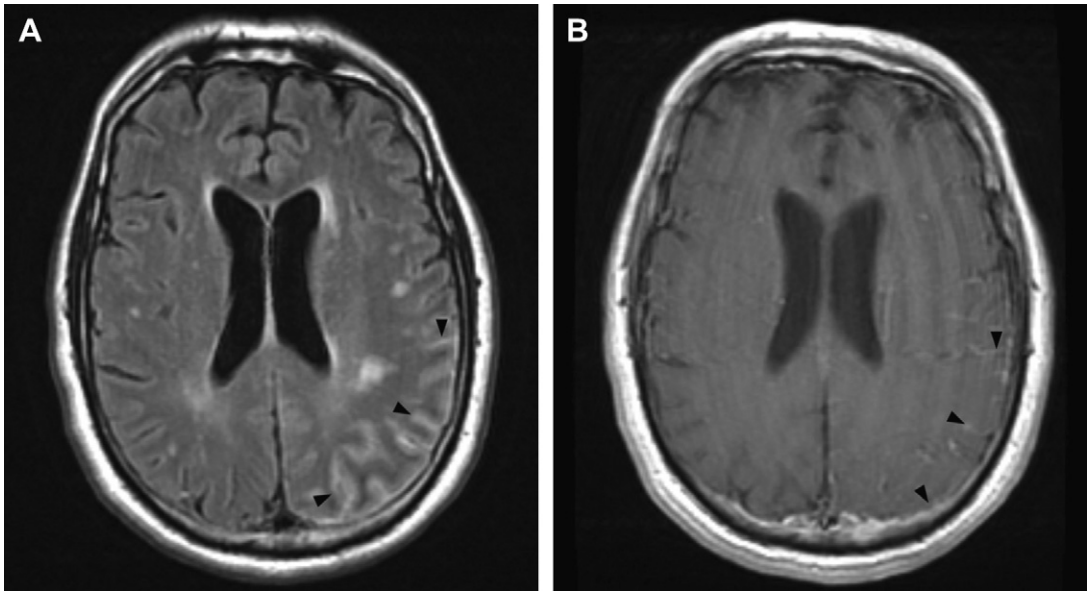

Fig. 19. (*A*) Axial FLAIR image through the brain shows increased signal along the left parietal cerebral sulci (*arrowheads*) in a patient with meningoencephalitis. (*B*) Corresponding axial T1WI shows localized pial enhancement along the parietal sulci and overlying meninges (*arrowheads*).

Box 5
Differential diagnosis of sulcal hyperintensity on FLAIR images

- Meningitis
- SAH
- Leptomeningeal carcinomatosis
- Leptomeningeal melanosis
- Fat-containing tumors
- Acute stroke
- Moyamoya disease
- Increased blood pool/CSF ratio
- Contrast media
- Supplemental oxygen
- CSF pulsation
- Vascular pulsation
- Magnetic susceptibility artifact
- Motion artifact

of pyogenic abscess from other ring-enhancing lesions.[17] Evidence of restricted diffusion on DWI with reduced apparent diffusion coefficient (ADC) is highly suggestive of brain abscess; however, in the absence of restriction, proton MR spectroscopy is useful to distinguish brain abscesses from cystic tumors.[29]

In Vivo Proton MR Spectroscopy

Although there is no published study of in vivo MR spectroscopy (MRS) in meningitis, ex vivo spectroscopy of CSF has been attempted in TBM.[30] High-resolution ex vivo MRS of CSF showed presence of Lac, acetate, and sugars along with the signals from cyclopropyl rings (–0.5 to +0.5 ppm) and phenolic glycolipids (7.1 and 7.4 ppm); these have not been observed with pyogenic meningitis. The combination of ex vivo MRS with MR imaging (possibly MT imaging) may be of value in the diagnosis of TBM.

Diffusion Tensor Imaging

Although conventional MR imaging is more sensitive to perceiving secondary complications of meningitis, it is insensitive to subtle changes in tissue microstructure. Diffusion tensor imaging (DTI) is a relatively new MR imaging technique, which has been shown to provide tissue microstructural information. The commonly used DTI-derived metrics are fractional anisotropy (FA) and mean diffusivity (MD). High FA values have been shown in enhancing as well as nonenhancing cortical ribbon in neonatal and adult patients with bacterial meningitis compared with age-matched controls.[31,32] These investigators have proposed that the oriented inflammatory cells in the subarachnoid space caused by upregulated immune response in meningitis are responsible for increased FA values. Increased FA values in the enhancing as well as nonenhancing cortical regions suggest diffuse inflammatory activity in the pia-arachnoid in patients with meningitis. They also suggest that FA may be a better indicator of active and diffuse meningeal inflammation than postcontrast T1WI. The inflammatory molecules like soluble intracellular adhesion molecules, tumor necrosis factor α, and interleukin 1β in the CSF of neonatal meningitis have shown strong correlation with FA values in the cortical region, confirming that the increased FA values may be used as a surrogate marker of inflammatory molecules in meningitis.[33] Periventricular white matter of neonatal brain is known to be vulnerable to oxidative and hypoxic/ischemic injury secondary to neuroinfections. A recent DTI study has reported decreased FA values in the periventricular white matter regions of neonates with bacterial meningitis compared with age-matched/sex-matched healthy controls, suggesting microstructural white matter injury.[34]

CRYPTOCOCCOSIS

Cryptococcus neoformans, an encapsulated yeastlike fungus infection, may occur in immunocompetent individuals but is more common in immunocompromised patients.[35–37] It is a ubiquitous organism found in mammal and bird feces, particularly in pigeon droppings.[38,39] It represents the most common fungal CNS infection in AIDS, occurring in approximately 5% to 10% of patients.[37] The infection is acquired through inhalation and then disseminates hematogenously from the lung to the CNS, with pathogenesis similar to that of TBM.[37,40,41] CNS is the preferred site for cryptococcal infection because anticryptococcal factors present in serum are absent in CSF and the polysaccharide capsule of the fungus protects it from host inflammatory response.[35] Most patients with CNS cryptococcosis present with symptoms and signs of subacute meningitis or meningoencephalitis.[35,39] Immunocompetent patients tend to present with localized, indolent neurologic disease and more intense inflammatory responses, but have a better clinical outcome.[42]

CNS infection can be either meningeal or parenchymal.[43] Imaging findings are variable and frequently minimal. MR and CT abnormalities range

from no abnormality to meningeal enhancement (**Fig. 20**), abscesses, intraventricular or intraparenchymal cryptococcomas, gelatinous pseudocysts, or hydrocephalus.[35,36,44] Hydrocephalus is the most common, although nonspecific, finding. Intraparenchymal and intraventricular mass lesions are less common,[44] because cryptococcus extends from the subarachnoid space along the perivascular (Virchow-Robin) spaces, which become dilated, resulting in pseudocyst formation without involvement of the brain parenchyma (**Fig. 20**). These widened perivascular spaces are visualized as hypodensities on CT and have CSF intensity on both T1WI and T2WI, which fail to enhance.[36,37] Evidence of clusters of these cysts in the basal ganglia and thalami strongly suggests cryptococcal infection.[43] Cerebral infarctions may occur in 4% of patients with cryptococcal meningitis in the acute stage and during the treatment and are usually observed in the basal ganglia, internal capsule, and thalamus.[45]

PARASITIC MENINGITIS

Parasitic diseases are common among tourists, immigrants from areas with highly endemic infection, and immunocompromised people.

CYSTICERCOSIS

Cysticercosis is the most common and most widely disseminated parasitic infection in the world, and is caused by ingestion of the ova of pork tapeworm (*Taenia solium*).[46] Humans become the intermediate host after ingestion of ova, usually on contaminated vegetables or water; however, the main intermediate host of *T solium* is pig. Humans can also become the definitive host when poorly cooked pork infected with cysticercosis is ingested. When the eggs mature, larvae are released into the bloodstream, causing neurocysticercosis. The common locations include subarachnoid spaces, typically the basal cisterns and deep within the sulci, hemispheric parenchyma at the gray matter–white matter interface and in the ventricles (the fourth ventricle is most common) or combination of these sites.[15,21,37,47]

Three clinicopathologic forms may be identified: meningobasilar (55%), ventricular (15%), and parenchymal (30%).[48]

Cysticercal meningoencephalitis is caused by infiltration of the meninges and the parenchyma of the brain by many parasites, and inflammation in the surrounding tissue is responsible for meningitis and encephalitis.[49,50] Around 60% of cysticercal meningoencephalitis cases have been reported to have associated parenchymal lesions.[51] Most cases described are chronic in evolution,[52] and isolated acute meningitis is rare.[53] The diagnosis, suggested by epidemiologic and clinical findings, is confirmed by specific serologic tests,[54,55] and by imaging.[56–58] The presence of CSF eosinophilia and the coexistent inflammatory granuloma suggests the possibility of cysticercal meningitis. Cysticercosis is the commonest cause of CSF eosinophilia in endemic areas.[49] Other causes of eosinophilic meningitis are listed in **Box 6**.

Helminthic Eosinophilic Meningitis

Eosinophilic meningitis is a rare clinical entity and is defined by the presence of 10 or more eosinophils/L in the CSF or a CSF eosinophilia of at least 10%. The most common cause is invasion of the CNS by helminthic parasites, particularly *A cantonensis*, but other infections as well as noninfectious conditions may also be associated (see **Box 6**).[59,60]

A cantonensis, or rat lungworm, infection occurs by eating poorly cooked or raw fish, slugs, snails,

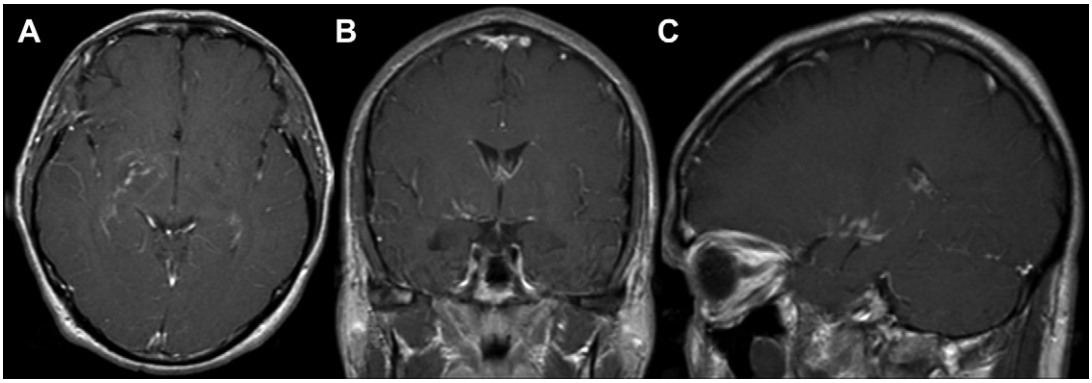

Fig. 20. Cryptococcal meningoencephalitis in an immunocompetent patient. Postcontrast axial, coronal, and sagittal images (*A–C*) show increased leptomeningeal enhancement. CSF showed India ink positive yeast, and culture confirmed it to be *Cryptococcus neoformans*.

Box 6
Causes of eosinophilic meningitis

- Coccidioidal meningitis
- *Angiostrongylus cantonensis*
- *Paragonimus westermani*
- *Gnathostoma spinigerum*
- Intrathecal injection of foreign proteins
- Insertion of rubber tubing into the CNS in the course of neurosurgery

or vegetables contaminated by infected rat, and humans are accidental hosts. Angiostrongyliasis is diagnosed by a history of exposure, CSF finding, and serology. CSF shows eosinophilia-increased protein with normal sugar level. A CT scan is usually normal. MR imaging may show prominence of Virchow-Robin spaces, periventricular hyperintense T2 signals, and enhancing subcortical lesions. Proton MRS may show decreased choline in the lesions. Diagnosis is confirmed by showing the larvae from CNS and by Western blot analysis to identify the presence of antibodies against *A cantonensis* in either the acute or convalescent phase of the illness. The prognosis is generally good and most symptoms resolve within weeks, and long-term sequelae are rare.[60,61]

G spinigerum, a gastrointestinal parasite of wild and domestic dogs and cats, may cause eosinophilic meningoencephalitis. This situation is common in Southeast Asia, China, and Japan but has been reported sporadically worldwide. Humans acquire the infection after ingestion of undercooked infected fish and poultry.[60]

B procyonis is an ascarid parasite that is prevalent in the raccoon populations in the United States and rarely causes human eosinophilic meningoencephalitis. Human infections occur after accidental ingestion of food products contaminated with raccoon feces.[60]

Amoebic Meningoencephalitis

Infection with free-living amoebas (eg, *Acanthamoeba, Balamuthia*, and *Naegleria*) is an infrequent but often life-threatening human illness, even in immunocompetent individuals, with nonspecific imaging findings.[62] *N fowleri* is the only recognized human pathogenic species of *Naegleria*, and it is the agent of primary amoebic meningoencephalitis. The parasite has been isolated in lakes, pools, ponds, rivers, tap water, and soil. Infection occurs when swimming or playing in the contaminated water sources. The *N fowleri* amoebas invade the CNS through the nasal mucosa and cribriform plate.[62]

Toxoplasmosis

Toxoplasmosis is caused by an obligate intracellular protozoan, *Toxoplasma gondii*. This is the most frequent opportunistic infection in patients with HIV. Toxoplasmosis is frequently multifocal, has a predilection for basal ganglia, does not show periventricular spread, and may occasionally hemorrhage. Infection may be acquired prenatally and may present with multiple small calcified lesions scattered in the parenchyma as well as in the periventricular region with hydrocephalus.[15,36,37] Although toxoplasmosis meningitis has been described, it is rare. In some series, the incidence of toxoplasmic meningoencephalitis has been reported from 3% to 50% in HIV-positive patients.[63] Because toxoplasmic meningitis is rare, purulent or TBM, lymphoma, and other infections should be considered in the differential diagnosis. The diagnosis is established with both serologic tests and histopathologic examinations.[64]

Neurosyphilis

Syphilis is usually a sexually transmitted disease caused by the spirochete *Treponema pallidum*. Three well-characterized clinical phases have been described; although CNS involvement can occur in any phase, it usually occurs in the tertiary stage. Neurosyphilis usually results from small vessel end arteritis of the meninges, brain, and spinal cord.[21,22] Acute syphilitic meningitis is a common manifestation in HIV-positive patients who are infected by *Treponema pallidum*.[22] Making the diagnosis is often difficult, because most patients are either asymptomatic or present with nonspecific symptoms, and there is a wide range of neuroimaging findings.[18,65,66] Neurosyphilis can be divided into (1) meningovascular syphilis and (2) syphilitic gumma.[22]

The meningovascular syphilis presents with widespread thickening of the meninges, with lymphocytic infiltration around the meninges and small vessels. This situation leads to cortical and subcortical infarcts in the basal ganglia and middle cerebral artery territories along with varying degrees of narrowing and ectasia of the basilar, proximal anterior cerebral, middle cerebral, and supraclinoid carotid arteries.[65] CT shows multiple low-density areas involving both gray and white matter with linear nonhomogenous enhancement. MR imaging is superior to CT and shows a gyriform pattern of enhancement along with meningeal enhancement.[37] The manifestations of syphilitic gumma include leptomeningeal granulomas, known as gummata in the meninges and blood vessels, which may also occur intra-axially into

the brain parenchyma and be indistinguishable from primary brain tumors, meningiomas, or sarcoidosis.[65–67] Bilateral mesial temporal T2 hyperintensity has recently been reported in neurosyphilis, and represents an important although rare differential diagnostic consideration for characteristic herpes simplex encephalitis MR imaging findings.[37,68] Cranial nerve involvement has also been reported, with optic and vestibulocochlear nerves most commonly affected.[21] Later stages may show cerebral atrophy.[21,22]

Neuroborreliosis (Lyme Disease)

Lyme disease is caused by the spirochete *Borrelia burgdorferi*, transmitted most commonly by the deer tick (*Ixodes dammini*), and is endemic in 3 regions in the United States (the coastal northeast states [from Massachusetts to Maryland], the midwest [Minnesota and Wisconsin], and the west [California, Oregon, Utah, and Nevada]), certain parts of Europe, and Asia.[69–72] Approximately 10% to 15% of patients develop variable neurologic symptoms, ranging from meningitis, encephalopathy, cranial nerve palsies, and radiculoneuropathy.[73,74] The pathophysiology includes direct invasion of the parenchyma, or a vasculitic or immunologic process.[75] Diagnosis is based on clinical findings and serology and the most likely diagnosis in patients with moderate pleocytosis, high protein, and intrathecal immunoglobulin synthesis is neuroborreliosis in endemic areas.

On MR imaging, findings include (1) most commonly a normal scan; (2) high-signal abnormalities on T2 and FLAIR, which can vary in size from punctuate to large mass lesions; and (3) contrast-enhancing parenchymal lesions, meninges, labyrinth, and cranial nerves. Other abnormalities include hydrocephalus and high intensity in the pons, thalamus, or basal ganglia.[76–78]

Lymphocytic meningoradiculitis or Garin-Bujadoux-Bannwarth syndrome is a European variety of Lyme disease and is clinically characterized by severe radicular pains with sensory and motor impairment and cranial nerve palsies, especially unilateral or bilateral facial weakness. The disease is often self-limiting, and in some cases it may be difficult to distinguish Bannwarth syndrome from neurosyphilis.[79,80]

COMPLICATIONS OF MENINGITIS

Complications of bacterial meningitis include hydrocephalus, ventriculitis, extra-axial collections (sterile subdural effusion, subdural/epidural empyema), cerebritis, and abscess, edema with or without cerebral herniation, cranial nerve involvement, thrombosis/infarction, and vasculopathy.[1,15,21,81]

Hydrocephalus

A mild, transient communicating hydrocephalus is the most common complication in patients with meningitis.[82] It may develop either because of the blockage of CSF resorption in the Pachionian granulations by inflammatory debris (extraventricular or communicating hydrocephalus) or related to aqueductal obstruction (intraventricular or noncommunicating hydrocephalus).[1,12] It is easily detected by CT or MR imaging; however, in infants, cranial ultrasonography may be used for this purpose. The most useful indicators are dilatation of the third ventricle or temporal horns.[81] In some patients, the ventricular system remains dilated and never returns to normal, so-called arrested hydrocephalus, which requires no therapy (see **Fig. 6**). A CSF-shunting procedure may be required in some patients to avoid permanent CNS injury or death from brain herniation.[1,12]

Extra-axial Collections

Extra-axial fluid collections can be sterile (effusions) or infected/purulent (empyema).[83] Subdural effusion is a common complication and is seen in up to one-third of patients with meningitis. It is most commonly seen with pneumococcal infection.[81] These effusions are believed to be caused by irritation of the dura mater by infectious agents and their products, or secondary to inflammation of subdural veins.[83] It must be differentiated from the normal prominent subarachnoid spaces often seen in infants by the presence of veins coursing through the collection, which indicates that the fluid is located in the subarachnoid space. These collections usually occur along the frontal and temporal convexities, and tend to resolve spontaneously over weeks to months. Some may require drainage, mostly when they are large and result in mass effect.[12] On CT and MR imaging, these effusions are seen as crescentic extra-axial fluid collections and show the same density and signal intensity as CSF (see **Figs. 8**, **9** and **16**).[1,15] Some effusions develop a fibrin network and membranes and may show peripheral or central enhancement on contrast-enhanced MR imaging, which makes it difficult to distinguish them from empyema.[81] Empyema is an uncommon collection, which occurs secondary to meningitis, sinusitis, otitis media, osteomyelitis, and trauma.[83] Persistence of neurologic findings suggests the likelihood of an empyema. Empyema generally needs to be drained surgically.[12] Subdural empyema is the

collection of pus between the dura and the leptomeninges and can be found over the convexities or interhemispherically. It occurs usually secondary to retrograde thrombophlebitis via the calvarial emissary veins from an adjacent infection.[1,83] Approximately up to 15% of all subdural fluid collections become or are empyema.[12] CT shows a hypodense or isodense, crescentric or lenticular extra-axial collection slightly denser than CSF. MR imaging is more sensitive than CT for delineating such collections. Compared with sterile collections, empyema may show slightly higher signal intensity on T1WI and especially FLAIR images. Contrast-enhanced CT and MR imaging show an intensely enhancing membrane surrounding the empyema.[12,83] High T2 signal intensity in the underlying cortex and presence of neighboring venous thrombosis, infarction, cerebritis, and abscess also support the diagnosis of subdural empyema. Similar to abscesses, empyemas are typically bright on DWI (see **Fig. 9**), consistent with restricted diffusion of pus, whereas sterile collections are similar to CSF.[84]

In epidural empyema, collection of pus occurs between the dura and calvaria. These patients have a more insidious and benign course because the dura acts as a barrier, protecting brain parenchyma from complications. This situation also explains the occasional presence of low or mixed signal intensity on DWI, because the pus becomes less viscous.[25,83] It shows similar signal characteristics on T1-weighted and T2-weighted images and the attenuation in CT, as for subdural empyema. Contrast administration shows a thick dural enhancement. Imaging studies may also show displacement of falx and dural sinuses away from the inner table, indicating epidural location of the collection.[1,15,83]

Cerebritis and Abscesses

Cerebritis and abscesses may have a variety of causes. In the context of the present discussion, spread by contiguous infection of the meninges by retrograde thrombophlebitis, or direct extension into the brain via the pia mater or along the perivascular spaces may occur in the later stages of the infectious process.[1] Initially, there is an area of focal cerebritis, characterized by vascular congestion, petechial hemorrhage, and edema.[12] CT shows an ill-defined area of low attenuation with subtle mass effect. It shows prolonged T1 and T2 signal intensity on MR images and little or no contrast enhancement (see **Figs. 17** and **18**; **Fig. 21**).[37,83] Because there is no purulent fluid, the key diagnostic sequence is DWI, with marked diffusion restriction, which might be attributed to hypercellularity from abundant infiltration of inflammatory cells, brain ischemia, or cytotoxic edema.[85] As the brain attempts to contain the infection, a capsule of collagen and granulation tissue is formed, the central portion undergoes liquefactive necrosis, and abscess develops.[1] These abscesses are commonly located at the gray matter–white matter junction, mostly in the frontal and temporal lobes.[12,86] Approximately 90% of abscesses are pyogenic, and despite the antibiotic treatment, the mortality remains as high as 14%.[12] Clinical diagnosis remains challenging, because the signs and symptoms often are nonspecific and usually overlap with the presence of a focal mass lesion.[67,86] In the initial stages of abscess formation, there is an incomplete rim of enhancement, which allows antibiotics to penetrate, and many lesions are arrested at this stage.[12] In due course, a mature abscess may form. Imaging at this stage shows a well-defined, smooth, complete capsular ring, which enhances

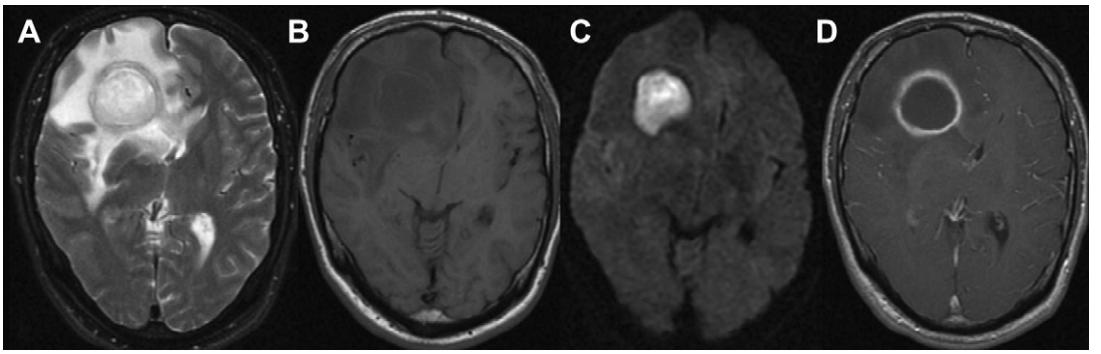

Fig. 21. Cerebral abscess in a 46-year-old man who presented with seizures and fever. Axial T2WI (*A*) at the level of ventricles showing a heterogeneous intensity lesion with surrounding edema in right frontal region. The lesion is hypointense on T1WI (*B*), with peripheral enhancement on postcontrast T1WI (*D*). On DWI (*C*), the lesion shows restricted diffusion. Pus culture grew *Staphylococcus aureus*.

strongly on contrast study. It is visualized as a thin, markedly hypointense ring on T2-weighted MR images, with prominent surrounding vasogenic edema.[12,87] The low T2-weighted signal intensity of the abscess rim is believed to be secondary to the presence of paramagnetic oxygen-free radicals inside macrophages.[12] The proteinaceous, necrotic fluid within the abscess cavity is hyperintense to CSF on T1 and FLAIR. Ring-enhancing brain lesions are nonspecific and need to be distinguished from other cystic lesions, primarily necrotic neoplasms.[37] In contrast to other ring-enhancing lesions, an abscess has a tendency to grow into the white matter, hence the abscess wall is usually thinner on the side that is closer to the ventricular system. The capsule is also generally smoother on the outside than on the inside.[12,25] On DWI, brain abscesses are seen as strong hyperintense foci with reduced ADC values (see **Fig. 18**). DWI is particularly useful in differentiating brain abscesses from necrotic or cystic tumor. Necrotic or cystic tumors generally have low to intermediate DWI signal and increased ADC values; however, cases of metastatic brain tumors with DWI hyperintensity and low ADC values have also been described.[88–90] In a recent study using DTI, it was shown that brain abscess cavity shows regions of increased FA values with restricted MD, compared with other cystic intracranial lesions. High FA in the brain abscess suggests inflammatory cell adhesion as a result of the presence of neuroinflammatory molecules, which suggests active inflammation. Hence DTI-derived FA could be used as potential surrogate marker of noninvasively assessing disease activity in patients with brain abscesses.[91] A perfusion MR study may also distinguish brain abscesses that show relative decrease in cerebral blood volume (CBV) from neoplasms, which show significantly increased CBV.[92] On MRS, spectra from brain abscesses reveal increased peaks of acetate (1.92 ppm), succinate (2.4 ppm), lactate (1.3 ppm), and other amino acids (0.9 ppm).[91] Main brain metabolites like *N*-acetylaspartate, creatine, and choline are usually not detectable. Although resonances of amino acids and lactate are seen in all bacterial abscesses, presence of acetate and succinate suggests anaerobic bacterial infection.[93]

Cranial Nerve Involvement

Cranial nerve dysfunction is likely related to direct inflammation or the result of direct stretching or pressure caused by shift of intracranial structures. The eighth nerve (vestibulocochlear) is most commonly affected and some degree of sensorineural hearing loss occurs in up to 30% of patients. It is most common after infection with *Streptococcus pneumoniae*. There is usually bilateral involvement, and once hearing loss occurs, it tends to be permanent. Hearing loss is probably the result of the spread of infection to the inner ear.[94] Other commonly affected nerves are the seventh (facial) and third (oculomotor) nerve. Second (optic) nerve involvement may occur, but is usually transient. Transient palsy of the sixth nerve can be seen as a sign of increased intracranial pressure or related to complication of lumbar puncture.

There are no specific imaging features for cranial nerve involvement in patients with pyogenic meningitis. In the chronic phase, CT may show sclerosis of the inner ear structures (labyrinthitis ossificans). However, thin-section T2-weighted MR imaging may show lack of normal high signal of the endolymph and perilymph in the labyrinth, before these changes become obvious on CT.[12] In addition, conductive-type hearing loss may be present in meningitis, secondary to middle ear infection or use of ototoxic antibiotics.[12]

Thrombosis and Infarct

Venous thrombosis results in cerebral infarctions in up to 30% of affected patients and is more commonly seen in children. It may arise as a direct consequence of meningitis or secondary to adjacent mastoiditis, which itself is a cause of meningitis.[12] It may affect the cortical venous sinuses or the cortical veins. The clinical manifestations of venous thrombosis are highly variable, ranging from no change in alertness, developing mild confusion, or progressing to coma. Focal neurologic deficits have also been described depending on the area of the involvement. Cranial nerve findings can also be present.[81] Venous infarcts involve nonarterial territories and are usually bilateral, show multiplicity, and tend to occur in the convexities. Areas of hemorrhage are seen in up to 25% of patients. On imaging, acute thrombosis of cortical veins or sinuses shows high attenuation on CT and is seen as high signal on T1-weighted MR images or as filling defects on MR or CT venography. Many venous infarcts are seen as nonspecific areas of high T2 signal intensity and are difficult to distinguish from areas of cerebritis. Because the identification of thrombosed cortical vein is difficult, many venous infarctions are only presumed diagnoses. DWI findings are also variable and are not predictive of infarction. Hemorrhages within these infarcts further affect ADC calculations.[95]

Vasculopathy

Cerebral infarcts associated with meningitis occur because of inflammatory-induced arterial spasms or because of direct inflammation of the walls of arteries/arterioles ending with an infectious arteritis and tend to affect the basal ganglia. However, occlusion of the large arterial branch can occur, resulting in cortical infarctions.[1] Narrowing and spasm of the larger-caliber arteries, irregularities of medium-size arteries, and occlusion of distal branches can be seen on catheter or MR angiography.[12]

VENTRICULITIS

Ventriculitis is a rare cerebral infection that has been variably referred to as ependymitis, intraventricular abscess, ventricular empyema, and pyocephalus.[96–100] With the increasing incidence of bacterial meningitis over the last 30 years because of nosocomial infections, the number of cases of ventriculitis is also likely to increase.[101] It is seen in 30% of all patients and is more common in the younger age group.[12,81] The 2 most common microorganisms causing ventriculitis are *Staphylococcus* and *Enterobacter*.[100]

There are multiple possible routes through which a pathogen might enter the intraventricular system, including direct implantation secondary to trauma or neurosurgical procedures, such as ventricular catheter placement; contiguous extension, such as rupture of a brain abscess; and extension into the ventricles and hematogenous spread to the subependyma or the choroid plexus.[1,97,101] Backflow of CSF from the extraventricular spaces into the intraventricular space might be considered as another possible route of infection leading to ventriculitis. This could be a potential explanation for the observation that ventriculitis is often associated with meningitis.[102]

Ventriculitis is important to recognize because its signs and symptoms may be subtle, its course can be indolent but lethal, and it is a potential source of persistent infection, even when meningitis is treated.[103–105] Early diagnosis is essential for the appropriate treatment of this life-threatening condition. Neuroimaging is one of the available diagnostic tools besides laboratory investigations that play an important role in diagnosing this condition.

Cranial sonography is a useful imaging modality in the evaluation of ventriculitis, especially in infants. The most common findings include an irregular and echogenic ependyma, the presence of intraventricular debris and stranding, often associated with ventricular dilatation. Intraventricular adhesions and septae are seen as chronic complications of meningitis in about 10% of patients and their identification is important in planning for appropriate shunt placement. Sonography often shows them better than CT.[106–109]

On MR imaging, the ependyma is thick and enhances markedly (**Fig. 22**). The ventricular walls frequently show high T2 signal intensity, the ventricles themselves may be dilated, and debris are usually seen in their dependent portions.[100] Usually, these debris are of high signal on DWI, with reduced ADC value (see **Fig. 22**), and are seen as fluid levels of high signal intensity on FLAIR images.[100,110] However, higher ADC values might be observed when pus is diluted by nonpurulent CSF.[110] Presence of irregular ventricular debris is especially characteristic of ventriculitis. CT findings are similar to those of MR imaging. Intraventricular adhesions and septae may entrap portions of the ventricles and result in segmental dilation.[12,81] Choroid plexitis is another finding associated with ventriculitis. Imaging findings include a poorly defined margin of a swollen choroid plexus and enhancement on contrast study.[111] Unlike viral infections, pyogenic ventriculitis almost never results in periventricular calcifications.[12]

NONINFECTIOUS MENINGITIS

A diverse group of noninfectious processes can mimic CNS infections. Clinical manifestations primarily take the form of a chronic meningitic syndrome. They usually present with subacute onset, headache, fever, and stiff neck. Encephalitic signs also can occur, and seizures are not uncommon. CSF is marked by increased protein and decreased glucose levels, and usually lymphocytic pleocytosis.

Mild meningeal enhancement is present in most patients after neurosurgery, and should not be interpreted as meningitis. Leptomeningeal enhancement is rare after a lumbar puncture, and in the appropriate clinical setting, meningitis needs to be considered in such patients.[1]

Chemical Meningitis

The concept of chemical meningitis was first described by Cushing in 1920,[112] when he noted waves of fever after operating on cerebellar tumors. Chemical meningitis occurs in response to a nonbacterial irritant introduced into the subarachnoid space (eg, blood, dermoid cyst rupture and methotrexate instillation). Evaluation of CSF in these patients showed leukocytosis, increased protein low glucose levels, and negative cultures.[113]

Recurrent Meningitis

Recurrent meningitis is more common in adults and is said to have an incidence of 8%, and about

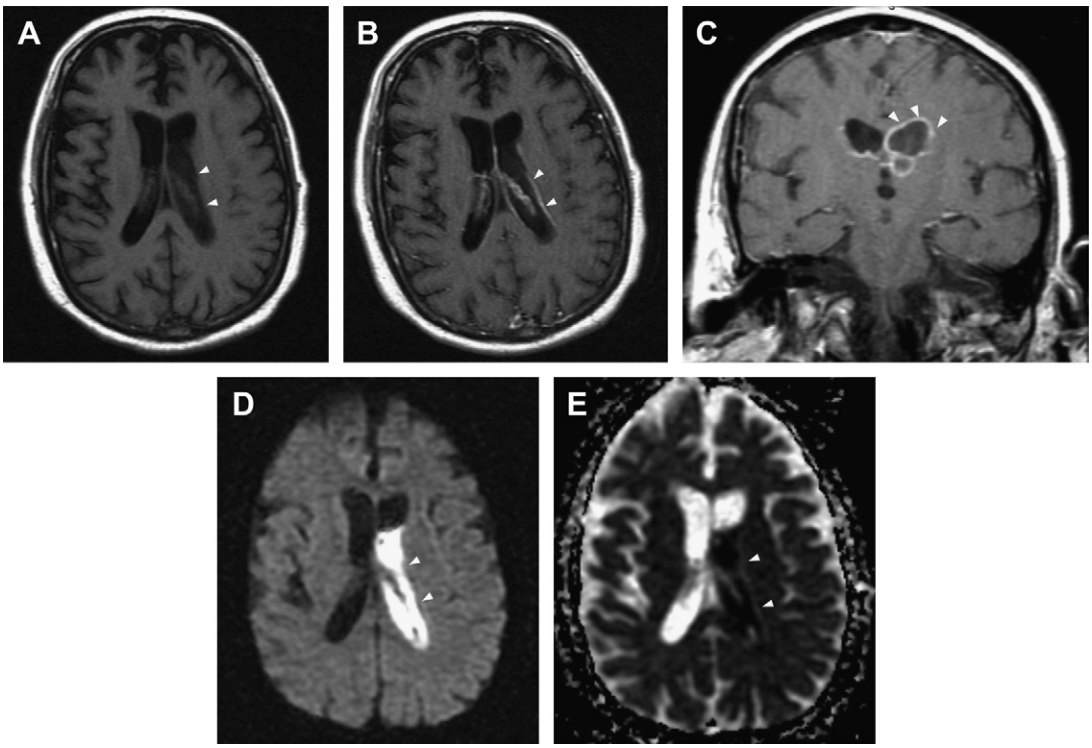

Fig. 22. Bacterial ventriculitis. (*A*) Axial T1WI shows subtle increased signal within the left lateral ventricle, indicating debris. (*B*, *C*) Axial and coronal T1WI after contrast shows increased ependymal enhancement along the left lateral ventricle consistent with ventriculitis. (*D*, *E*) DWI and corresponding ADC map show restricted diffusion within the left lateral ventricle, suggestive of abscess formation.

16% of all meningitis episodes are reported to be recurrent in nature. The interval between the bouts of meningitis may be months or even years. The most common underlying lesion (75%) is a bone defect, allowing for the intracranial compartment to communicate with the sinonasal or middle ear cavities, circumventing the usual immune defense mechanisms. The most common responsible microorganisms are streptococci and gram-negative bacilli.[1]

Mollaret Meningitis

Mollaret meningitis is a rare syndrome characterized by recurrent episodes of viral (aseptic) meningitis, most commonly seen in young females, with a possible link with herpes simplex virus. Each episode of Mollaret meningitis presents fulminantly with high fever, severe headache, and meningitic signs. Lumbar puncture reveals a neutrophilic and lymphocytic pleocytosis, with mildly increased protein and normal glucose levels. It can be diagnosed by polymerase chain reaction analysis of spinal fluid for the presence of viruses, in particular herpes simplex type 2. No specific imaging features have been described.[114]

SUMMARY

Many infectious and noninfectious inflammatory conditions can affect the cranial meninges. Knowledge of the normal anatomy of the meninges and the extra-axial spaces and its varied pathophysiologic states in meningitis aids in understanding the imaging appearances. Imaging studies can be normal in the early stages of the diseases, but MR imaging with its advanced techniques is a promising and sensitive technique in evaluation of patients suspected of having meningitis or its complications, or other processes affecting the subarachnoid space. One of the major roles of imaging is early identification of potentially serious complications, thus reducing morbidity and mortality.

ACKNOWLEDGMENTS

We are extremely grateful to Carolyn Nowak, B.A. and Michelle Kim, B.A., for their artistic skills rendered in creating the true-to-life medical illustrations that greatly enhanced the manuscript.

REFERENCES

1. Kanamalla US, Ibarra RA, Jinkins JR. Imaging of cranial meningitis and ventriculitis. Neuroimaging Clin North Am 2000;10:309–31.
2. Griffin DE. Approach to patient with infection of central nervous system. In: Gorbach SL, Barlett JG, Blacklow NR, editors. Infectious disease. 2nd edition. Philadelphia: WB Saunders; 1997. p. 1377.
3. Sze G, Soletsky S, Bronen R, et al. MR imaging of the cranial meninges with emphasis on contrast enhancement and meningeal carcinomatosis. Am J Neuroradiol 1989;10:965–75.
4. Meltzer CC, Fukui MB, Kanal E, et al. MR imaging of the meninges. Part I. Normal anatomic features and nonneoplastic disease. Radiology 1996;201: 297–308.
5. Quint DJ, Eldevik OP, Cohen JK. Magnetic resonance imaging of normal meningeal enhancement at 1.5T. Acad Radiol 1996;6(3):463–8.
6. Smirniotopoulos JG, Murphy FM, Rushing EJ, et al. Patterns of contrast enhancement in the brain and meninges. Radiographics 2007;27(2):525–51.
7. Dietemann JL, Correia Bernardo R, Bogorin A, et al. Normal and abnormal meningeal enhancement: MRI features. J Radiol 2005;86(11):1659–83.
8. Sage MR, Wilson AJ, Scroop R. Contrast media and the brain: the basis of CT and MR imaging enhancement. Neuroimaging Clin N Am 1998;8: 695–707.
9. Burke JW, Podrasky AE, Bradley WG Jr. Meninges: benign postoperative enhancement on MR images. Radiology 1990;174:99–102.
10. Mittl RL Jr, Yousem DM. Frequency of unexplained meningeal enhancement in the brain after lumbar puncture. Am J Neuroradiol 1994;15:633–8.
11. van de Beek D, de Gans J, Spanjaard L, et al. Clinical features and prognostic factors in adults with bacterial meningitis. N Engl J Med 2004;351(18): 1849–59 [Erratum in: N Engl J Med. 2005 Mar 3; 352(9):950].
12. Castillo M. Imaging of meningitis. Semin Roentgenol 2004;39(4):458–64.
13. Becker LE. Infections of the developing brain. Am J Neuroradiol 1992;13(2):537–49.
14. Harris TM, Edwards MK. Meningitis. Neuroimaging Clin N Am 1991;1:39–56.
15. Wong J, Quint DJ. Imaging of central nervous system infections. Semin Roentgenol 1999;34(2): 123–43.
16. Hasbun R, Abrahams J, Jekel J, et al. Computed tomography of the head before lumbar puncture in adults with suspected meningitis. N Engl J Med 2001;345:1727–33.
17. Kastrup O, Wanke I, Maschke M. Neuroimaging of infections of the central nervous system. Semin Neurol 2008;28(4):511–22.
18. Gee GT, Bazan C 3rd, Jinks JR. Miliary tuberculosis involving the brain: MR findings. AJR Am J Roentgenol 1992;159(5):1075–6.
19. Okagaki H. Fundamentals of neuropathology. 2nd edition. New York: Igaku-Shoin; 1989.
20. Jinkins JR. Computed tomography of intracranial tuberculosis. Neuroradiology 1991;33(2):126–35.
21. Osborn AG. Infections of the brain and its linings. In: Diagnostic neuroradiology. St Louis (MO): Mosby; 1994. p. 673–715.
22. Zee CS, Go JL, Kim P, et al. Cerebral infections and inflammation. In: Haaga JR, Lanzieri CF, Gilkeson RC, editors. CT and MR imaging of the whole body. 4th edition. St Louis (MO): Mosby; 2002. p. 207–10.
23. Parmar H, Sitoh YY, Anand P, et al. Contrast-enhanced FLAIR imaging in the evaluation of infectious leptomeningeal diseases. Eur J Radiol 2006; 58(1):89–95.
24. Stuckey SL, Goh TD, Heffernan T, et al. Hyperintensity in the subarachnoid space on FLAIR MRI. AJR Am J Roentgenol 2007;189(4):913–21.
25. Karampekios S, Hesselink J. Cerebral infections. Eur Radiol 2005;15(3):485–93.
26. Kioumehr F, Dadsetan MR, Feldman N, et al. Post-contrast MRI of cranial meninges: leptomeningitis versus pachymeningitis. J Comput Assist Tomogr 1995;19(5):713–20.
27. Gupta RK, Kathuria MK, Pradhan S. Magnetization transfer MR imaging in CNS tuberculosis. Am J Neuroradiol 1999;20:867–75.
28. Kamra P, Azad R, Prasad KN, et al. Infectious meningitis: prospective evaluation with magnetization transfer MRI. Br J Radiol 2004;77(917):387–94.
29. Mishra AM, Gupta RK, Jaggi RS, et al. Role of diffusion-weighted imaging and in vivo proton magnetic resonance spectroscopy in the differential diagnosis of ring-enhancing intracranial cystic mass lesions. J Comput Assist Tomogr 2004;28(4):540–7.
30. Gupta RK. Tuberculosis and other non-tuberculous bacterial graunulomatous infections. In: Gupta RK, Lufkin RB, editors. MR imaging and spectroscopy of central nervous system infection. New York: Kluwer Academic/Plenum Publishers; 2001. p. 95–145.
31. Nath K, Husain M, Trivedi R, et al. Clinical implications of increased fractional anisotropy in meningitis associated with brain abscess. J Comput Assist Tomogr 2007;31:888–93.
32. Trivedi R, Malik GK, Gupta RK, et al. Increased anisotropy in neonatal meningitis: an indicator of meningeal inflammation. Neuroradiology 2007;49: 767–75.
33. Yadav A, Malik GK, Trivedi R, et al. Correlation of CSF neuroinflammatory molecules with leptomeningeal cortical subcortical white matter fractional anisotropy in neonatal meningitis. Magn Reson Imaging 2009;27(2):214–21.

34. Malik GK, Trivedi R, Gupta A, et al. Quantitative DTI assessment of periventricular white matter changes in neonatal meningitis. Brain Dev 2008; 30:334–41.
35. Jain KK, Mittal SK, Kumar S, et al. Imaging features of central nervous system fungal infections. Neurol India 2007;55(3):241–50.
36. Kovoor JM, Mahadevan A, Narayan JP, et al. Cryptococcal choroid plexitis as a mass lesion: MR imaging and histopathologic correlation. Am J Neuroradiol 2002;23:273–6.
37. Rumboldt Z, Thurnher MM, Gupta RK. Central nervous system infections. Semin Roentgenol 2007;42(2):62–91.
38. Awasthi M, Patankar T, Shah P, et al. Cerebral cryptococcosis: atypical appearances on CT. Br J Radiol 2001;74:83–5.
39. Kathuria MK, Gupta RK. Fungal infections. In: Gupta RK, Lufkin RB, editors. MR imaging and spectroscopy of central nervous system infections. New York: Kluwer Press; 2001. p. 177–203.
40. Ruiz A, Post MJ, Bundschu CC. Dentate nuclei involvement in AIDS patients with CNS cryptococcosis: imaging findings with pathologic correlation. J Comput Assist Tomogr 1997;21:175–82.
41. Sibtain NA, Chinn RJ. Imaging of the central nervous system in HIV infection. Imaging 2002; 14:48–59.
42. Lui G, Lee N, Ip M, et al. Cryptococcosis in apparently immunocompetent patients. QJM 2006;99: 143–51.
43. Saigal G, Post MJD, Lolayekar S, et al. Unusual presentation of central nervous system cryptococcal infection in an immunocompetent patient. AJNR Am J Neuroradiol 2005;26:2522–6.
44. Vender JR, Miller DM, Roth T, et al. Intraventricular cryptococcal cysts. Am J Neuroradiol 1996;17: 110–3.
45. Aharon-Peretz J, Kliot D, Finkelstein R, et al. Cryptococcal meningitis mimicking vascular dementia. Neurology 2004;62:2135.
46. Pittella JE. Neurocysticercosis. Brain Pathol 1997; 7(1):681–93.
47. Salzman KL. Parasites, miscellaneous. In: Diagnostic imaging: brain. Salt Lake City (UT): Amirsys; 2004. p. 8–53.
48. La Mantia L, Costa A, Eoli M, et al. Racemose neurocysticercosis after chronic meningitis: effect of medical treatment. Clin Neurol Neurosurg 1995; 97(1):50–4.
49. Mishra D, Sharma S, Gupta S, et al. Acute cysticercal meningitis–missed diagnosis. Indian J Pediatr 2006;73(9):835–7.
50. Puri V, Sharma DK. Neurocysticercosis in children. Indian Pediatr 1991;28:1309–17.
51. Kalra V, Mittal R, Rana KS, et al. Neurocysticercosis: Indian experience. In: Perat MV, editor. New developments in neurology. Bologna (Italy): Monduzzi Editore S.P.A; 1998. p. 353–9.
52. Joubert J. Cysticercal meningitis–a pernicious form of neurocysticercosis which responds poorly to praziquantel. S Afr Med J 1990;77:528–30.
53. Visudhipan P, Chiemchanya S. Acute cysticercal meningitis in children: response to praziquantel. Ann Trop Paediatr 1997;17:9–13.
54. Jubelt B, Miller JR. Parasitic infections. In: Rowland LP, editor. Merritt's textbook of neurology. 8th edition. Philadelphia/London: Lea & Febiger; 1989. p. 164–76, chapter II.
55. Tsang VC, Brand JA, Boyer AE. An enzyme-linked immunoelectro-transfer blot assay and glycoprotein antigens for diagnosing human cysticercosis *(Taenia solium)*. J Infect Dis 1989;159:50–9.
56. Zee CS, Segall HD, Apuzzo ML, et al. Intraventricular cysticercal cysts: further neuroradiological observations and neurosurgical implications. AJNR Am J Neuroradiol 1984;5:727–30.
57. Teitelbaum GP, Otto RJ, Lin M, et al. MR imaging of neurocysticercosis. Am J Radiol 1989;153:857–66.
58. Zee CS, Segall HD, Destian S, et al. MRI of intraventricular cysticercosis: surgical implications. J Comput Assist Tomogr 1993;17(6):932–9.
59. Ramirez-Avila L, Slome S, Schuster FL, et al. Eosinophilic meningitis due to *Angiostrongylus* and *Gnathostoma* species. Clin Infect Dis 2009;48(3):322–7.
60. Lo Re V 3rd, Gluckman SJ. Eosinophilic meningitis. Am J Med 2003;114(3):217–23.
61. Kanpittaya J, Jitpimolmard S, Tiamkao S, et al. MR findings of eosinophilic meningoencephalitis attributed to *Angiostrongylus cantonensis*. Am J Neuroradiol 2000;21(6):1090–4.
62. Singh P, Kochhar R, Vashishta RK, et al. Amebic meningoencephalitis: spectrum of imaging findings. Am J Neuroradiol 2006;27(6):1217–21.
63. Goto M, Takahashi T, Kanda T, et al. Detection of *Toxoplasma gondii* by polymerase chain reaction in cerebrospinal fluid from human immunodeficiency virus-1-infected Japanese patients with focal neurological signs. J Int Med Res 2004;32(6):665–70.
64. Okubo Y, Shinozaki M, Yoshizawa S, et al. Diagnosis of systemic toxoplasmosis with HIV infection using DNA extracted from paraffin-embedded tissue for polymerase chain reaction: a case report. J Med Case Reports 2010;4:265.
65. Brightbill TC, Ihmeidan IH, Post MJ, et al. Neurosyphilis in HIV-positive and HIV-negative patients: neuroimaging findings. Am J Neuroradiol 1995; 16:703–11.
66. Tien RD, Gean-Marton AD, Mark AS. Neurosyphilis in HIV carriers: MR findings in six patients. Am J Roentgenol 1992;158:1325–8.
67. Ances BM, Danish SF, Kolson DL, et al. Cerebral gumma mimicking glioblastoma multiforme. Neurocrit Care 2005;2(3):300–2.

68. Bash S, Hathout GM, Cohen S. Mesiotemporal T2-weighted hyperintensity: neurosyphilis mimicking herpes encephalitis. Am J Neuroradiol 2001;22: 314–6.
69. Agarwal R, Sze G. Neuro-lyme disease: MR imaging findings. Radiology 2009;253(1):167–73.
70. Finkel MF. Lyme disease and its neurologic complications. Arch Neurol 1988;45(1):99–104.
71. Falco RC, Fish D. Prevalence of *Ixodes dammini* near the homes of Lyme disease patients in Westchester County, New York. Am J Epidemiol 1988; 127(4):826–30.
72. Wright SW, Trott AT. North American tickborne diseases. Ann Emerg Med 1988;17(9):964–72.
73. Fernandez RE, Rothberg M, Ferencz G, et al. Lyme disease of the CNS: MR imaging findings in 14 cases. Am J Neuroradiol 1990;11(3):479–81.
74. Garcia-Monaco JC, Benach JL. Lyme neuroborreliosis. Ann Neurol 1995;37:691–702.
75. Ramesh G, Borda JT, Gill A, et al. Possible role of glial cells in the onset and progression of Lyme neuroborreliosis. J Neuroinflammation 2009;6:23.
76. Demaerel P, Wilms G, Van Lierde S, et al. Lyme disease in childhood presenting as primary leptomeningeal enhancement without parenchymal findings on MR. Am J Neuroradiol 1994;15(2): 302–4.
77. Kőchling J, Freitag HJ, Bollinger T, et al. Lyme disease with lymphocytic meningitis, trigeminal palsy and silent thalamic lesion. Eur J Paediatr Neurol 2008;12(6):501–4.
78. Huisman TA, Wohlrab G, Nadal D, et al. Unusual presentations of neuroborreliosis (Lyme disease) in childhood. J Comput Assist Tomogr 1999;23(1): 39–42.
79. Koudstaal PJ, Vermeulen M, Wokke JH. Argyll Robertson pupils in lymphocytic meningoradiculitis (Bannwarth's syndrome). J Neurol Neurosurg Psychiatry 1987;50(3):363–5.
80. Vianello M, Marchiori G, Giometto B. Multiple cranial nerve involvement in Bannwarth's syndrome. Neurol Sci 2008;29(2):109–12.
81. Hughes DC, Raghavan A, Mordekar SR, et al. Role of imaging in the diagnosis of acute bacterial meningitis and its complications. Postgrad Med J 2010;86(1018):478–85.
82. Cabral DA, Flodmark O, Farrell K, et al. Prospective study of computed tomography in acute bacterial meningitis. J Pediatr 1987;111:201–5.
83. Ferreira NP, Otta GM, do Amaral LL, et al. Imaging aspects of pyogenic infections of the central nervous system. Top Magn Reson Imaging 2005; 16(2):145–54.
84. Wong AM, Zimmerman RA, Simon EM, et al. Diffusion-weighted MR imaging of subdural empyema in children. Am J Neuroradiol 2004;25: 1016–21.
85. Tung GA, Rogg JM. Diffusion-weighted imaging of cerebritis. Am J Neuroradiol 2003;24:1110–3.
86. Rana S, Albayram S, Lin DD, et al. Diffusion-weighted imaging and apparent diffusion coefficient maps in a case of intracerebral abscess with ventricular extension. Am J Neuroradiol 2002; 23:109–12.
87. Falcone S, Post MJ. Encephalitis, cerebritis, and brain abscess: pathophysiology and imaging findings. Neuroimaging Clin N Am 2000;10:333–53.
88. Hartmann M, Jansen O, Heiland S, et al. Restricted diffusion within ring enhancement is not pathognomonic for brain abscess. Am J Neuroradiol 2001; 22:1738–42.
89. Holtas S, Geijer B, Stromblad LG, et al. A ring-enhancing metastasis with central high signal on diffusion-weighted imaging and low apparent diffusion coefficients. Neuroradiology 2000;42:824–7.
90. Guzman R, Barth A, Lovblad KO, et al. Use of diffusion-weighted magnetic resonance imaging in differentiating purulent brain processes from cystic brain tumors. J Neurosurg 2002;97:1101–7.
91. Gupta RK, Nath K, Prasad A, et al. In vivo demonstration of neuroinflammatory molecule expression in brain abscess with diffusion tensor imaging. Am J Neuroradiol 2008;29(2):326–32.
92. Erdogan C, Hakyemez B, Yildirim N, et al. Brain abscess and cystic brain tumor: discrimination with dynamic susceptibility contrast perfusion-weighted MRI. J Comput Assist Tomogr 2005;29:663–7.
93. Garg M, Gupta RK, Husain M, et al. Brain abscesses: etiologic categorization with in vivo proton MR spectroscopy. Radiology 2004;230:519–27.
94. Beijen J, Casselman J, Joosten F, et al. Magnetic resonance imaging in patients with meningitis induced hearing loss. Eur Arch Otorhinolaryngol 2009;266:1229–36.
95. Ducreux D, Oppenheim C, Vandamme X, et al. Diffusion-weighted imaging patterns of brain damage associated with cerebral venous thrombosis. Am J Neuroradiol 2001;22:261–8.
96. Bakshi R, Kinkel P, Mechtler L, et al. Cerebral ventricular empyema associated with severe adult pyogenic meningitis: computed tomography findings. Clin Neurol Neurosurg 1997;99:252–5.
97. Barloon TJ, Yuh WT, Knepper LE, et al. Cerebral ventriculitis: MR findings. J Comput Assist Tomogr 1990;14:272–5.
98. Bodino J, Lylyk P, Del Valle M, et al. Computed tomography in purulent meningitis. Am J Dis Child 1982;136:495–501.
99. Vachon L, Mikity V. Computed tomography and ultrasound in purulent ventriculitis. J Ultrasound Med 1987;6:269–71.
100. Fukui MB, Williams RL, Mudigonda S. CT and MR imaging features of pyogenic ventriculitis. Am J Neuroradiol 2001;22:1510–6.

101. Lambo A, Nchimi A, Khamis J, et al. Primary intraventricular brain abscess. Neuroradiology 2003;45: 908–10.
102. Fujikawa A, Tsuchiya K, Honya K, et al. Comparison of MRI sequences to detect ventriculitis. Am J Roentgenol 2006;187(4):1048–53.
103. Rahal JJ Jr, Hyams PJ, Simberkoff MS, et al. Combined intrathecal and intramuscular gentamicin for gram-negative meningitis: pharmacologic study of 21 patients. N Engl J Med 1974;290:1394–8.
104. Kaiser A, McGee Z. Aminoglycoside therapy of gram-negative bacillary meningitis. N Engl J Med 1975;293:1215–20.
105. Durand M, Calderwood S, Weber D, et al. Acute bacterial meningitis in adults: a review of 493 episodes. N Engl J Med 1993;328:21–8.
106. Yikilmaz A, Taylor GA. Sonographic findings in bacterial meningitis in neonates and young infants. Pediatr Radiol 2008;38(2):129–37.
107. Han BK, Babcock DS, McAdams L. Bacterial meningitis in infants: sonographic findings. Radiology 1985;154:645–50.
108. Tatsuno M, Hasegawa M, Okuyama K. Ventriculitis in infants: diagnosis by color Doppler flow imaging. Pediatr Neurol 1993;9:127–30.
109. Reeder JD, Sanders RC. Ventriculitis in the neonate: recognition by sonography. Am J Neuroradiol 1983;4:37–41.
110. Mathews VP, Smith RR. Choroid plexus infections: neuroimaging appearances of four cases. Am J Neuroradiol 1992;13:374–8.
111. Pezzullo JA, Tung GA, Mudigonda S, et al. Diffusion-weighted MR imaging of pyogenic ventriculitis. Am J Roentgenol 2003;180:71–5.
112. Cushing H. Experiences with the cerebellar astrocytomas: a critical review of seventy-six cases. Surg Gynecol Obstet 1931;52:129–91.
113. Sanchez GB, Kaylie DM, O'Malley MR, et al. Chemical meningitis following cerebellopontine angle tumor surgery. Otolaryngol Head Neck Surg 2008;138(3):368–73.
114. Prandota J. Mollaret meningitis may be caused by reactivation of latent cerebral toxoplasmosis. Int J Neurosci 2009;119(10):1655–92.