Diagnostic Imaging

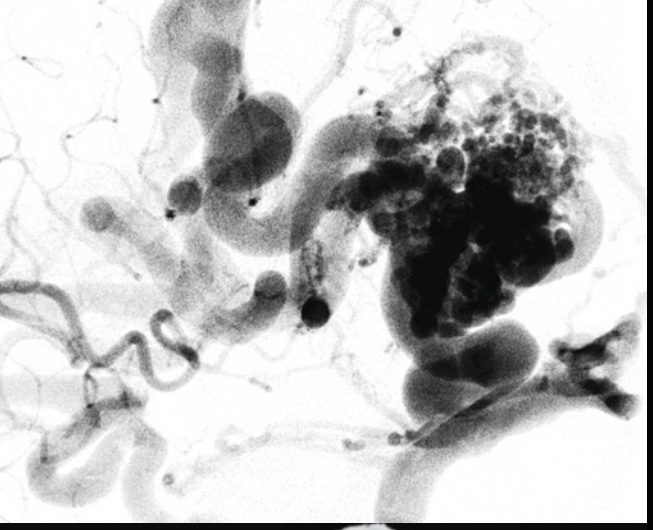
Brain

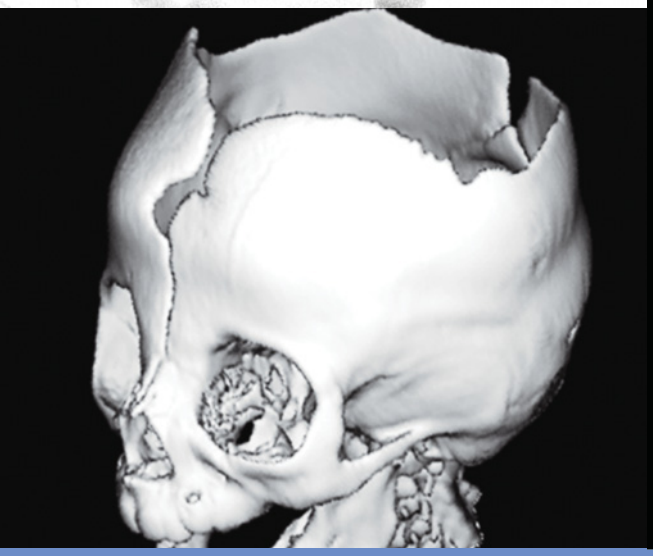
THIRD EDITION

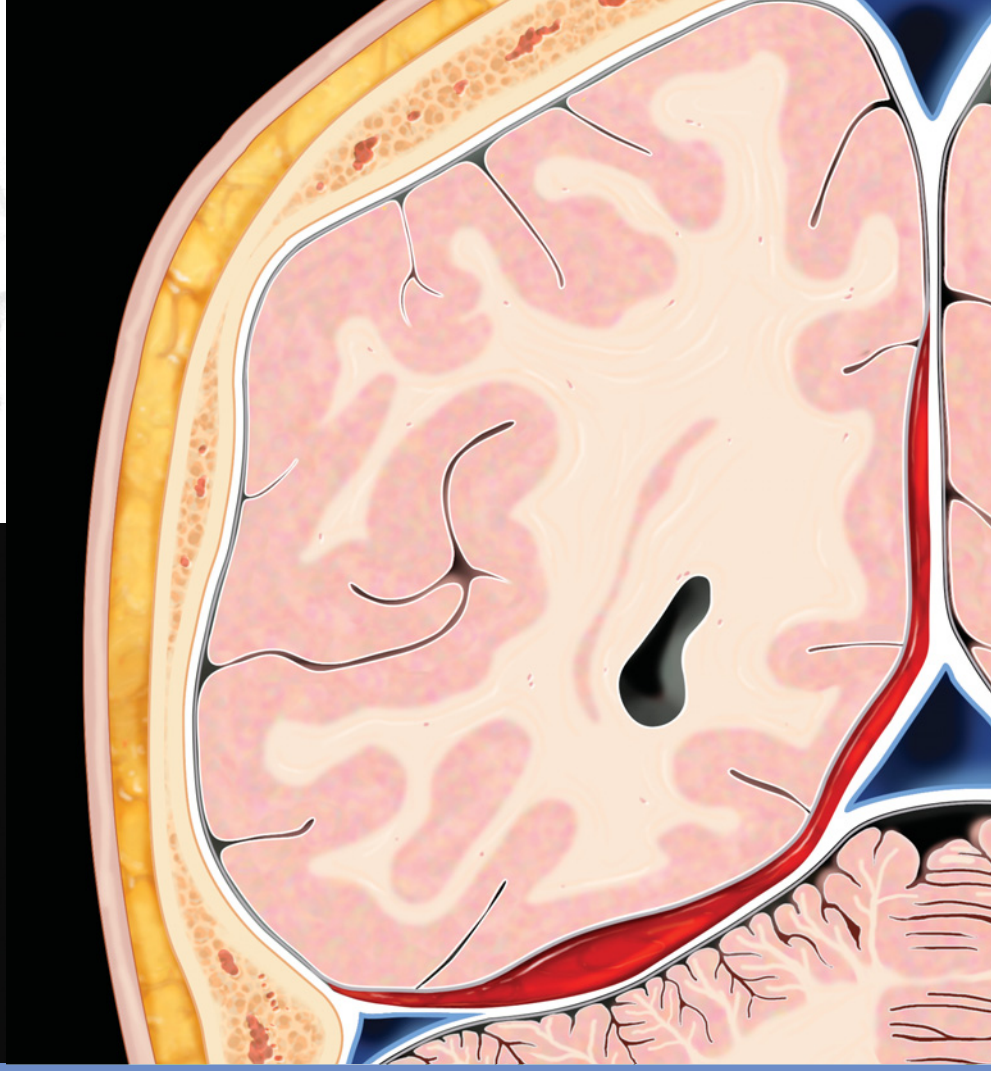
Osborn | Salzman | Jhaveri

AMIRSYS®

ELSEVIER



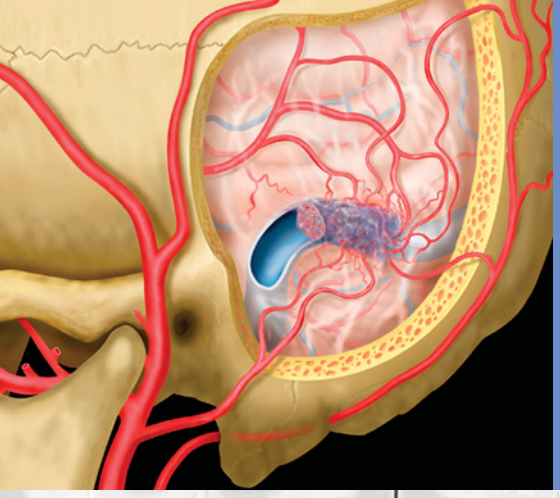


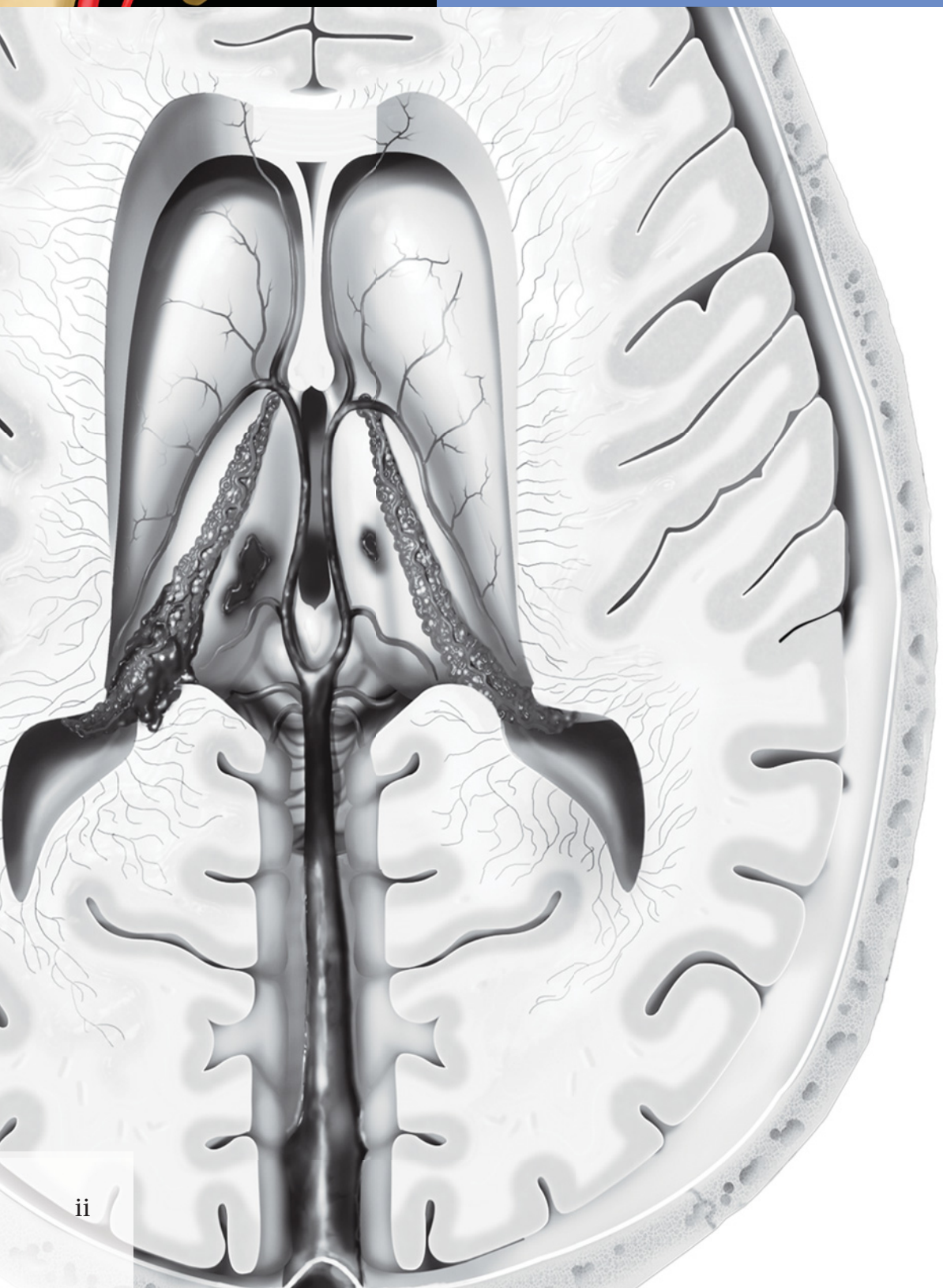


Diagnostic Imaging

Brain

THIRD EDITION





Diagnostic Imaging

Brain

THIRD EDITION

Anne G. Osborn, MD, FACR
University Distinguished Professor
William H. and Patricia W. Child Presidential Endowed Chair
University of Utah School of Medicine
Salt Lake City, Utah

Karen L. Salzman, MD
Professor of Radiology
Leslie W. Davis Endowed Chair in Neuroradiology
University of Utah School of Medicine
Salt Lake City, Utah

Miral D. Jhaveri, MD
Associate Professor
Division Head, Neuroradiology
Department of Diagnostic Radiology and Nuclear Medicine
Rush University Medical Center
Chicago, Illinois

ELSEVIER

1600 John F. Kennedy Blvd.
Ste 1800
Philadelphia, PA 19103-2899

DIAGNOSTIC IMAGING: BRAIN, THIRD EDITION ISBN: 978-0-323-37754-6

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

With respect to any drug or pharmaceutical products identified, readers are advised to check the most current information provided (i) on procedures featured or (ii) by the manufacturer of each product to be administered, to verify the recommended dose or formula, the method and duration of administration, and contraindications. It is the responsibility of practitioners, relying on their own experience and knowledge of their patients, to make diagnoses, to determine dosages and the best treatment for each individual patient, and to take all appropriate safety precautions.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Publisher Cataloging-in-Publication Data

Diagnostic imaging. Brain / [edited by] Anne G. Osborn, Karen L. Salzman, and Miral D. Jhaveri.
3rd edition.
pages ; cm
Brain
Includes bibliographical references and index.
ISBN 978-0-323-37754-6 (hardback)
1. Brain--Pathophysiology--Handbooks, manuals, etc. 2. Central nervous system--Diseases--Handbooks, manuals, etc. 3. Brain--Imaging--Handbooks, manuals, etc.
I. Osborn, Anne G., 1943- II. Salzman, Karen L. III. Jhaveri, Miral D. IV. Title: Brain.
[DNLM: 1. Brain--physiopathology--Atlases. 2. Central Nervous System Diseases--pathology--Atlases. 3. Neuroimaging--methods--Atlases. WL 301]
RC386.5.D515 2015
616.8--dc23

International Standard Book Number: 978-0-323-37754-6

Cover Designer: Tom M. Olson, BA
Cover Art: James A. Cooper, MD and Lane R. Bennion, MS

Printed in Canada by Friesens, Altona, Manitoba, Canada

Last digit is the print number: 9 8 7 6 5 4 3 2 1

Dedications

To our neuroradiology friends and colleagues all over the world: Thanks for your longstanding interest, support, and generosity in sharing cases and concepts. This newest edition is for you.

AO

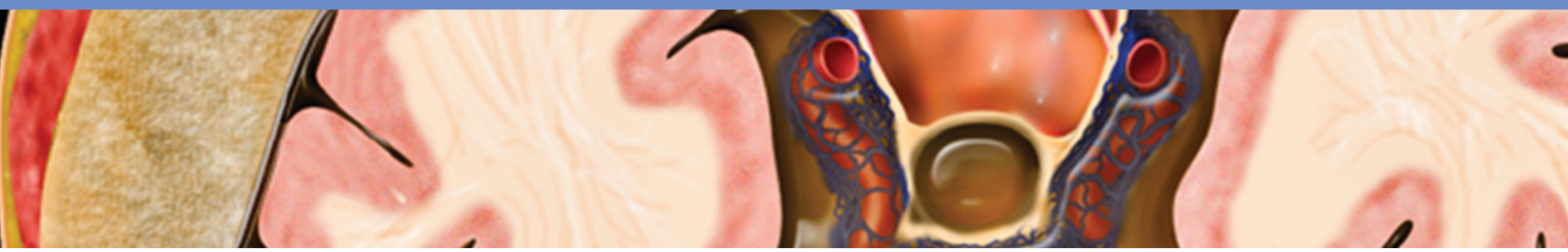
To the loves of my life: Craig, Sophia, Aubrey, and Ian. Thank you for your endless patience, love, and support.

KLS

To Palmi and Aanya: Thanks for all your support and patience.
To Michael and Beverly: Thanks for everything.

MJ

Contributing Authors



A. James Barkovich, MD
Professor of Radiology and Biomedical Imaging, Neurology, Pediatrics, and Neurological Surgery
UCSF-Benioff Children's Hospital
University of California, San Francisco
San Francisco, California

H. Ric Harnsberger, MD
R.C. Willey Chair in Neuroradiology
Professor of Radiology and Otolaryngology
University of Utah School of Medicine
Salt Lake City, Utah

Luke N. Ledbetter, MD
Assistant Professor of Radiology
Division of Neuroradiology
University of Kansas Medical Center
Kansas City, Kansas

Nicholas A. Koontz, MD
Assistant Professor of Clinical Radiology
Department of Radiology and Imaging Sciences
Indiana University School of Medicine
Indianapolis, Indiana

Kevin R. Moore, MD
Pediatric Neuroradiologist
Primary Children's Hospital
Salt Lake City, Utah

Charles Raybaud, MD, FRCPC
Derek Harwood-Nash Chair in Medical Imaging
Division Head of Neuroradiology
The Hospital for Sick Children
Professor of Radiology
University of Toronto
Toronto, Ontario, Canada

Anna Illner, MD
Pediatric Neuroradiologist
Texas Children's Hospital
Assistant Professor of Radiology
Baylor College of Medicine
Houston, Texas

Sheri L. Harder, MD, FRCPC
Assistant Professor of Radiology
Division of Neuroradiology
Loma Linda University Medical Center
Loma Linda, California

Gregory L. Katzman, MD, MBA
Professor of Neuroradiology
Vice Chair of Radiology Operations
Chief Quality Officer
Chief Business Development Officer
Department of Radiology
University of Chicago School of Medicine
Chicago, Illinois

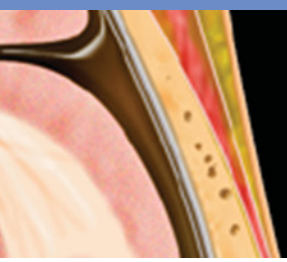
Bronwyn E. Hamilton, MD
Professor of Radiology
Oregon Health & Science University
Portland, Oregon

Lubdha M. Shah, MD
Associate Professor of Radiology
Division of Neuroradiology
University of Utah School of Medicine
Salt Lake City, Utah

Perry P. Ng, MBBS (Hons), FRANZCR
Adjunct Associate Professor
Department of Radiology
University of Utah School of Medicine
Salt Lake City, Utah
Interventional Neuroradiologist
Centura Health Physician Group
Denver, Colorado

Gary M. Nesbit, MD
Professor of Radiology, Neurology, Neurological Surgery
Dotter Interventional Institute
Oregon Health & Science University
Portland, Oregon

Ulrich Rassner, MD
Associate Professor of Radiology
Division of Neuroradiology
University of Utah School of Medicine
Salt Lake City, Utah



Laurie A. Loevner, MD
Chief, Division of Neuroradiology
Director, Head and Neck Radiology
Professor of Radiology, Otorhinolaryngology: Head and Neck Surgery, and Neurosurgery
University of Pennsylvania Health System Perelman School of Medicine at the University of Pennsylvania
Philadelphia, Pennsylvania

Jeffrey S. Anderson, MD, PhD
Associate Professor of Radiology and Bioengineering
University of Utah School of Medicine
Salt Lake City, Utah

Chang Yueh Ho, MD
Assistant Professor of Radiology
Director of Pediatric Neuroradiology
Program Director of Pediatric Neuroradiology Fellowship
Riley Hospital for Children
Indiana University School of Medicine
Indianapolis, Indiana

Edward P. Quigley, III, MD, PhD
Associate Professor of Radiology
Division of Neuroradiology
University of Utah School of Medicine
Salt Lake City, Utah

John H. Rees, MD
Chief of Neuroradiology: Partners Imaging
Sarasota, Florida
Assistant Professor of Radiology
Georgetown University
Previously: Visiting Scientist
Armed Forces Institute of Pathology
Washington, DC

Majda M. Thurnher, MD
Associate Professor of Radiology
Medical University Vienna
Department of Biomedical Imaging and Image-Guided Therapy
Vienna, Austria

Gary L. Hedlund, DO
Adjunct Professor of Radiology
University of Utah School of Medicine
Pediatric Neuroradiologist
Department of Medical Imaging
Primary Children's Hospital
Salt Lake City, Utah

James M. Provenzale, MD
Professor of Radiology
Duke University Medical Center
Durham, North Carolina

Yoshimi Anzai, MD, MPH
Professor of Radiology
Associate Chief Medical Quality Officer
University of Utah
Salt Lake City, Utah

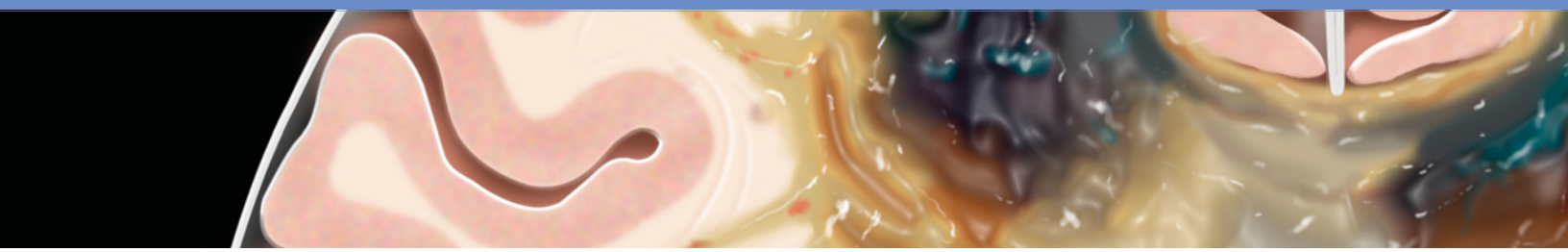
Susan I. Blaser, MD, FRCPC
Staff Neuroradiologist
The Hospital for Sick Children
Professor of Neuroradiology
University of Toronto
Toronto, Ontario, Canada

P. Ellen Grant, MD
Associate Professor in Radiology, Harvard Medical School
Founding Director, Center for Fetal-Neonatal Neuroimaging & Developmental Science
Director of Fetal and Neonatal Neuroimaging Research
Children's Hospital Boston Endowed Chair in Neonatology
Children's Hospital Boston
Boston, Massachusetts

Gilbert Vézina, MD
Director, Program in Neuroradiology
Children's National Medical Center
Professor of Radiology and Pediatrics
The George Washington University School of Medicine and Health Sciences
Washington, DC

Blaise V. Jones, MD
Associate Director of Radiology
Neuroradiology Section Chief
Cincinnati Children's Hospital Medical Center
Professor of Clinical Radiology and Pediatrics
University of Cincinnati College of Medicine
Cincinnati, Ohio

Preface

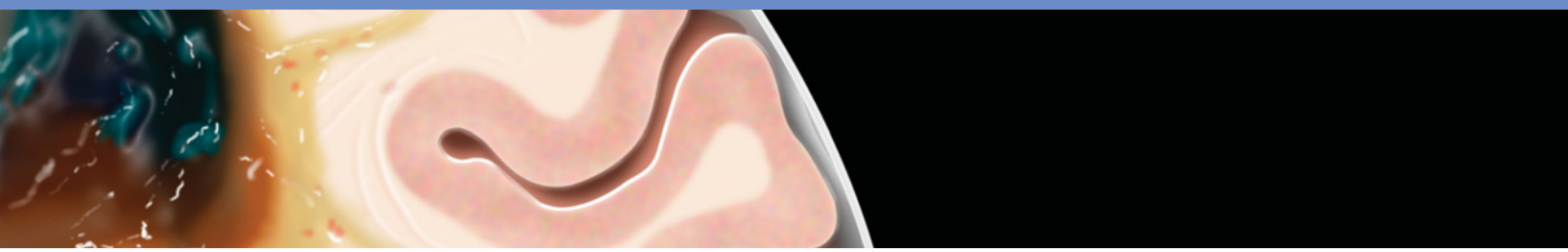


Welcome to one of the first volumes in the third series of the brand new *Diagnostic Imaging* books. You'll note that our newest book bears the imprint of both Amirsys and Elsevier. The fresh new look and layout reflects our best creative efforts. Yet, we've kept the synoptic, highly efficient bulleted text that you've come to expect from us as well as the beloved key facts summary boxes at the beginning of each diagnosis.

A lot has happened since we published the second edition of *Diagnostic Imaging: Brain* back in 2010. We've added new diagnoses, including important topics such as tumor pseudoprogression and pseudoresponse. New entities such as CLIPPERS and the hot subject of IgG4-related disease are included. There are literally thousands of new images in the diagnosis galleries together with references that have been updated with the latest findings. You told us you loved the section introductions that were a new feature of the second edition, so we've included new and updated introductions to reflect the current thinking on these general topics.

The second edition covered the fourth (2007) edition of the World Health Organization (WHO) classification and grading of brain tumors. These have been published every seven years. If you "do the math," you know the fifth edition would normally have been published in 2014. It wasn't. So before you ask, I'll tell you it isn't coming out in 2015 either. The field of tumor diagnosis is changing so rapidly with the advent of genomic analysis that it's almost impossible to keep up with it. Our neuropathology colleagues expect to publish an online update in 2016 (maybe). So, what we've done here is update the neoplasms section with the latest literature to give you the current best understanding of classification and grading. It's changing rapidly so stay tuned.

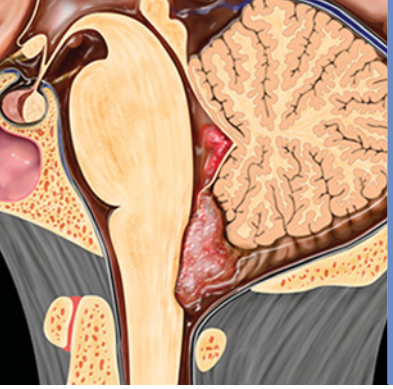
We've loved hearing from you. We appreciate (and pay close attention to) your ideas and input on what new diagnoses or information you'd like to see included. Many of you have shared cool cases with us, and we've selected images from some that are used in this new edition with our grateful acknowledgement. After all, YOU are the reason we keep doing these books. So thanks for your interest and input. Enjoy our newest "baby"!

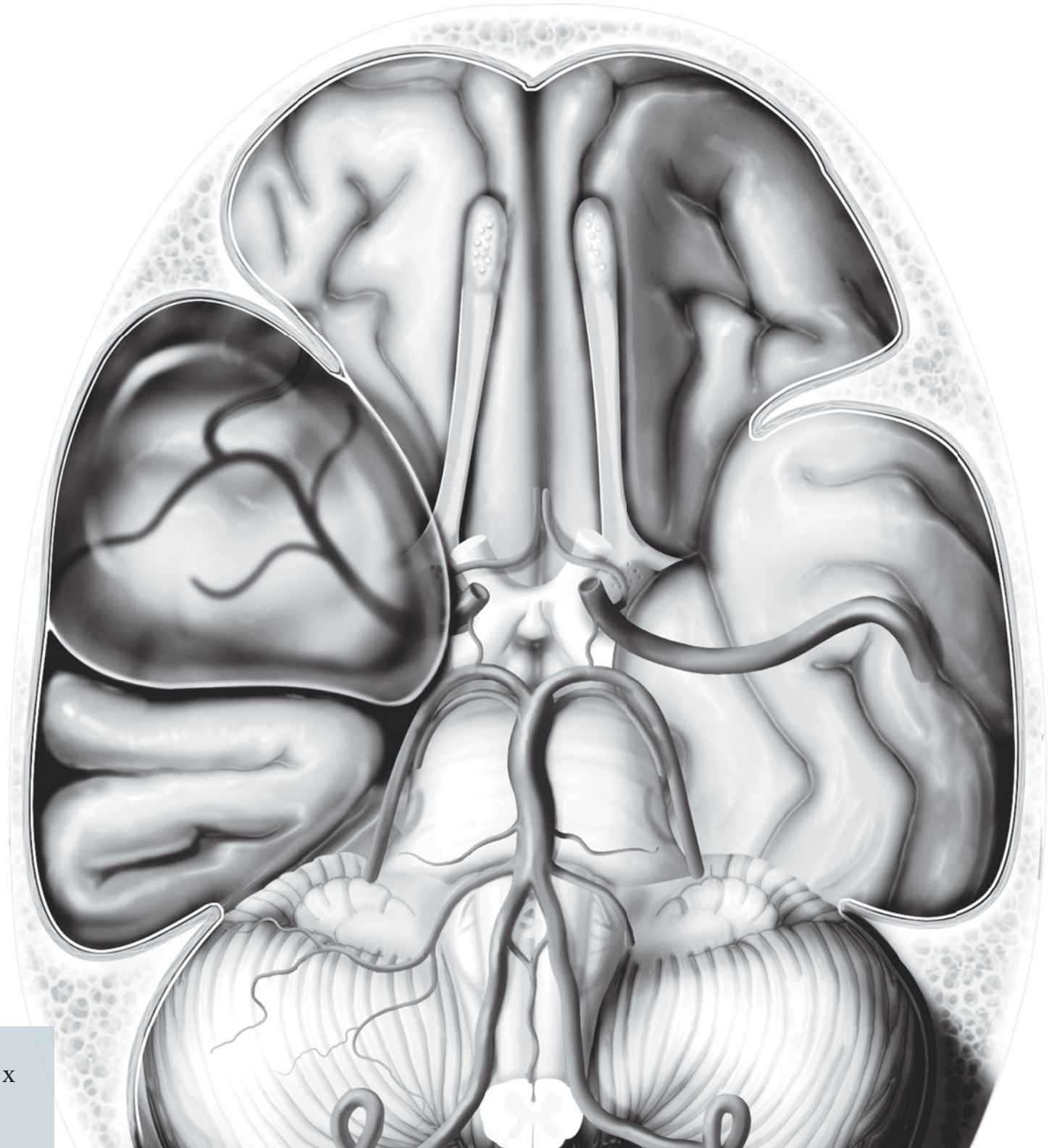


Anne G. Osborn, MD, FACR
University Distinguished Professor
William H. and Patricia W. Child Presidential Endowed Chair
University of Utah School of Medicine
Salt Lake City, Utah

Karen L. Salzman, MD
Professor of Radiology
Leslie W. Davis Endowed Chair in Neuroradiology
University of Utah School of Medicine
Salt Lake City, Utah

Miral D. Jhaveri, MD
Associate Professor
Division Head, Neuroradiology
Department of Diagnostic Radiology and Nuclear Medicine
Rush University Medical Center
Chicago, Illinois





Acknowledgements

Text Editors

Dave L. Chance, MA, ELS
Arthur G. Gelsinger, MA
Nina I. Bennett, BA
Sarah J. Connor, BA
Terry W. Ferrell, MS
Lisa A. Gervais, BA
Karen E. Concannon, MA, PhD

Image Editors

Jeffrey J. Marmorstone, BS
Lisa A. M. Steadman, BS

Medical Editors

Nicholas A. Koontz, MD
Remy Rosario Lobo, MD
Sarah Cantrell, MD

Illustrations

Lane R. Bennion, MS
Richard Coombs, MS
Laura C. Sesto, MA
James A. Cooper, MD

Art Direction and Design

Laura C. Sesto, MA
Tom M. Olson, BA

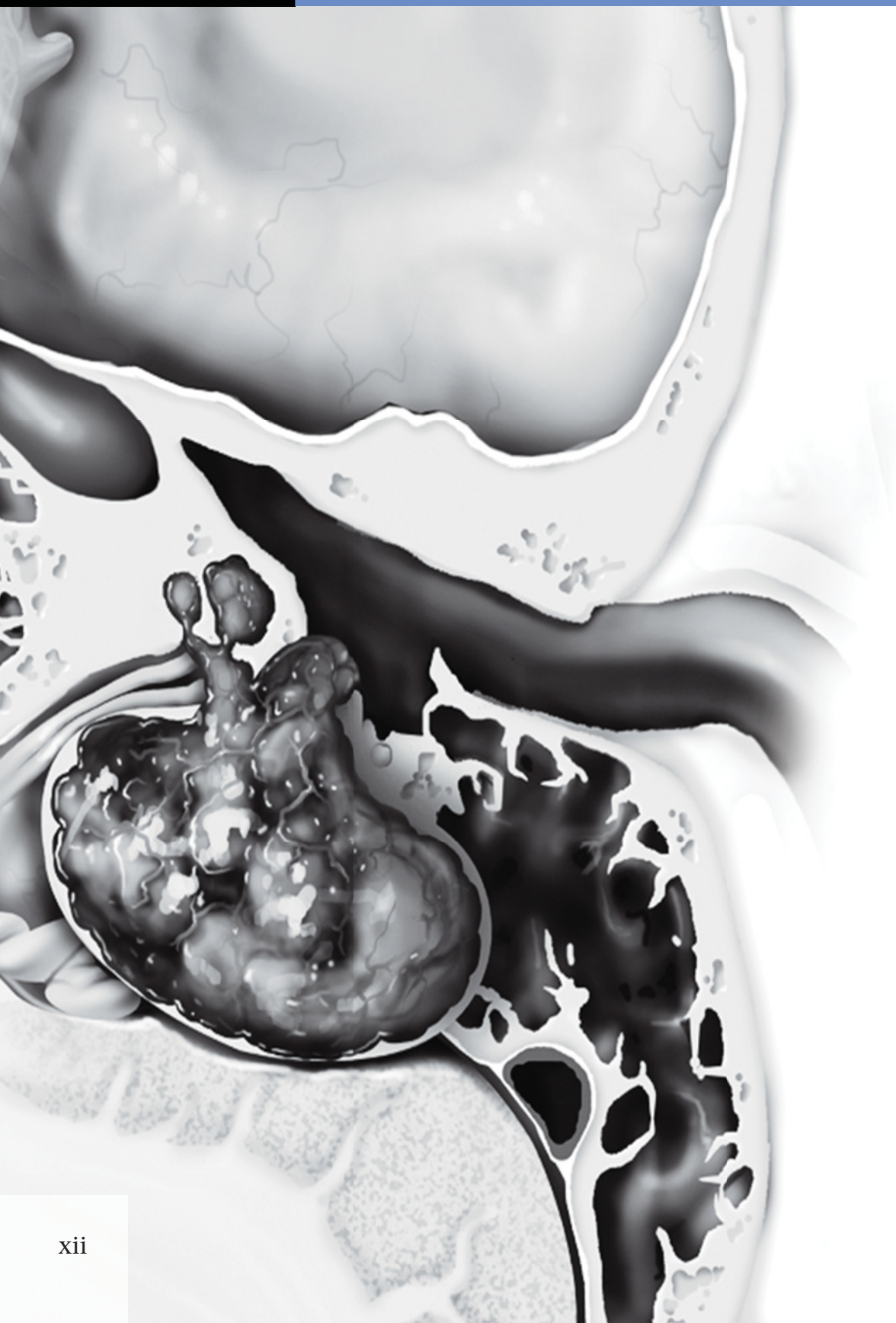
Lead Editor

Tricia L. Cannon, BA

Production Coordinators

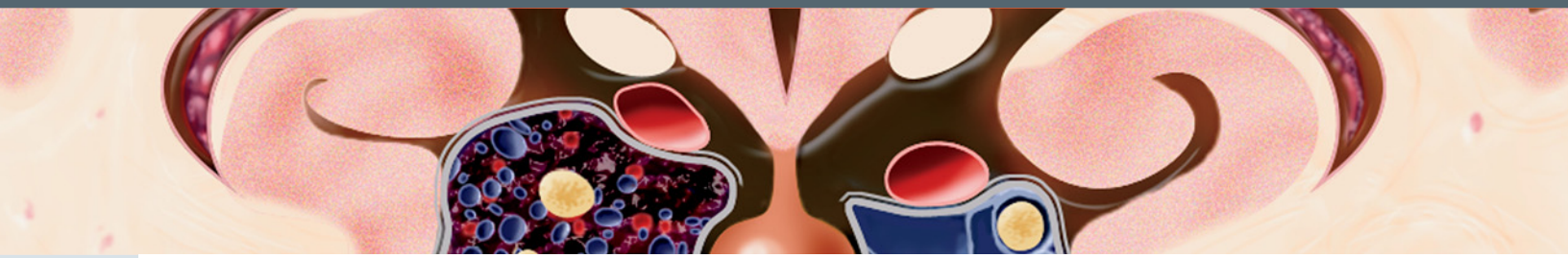
Rebecca L. Hutchinson, BA
Angela M. G. Terry, BA

ELSEVIER



Sections

TABLE OF CONTENTS



Part I: Pathology-Based Diagnoses

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

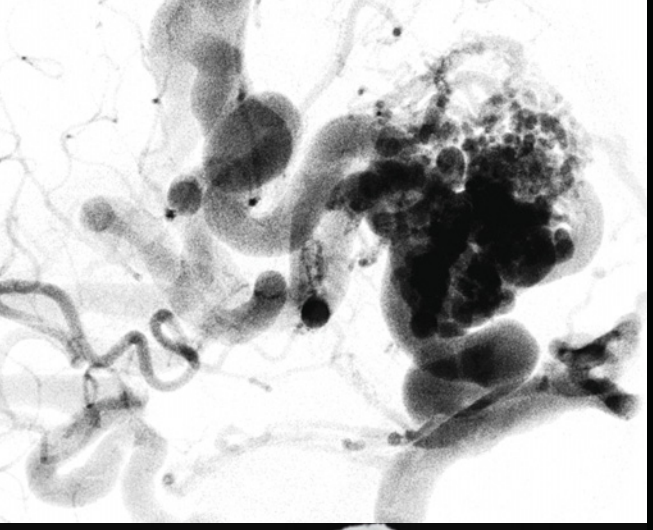
TABLE OF CONTENTS

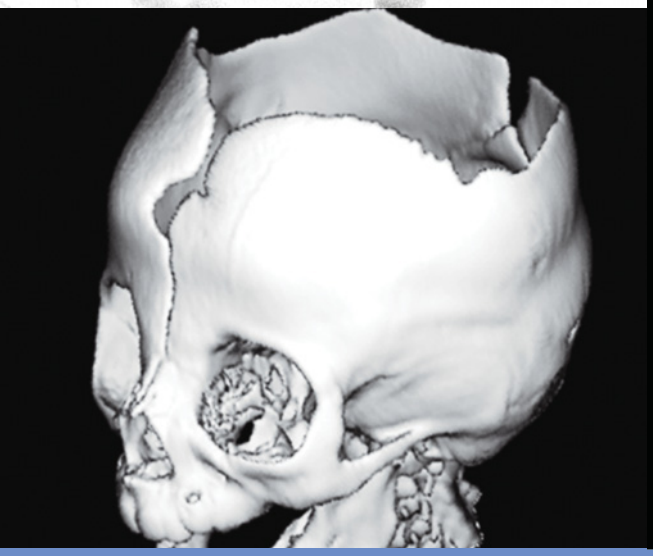
TABLE OF CONTENTS

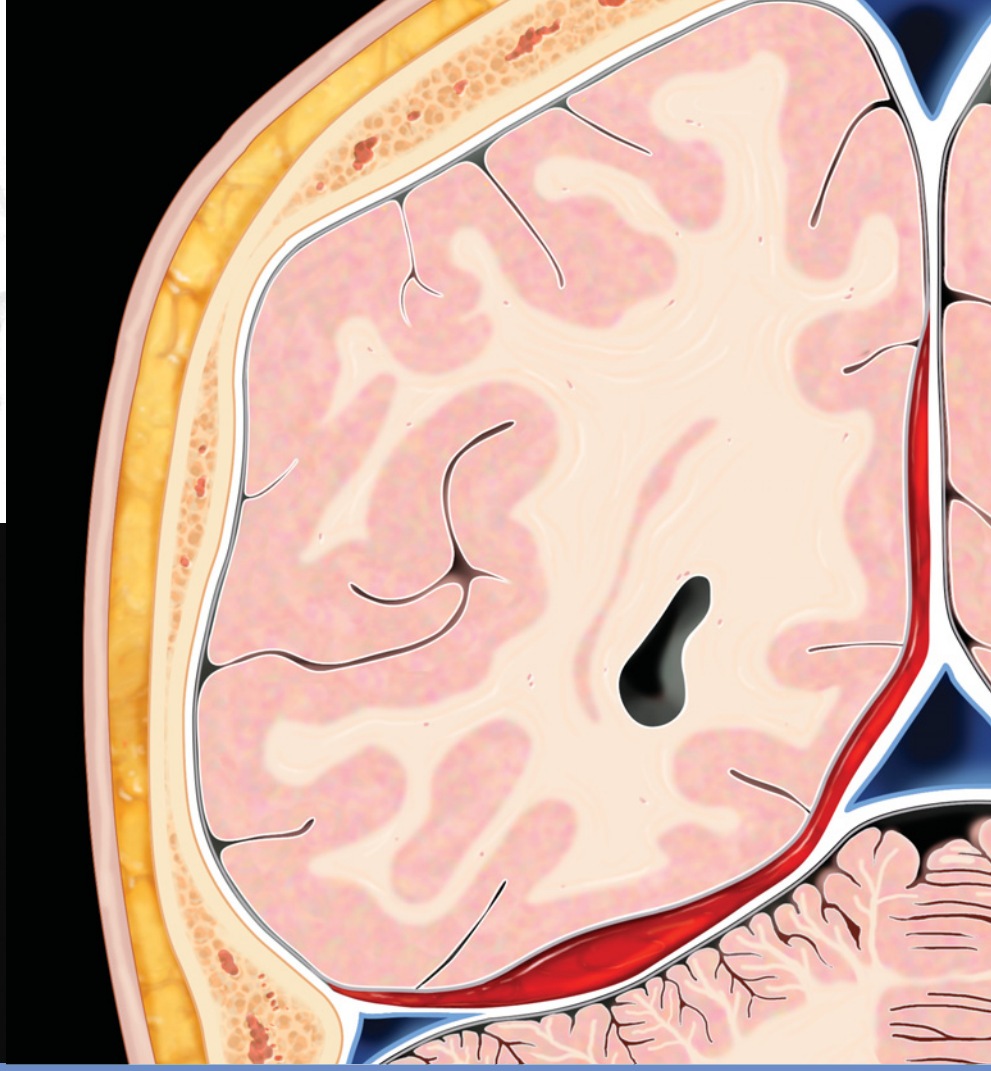
TABLE OF CONTENTS

TABLE OF CONTENTS

This page intentionally left blank







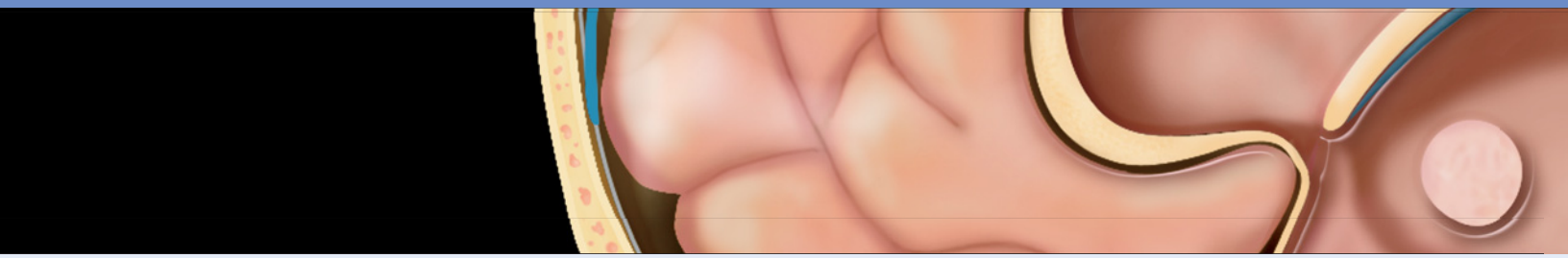
Diagnostic Imaging

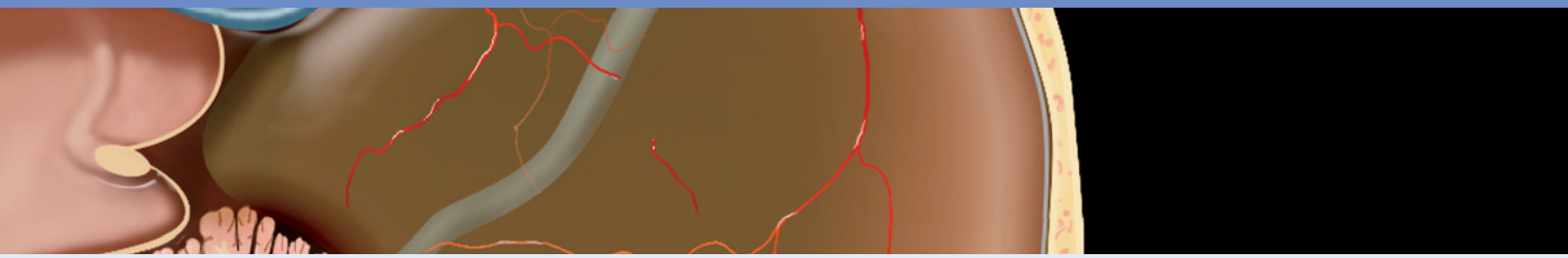
Brain

THIRD EDITION

PART I
SECTION 1

Congenital Malformations





Familial Tumor/Neurocutaneous Syndromes

General Imaging Approach to Brain Malformations

Whenever an infant or child is referred for imaging because of either seizures or delayed development, a brain malformation is a possible cause. If the child appears dysmorphic in any way (low-set ears, abnormal facies, hypotelorism), the likelihood of an underlying brain malformation is even higher. In all such cases, imaging should be geared toward showing a structural abnormality. The imaging sequences should maximize contrast between gray matter and white matter, have high spatial resolution, and should be acquired as volumetric data whenever possible so that images can be reformatted in any plane or as a surface rendering. The high resolution and ability to reformat will aid in the diagnosis of subtle abnormalities. High-resolution T1-weighted volumetric images are essential for this purpose. If possible, volumetric T2-weighted images can be acquired, but the images must have excellent spatial resolution and sharp contrast between gray matter and white matter, which is not currently easy to achieve with volumetric T2-weighted sequences. If contrast between gray and white matter is poor with volumetric acquisition, acquire two dimensional sequences (2D) in at least two planes and with relatively thin (3-4 mm) section size. FLAIR images are not particularly useful in looking for malformations, as the contrast between gray matter and white matter is often poor. Diffusion-weighted images are not currently of diagnostic utility, although the use of diffusion tensor imaging (DTI) to acquire color fractional anisotropy (FA) maps and perform tractography is useful to better understand the connectivity of the malformed brain and may become clinically useful in the near future.

After acquisition of appropriate images, image analysis must take place in an orderly manner. The midline structures (including cerebral commissures, septum pellucidum, nose and rhinencephalon, pituitary gland, and hypothalamus), the cerebral cortex (cortical thickness, gyral pattern, and cortical-white matter junction), cerebral white matter (myelination, presence of nodules or clefts), the basal ganglia, the ventricular system (are all ventricles completely present and normally shaped), the interhemispheric fissure, and the midbrain hindbrain structures (brainstem and cerebellum) should all be scrutinized in every patient.

Evaluate the midline structures first, as many disease processes of children take place in the midline, including anomalies of the cerebral commissures (corpus callosum, anterior commissure, and hippocampal commissure), midline tumors (suprasellar, pineal, brainstem, and fourth ventricle), anomalies of the cerebellar vermis, and anomalies of the craniocervical junction. Anomalies of the cerebral commissures are the most common of brain malformations; more than 130 syndromes involving them have been described. Many of these are associated with anomalies of the hypothalamus, so remember to always look at the hypothalamus and pituitary gland to ensure that the posterior pituitary gland is in the sella turcica and not in the median eminence of the hypothalamus. The midline leptomeninges are important in commisural development, so make sure to look for other anomalies associated with abnormal midline leptomeninges, such as interhemispheric lipomas and interhemispheric cysts when the commissures are absent or dysmorphic. Remember that large cerebrospinal fluid (CSF) spaces in the posterior fossa (mega cisterna magna) are often associated with anomalies of the cerebellum. The reason for this has only recently been discovered. Several cerebellar growth factors derive from the overlying leptomeninges. Therefore, abnormalities of the cerebellar leptomeninges may result in anomalies of the cerebellum itself, as well as abnormalities of the surrounding CSF spaces. This is the basis of development of the Dandy-Walker malformation: It requires abnormal development of the cerebellum itself and of the overlying leptomeninges. Looking at the midline image also gives an idea of the relative head size by assessing the craniofacial ratio. In the normal neonate, the ratio of the cranial vault to the face on midline images is 5:1 or 6:1. By the age of 2 years, it should be 2.5:1, and by age 10 years, it should be about 1.5:1.

After looking at the midline, evaluate the brain from outside to inside. Start with the cerebral cortex. Is the thickness normal (2-3 mm)? If it is too thick, think of pachygyria or polymicrogyria. Is the cortical-white matter junction smooth or irregular? If it is irregular, think of polymicrogyria or the cobblestone cortex seen associated with congenital muscular dystrophies such as muscle-eye-brain disease. The location of these abnormalities is important as well. Pachygyria more severe in the parietal and occipital lobes suggests a mutation of *TUBA1A*, whereas pachygyria worst in the frontal lobes suggests a mutation of *DCX*. Similarly, there are many different polymicrogyria syndromes that depend upon the location of the polymicrogyria: Bilateral frontal polymicrogyria is a different entity than bilateral perisylvian polymicrogyria or bilateral parasagittal parietooccipital polymicrogyria; it is important to be specific in reporting the location of the abnormality. If the cortex is abnormally thin, one should think of a prenatal injury (infectious or ischemic), particularly if the thinning is focal or multifocal.

After the cortex, look at the cerebral white matter. Make sure myelination is appropriate for age (there are many sources of normal myelination charts, including journal articles and textbooks). Then, look for areas of abnormal myelination within the deep white matter. Diffuse layers of hypomyelination or amyelination associated with overlying polymicrogyria should raise suspicion for congenital cytomegalovirus infection. More localized foci of delayed or absent myelination are often seen in deep white matter of patients with congenital muscular dystrophy and in the subcortical white matter of those with focal cortical dysplasias (FCDs). With FCDs, the absent myelination may be localized to a gyrus or may extend centrally as a curvilinear cone-shaped abnormality coursing from the cortex to the superolateral margin of a lateral ventricle (this is known as the "transmantle" sign). Also, look for nodules of heterotopic gray matter in the periventricular or deep white matter. Subcortical heterotopia typically extend from the cortex all the way to the lateral ventricular wall, while periventricular nodular heterotopia are more localized to the immediate subependymal/periventricular region. Heterotopia might be difficult to differentiate from unmyelinated or injured white matter on T1-weighted images, so be sure to look at T2-weighted images or FLAIR images to ensure that the lesion is isointense to gray matter on all sequences.

The basal ganglia are sometimes abnormal in disorders of neuronal migration, as they are formed from neurons generated in the medial and lateral ganglionic eminences, the same germinal zones that produce GABAergic neurons that migrate to the cerebral cortex. In particular, the basal ganglia tend to be dysmorphic in appearance in patients with

Brain Anomaly Imaging Checklist

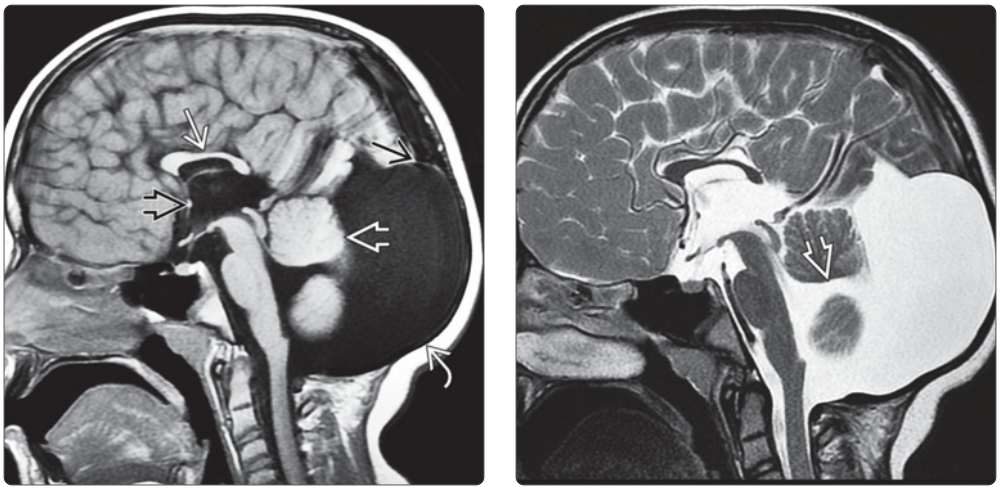
Anomaly	Findings
Anomalies of the Cerebral Cortex	
Agyria/pachygyria	Thick cortex, smooth inner margin, few shallow sulci
Polymicrogyria	Thin undulating cortex, irregular inner margin
Cobblestone cortex	Thick cortex, irregular inner margin, abnormal myelin
Focal cortical dysplasia	Blurred gray-white junction, ± abnormal myelination
White Matter Abnormalities With Cortical Malformation	
Polymicrogyria	Enlarged perivascular spaces
Cobblestone cortex	Delayed myelination, patchy hypomyelination
Congenital cytomegalovirus	Deep layers of hypomyelination/gliosis
Focal cortical dysplasia	Focal subcortical hypomyelination
Malformations Associated With Absent Septi Pellucidi	
Septooptic dysplasia	
Holoprosencephaly	
Bilateral schizencephaly	
Bilateral polymicrogyria	
Rhombencephalosynapsis	
Malformations with prolonged severe hydrocephalus	

subcortical heterotopia. In addition, the hippocampi are often abnormal in malformations of cortical development. In patients with lissencephaly, in particular, the hippocampi are incompletely folded. Sometimes, the only structural abnormalities in children with developmental delay are hippocampal; always look to make sure that they are fully folded and not too round.

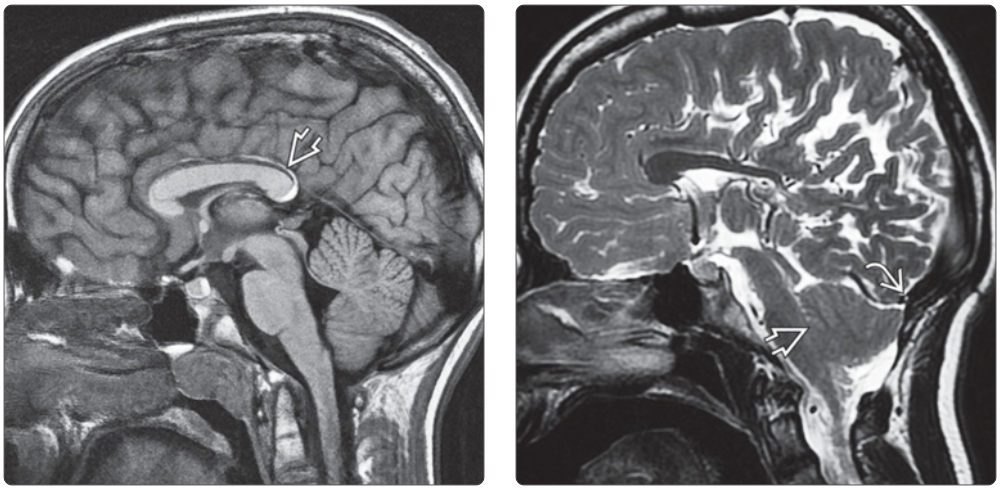
Always look at the entire interhemispheric fissure (IHF); if the cerebral hemispheres are continuous across the midline, holoprosencephaly should be diagnosed. In severe holoprosencephalies, the interhemispheric fissure is completely absent, whereas in milder forms of holoprosencephaly certain areas of the interhemispheric fissure will be absent (anterior IHF in semilobar holoprosencephaly, central IHF in syntelencephaly). Look at the septum pellucidum; absence of the septum is seen in corpus callosum dysgenesis/agenesis, septo-optic dysplasia, and in some cases of schizencephaly or bilateral polymicrogyria. While checking the septum, look at the lateral ventricles to ensure that they are normal in size and shape. Abnormally enlarged trigones and temporal horns are often associated with callosal anomalies and pachygyria. Enlarged frontal horns are often seen in bilateral frontal polymicrogyria.

Don't forget to look carefully at the posterior fossa; anomalies of the brainstem and cerebellum are commonly overlooked. Make sure that the 4th ventricle and cerebellar vermis are normally sized. In newborns, the vermis should extend from the inferior colliculi to the obex, while infants and older children should have a vermis that extends from the intercollicular sulcus to the obex. Also, make sure you see normal vermian fissures. If the fissuration of the vermis looks abnormal, look at an axial or coronal image to make sure the vermis is present; if the cerebellar hemispheres are continuous without a vermis between them, make a diagnosis of rhombencephalosynapsis. If the 4th ventricle has an abnormal rectangular shape (with a horizontal superior margin) with a narrow isthmus and small vermis, think about a molar tooth malformation. To confirm this diagnosis, look for the molar tooth sign of the lower midbrain, consisting of large, horizontal superior cerebellar peduncles extending posteriorly toward the cerebellum, and a longitudinal cleft in the superior vermis. Make sure that the components of the brainstem are of normal size; in a child, the height of the pons should be double that of the midbrain on the midline sagittal image. An important clue can be provided by looking at the size of the pons compared to that of the cerebellar vermis. Since much of the anterior pons is composed of the decussation of the middle cerebellar peduncles, development hypoplasia of the cerebellum is nearly always associated with hypoplasia of the ventral pons. If the pons is normal in the setting of a small cerebellum, it is most likely that the cerebellum lost volume near the end of gestation or after birth. Remember that a small posterior fossa, intracranial **hypo**tension, **or** intracranial **hyper**tension can result in descent of the cerebellum below the foramen magnum. Look for causes of a small posterior fossa (clival anomaly, anomaly of the craniovertebral junction), intracranial hypertension (space-occupying mass, hydrocephalus), or evidence of intracranial hypotension (large dural venous sinuses, large pituitary gland, "slumping" brainstem) before making a diagnosis of Chiari 1 malformation. Finally, remember to look at the size of the CSF spaces in the posterior fossa, enlargement of which may be a sign of abnormal leptomeningeal development.

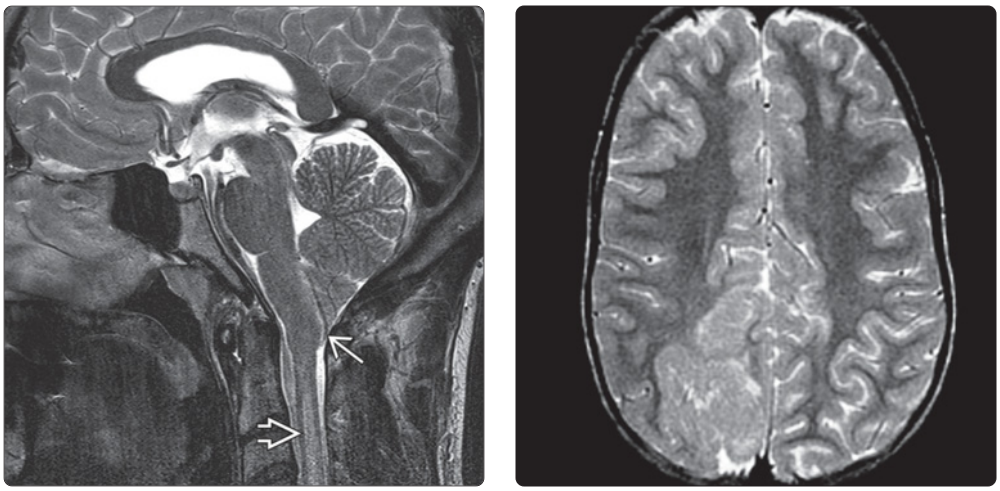
(Left) *Midline analysis using sagittal T1WI MR shows classic findings of Dandy Walker spectrum with a large posterior fossa cyst, high torcular and a small, upwardly rotated vermis. There is also a significant commissural anomaly with only a small corpus callosum remnant present. The rostrum and splenium are absent. The anterior commissure is present and appears normal.* **(Right)** *T2WI in the same case shows the 4th ventricle is open dorsally, contiguous with the huge posterior fossa cyst.*

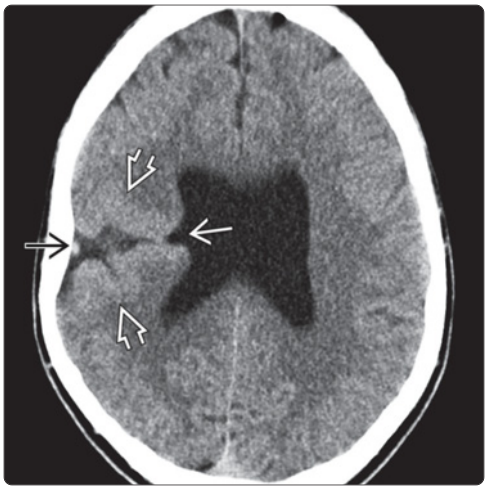


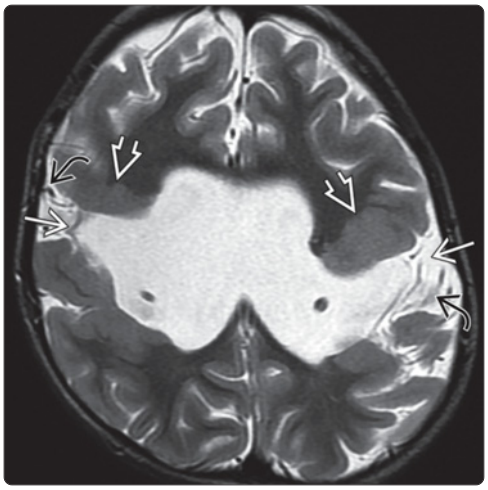
(Left) *Sagittal T1WI shows a hypoplastic callosum rostrum and splenium, plus a small interhemispheric lipoma.* **(Right)** *Sagittal T2WI shows a very small posterior fossa with a low-lying torcular and an elongated 4th ventricle that lacks a fastigium. This patient has a classic Chiari 2 malformation.*



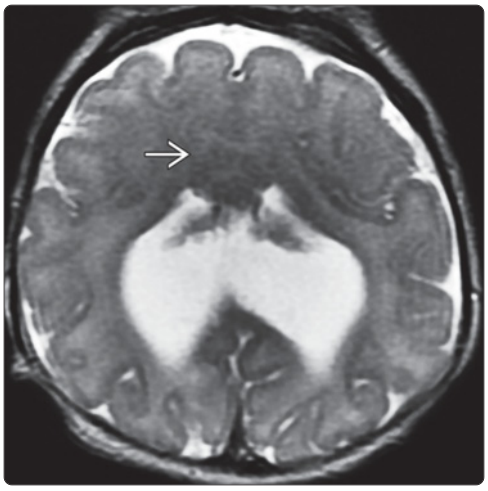
(Left) *Midline analysis of a sagittal T2WI shows a normal-sized posterior fossa. The cerebellar tonsils are pointed and displaced inferiorly 1 cm below the foramen magnum. Note cord hyperintensity, suggesting a "pre-syrinx" state in this case of Chiari 1 malformation.* **(Right)** *Axial T2WI in the same case shows the mass-like thickening of the right medial parietal gray matter and distorted sulcal-gyral pattern of cortical dysplasia.*

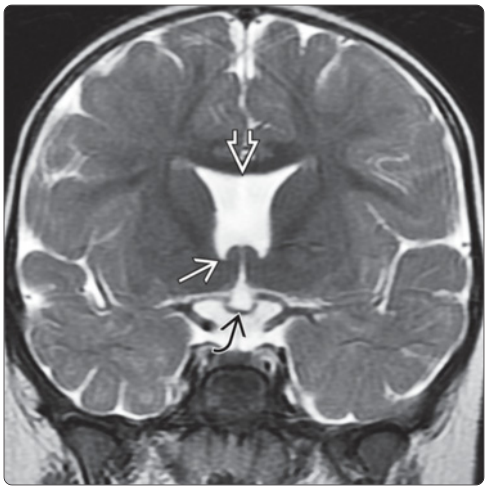




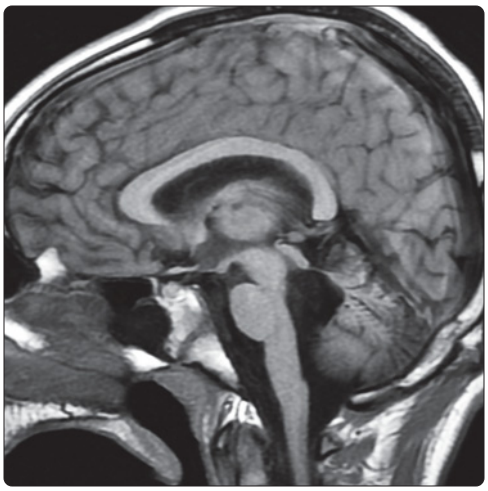


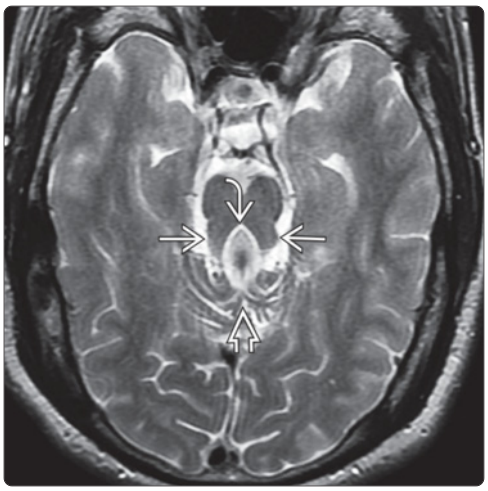
(Left) *Axial NECT scan in an 18-year-old male with seizures shows a unilateral schizencephalic cleft extending from the pial surface of the brain ⇨ to the ventricle. Note the characteristic CSF "nipple" ➡ at the ventricular margin. The cleft is lined by thickened, dysplastic gray matter ➡.* **(Right)** *Axial T2WI shows bilateral schizencephalic clefts ➡ lined by dysplastic gray matter ➡. Note the abnormal cortical veins ⇨ associated with the clefts.*





(Left) *Axial T2WI MR allows analysis of midline and shows absent interhemispheric fissure in frontal lobes (white matter continuous across midline ➡). This finding, plus the absence of frontal horns, gives the diagnosis of holoprosencephaly.* **(Right)** *Analysis of coronal images shows a squared-off appearance to the lateral ventricles with inferiorly pointed frontal horns ➡, absent septum pellucidum ➡, and hypoplastic optic chiasm ⇨ characteristic of septooptic dysplasia.*





(Left) *Midline analysis of posterior fossa structures shows an upwardly convex superior 4th ventricle and a dysplastic-appearing vermis.* **(Right)** *Axial T2WI in the same case shows the elongated 4th ventricle ➡, cleft vermis ➡, and thickened, horizontally oriented superior cerebellar peduncles ➡ forming the classic molar tooth sign of Joubert syndrome.*

Chiari 1

KEY FACTS

TERMINOLOGY

- Chiari 1 malformation (CM1)
  - CM1: Constellation of findings (not a disease, not simply a measurement)
- No clear consensus definition of what constitutes CM1
  - Traditional: Elongated, peg-shaped cerebellar tonsils extend below foramen magnum into upper cervical spinal canal
  - The "5 mm" criterion for tonsillar displacement below basion-opisthion line is flawed criterion
    - Tonsillar position is a morphometric distribution and also changes with time
    - Tonsillar position **plus** shape/configuration (elongated, pointed)
    - Tonsillar position also risk factor for syrinx (the lower the tonsils, the higher the risk)
  - "Crowding" of posterior fossa with compression of CSF spaces
  - Evaluate skull base, upper cervical spine
    - PF may be undersized, shallow (especially children)
    - Short clivus, CVJ assimilation anomalies common

TOP DIFFERENTIAL DIAGNOSES

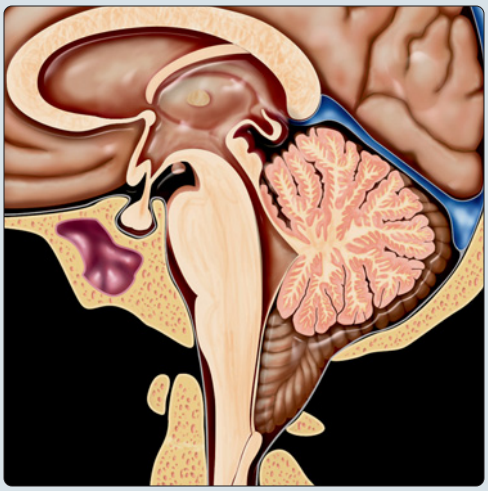
- Normal anatomic variant (normal-shaped tonsils below FM)
- Intracranial hypotension
  - Critical not to mistake this for CM1
- Acquired tonsillar herniation (don't call "acquired Chiari 1")
- "Complex Chiari malformation" ("Chiari 1.5" is neurosurgical term)
  - Tonsillar herniation complicated by other abnormalities (caudal descent of brainstem with low-lying obex, bony anomalies, such as "retroflexed" odontoid)

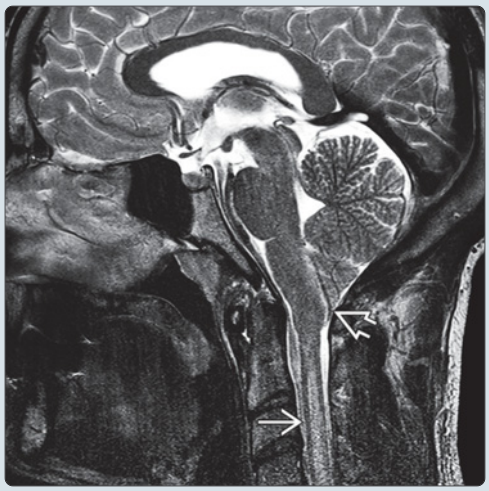
CLINICAL ISSUES

- Up to 50% of CM1 is asymptomatic

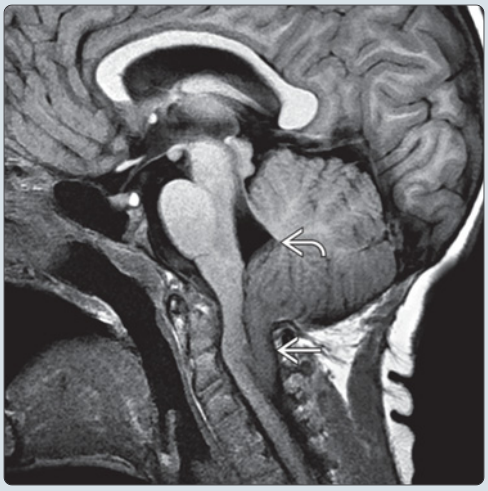
DIAGNOSTIC CHECKLIST

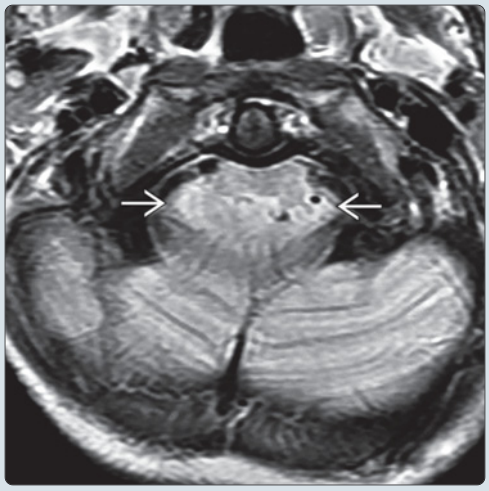
- Look for findings of intracranial hypotension before making diagnosis of CM1





(Left) *Sagittal graphic demonstrates pointed peg-like tonsils extending below foramen magnum, elongating the normally positioned 4th ventricle.* **(Right)** *Sagittal T2WI in a 23-year-old male with classic Chiari 1 malformation shows low-lying pointed tonsils and hyperintensity in the upper cervical cord that may represent "presyrinx" state.*





(Left) *Sagittal T1WI MR shows normal 4th ventricle position and appearance. The fastigium is in normal position, helping to distinguish from Chiari 2 malformation. There is inferior displacement of the ectopic cerebellar tonsils through the foramen magnum with odontoid process retroflexion and clivus foreshortening.* **(Right)** *Axial T2WI MR confirms inferior displacement of ectopic cerebellar tonsils through the foramen magnum, producing foramen magnum crowding.*

TERMINOLOGY

Abbreviations

- Chiari 1 malformation (CM1)

Synonyms

- Chiari type I

Definitions

- No clear consensus definition of what constitutes CM1
  - Traditional: Elongated, peg-shaped cerebellar tonsils extend below foramen magnum into upper cervical spinal canal
    - The "5 mm" criterion for tonsillar displacement below basion-opisthion line is flawed criterion
      - Tonsillar position is a morphometric distribution and also changes with time
  - CM1: Constellation of findings (not a disease, not simply a measurement)
    - Tonsillar position **plus** shape/configuration (elongated, pointed)
      - Tonsillar position also risk factor for syrinx (the lower the tonsils, the higher the risk)
    - "Crowding" of posterior fossa with compression of CSF spaces
    - Evaluate skull base, upper cervical spine
      - Short clivus, craniovertebral junctioni (CVJ) assimilation anomalies common

IMAGING

General Features

- Best diagnostic clue
  - Combination of inferiorly displaced "pointed" tonsils with "crowded" posterior fossa, effaced retrocerebellar CSF spaces at foramen magnum/upper cervical level
- Morphology
  - Low-lying, pointed peg-like tonsils with oblique vertical sulci, elongated but normally located 4th ventricle (normal dorsally-pointed fastigium)

CT Findings

- Bone CT
  - Often normal; abnormal cases → short clivus, CVJ segmentation/fusion anomalies

MR Findings

- T1WI
  - Pointed (not rounded) tonsils ≥ 5 mm below foramen magnum
  - "Tight" foramen magnum with small/absent cisterns
  - ± 4th ventricle elongation, hindbrain anomalies
- T2WI
  - Oblique tonsillar folia (sergeant's stripes like)
  - ± short clivus → apparent descent of 4th ventricle, medulla
  - ± syringohydromyelia (14-75%)
- MR cine
  - Disorganized CSF pulsation, ↑ brainstem/cerebellar tonsil motion → ↑ peak systolic velocity, ↓ flow through foramen magnum
    - Tonsillar pulsatility may be better predictor than CSF flow

Imaging Recommendations

- Best imaging tool
  - Multiplanar MR ± sagittal cine MR

DIFFERENTIAL DIAGNOSIS

Normal Tonsillar Displacement Below Foramen Magnum

- Tonsils may normally lie below foramen magnum
- Unless also pointed, with "crowded" appearance around FM, probably not CM1 and is normal anatomic variant

Intracranial Hypotension

- "Pull from below" (LP shunt, CSF leak) secondary to intracranial hypotension
  - "Sagging" brainstem, tonsillar herniation, smooth dural enhancement, dilated epidural plexus, retrospinal C1/C2 fluid collection, spinal hygroma
- Don't mistake this for Chiari 1
  - FM/C1 decompression can exacerbate CSF leak with disastrous consequences

Acquired Tonsil Herniation (Acquired Chiari 1)

- Acquired basilar invagination → small posterior fossa
  - Osteogenesis imperfecta
  - Paget disease
  - Craniosynostosis
  - Rickets
  - Achondroplasia
  - Acromegaly
- "Push from above"
  - Chronic VP shunt; thick skull, premature sutural fusion, arachnoidal adhesions
  - ↑ intracranial pressure (ICP), intracranial mass

Complex Chiari Malformation

- Sometimes called "Chiari 1.5" by neurosurgeons
  - Tonsillar herniation with caudal descent of brainstem (low-lying obex, nucleus gracilis)
  - Bony anomalies (such as retroflexed odontoid, C0-C1 assimilation, short clivus, etc.)
  - More severe clinical phenotype than CM1, may require anterior, as well as posterior, decompression

PATHOLOGY

General Features

- Etiology
  - Hydrodynamic theory
    - Systolic piston-like descent of impacted tonsils/medulla → plugging of CSF pathway at foramen magnum
    - During diastole, rapid recoil of brainstem/tonsils disimpacts foramen magnum, permits normal CSF diastolic pulsation
  - Posterior fossa underdevelopment theory
    - Underdeveloped occipital somites of paraxial mesoderm → small posterior fossa → secondary tonsillar herniation
    - But: Not all CM1 patients have small posterior fossae
- Genetics

- Autosomal dominant inheritance with reduced penetrance or autosomal recessive inheritance
- Syndromic/familial associations
  - Velocardiofacial/microdeletion chromosome 22, Williams syndrome, craniosynostosis, achondroplasia, Hajdu-Cheney syndrome, and Klippel-Feil syndrome
- Associated abnormalities
  - 4th occipital sclerotome syndromes (50%): Short clivus, CVJ segmentation/fusion anomalies
  - Osseous skull base/skeletal anomalies (25-50%)
    - Scoliosis ± kyphosis (42%); left thoracic curve
    - Retroflexed odontoid process (26%)
    - Platybasia, basilar invagination (25-50%)
    - Klippel-Feil syndrome (5-10%)
    - Incomplete C1 ring ossification (5%)
    - Atlantooccipital assimilation (1-5%)
  - Syringomyelia (30-60%); 60-90% in symptomatic CM1 patients
    - Most common C4-C6; holocord hydrosyringomyelia, cervical/upper thoracic syrinx, syringobulbia uncommon
  - Hydrocephalus (11%)
- FM arachnoid adhesions, obstruction → decreased communication between cranial, spinal CSF compartments

Staging, Grading, & Classification

- Diagnostic criteria: Herniation of at least 1 cerebellar tonsil > 5 mm or herniation of both tonsils ≥ 3-5 mm below line connecting basion with opisthion
  - Herniation of both tonsils ≥ 3-5 mm below foramen magnum + syrinx, cervicomedullary kink, 4th ventricular elongation, or pointed tonsils → congenital CM1
  - Tonsil herniation ≤ 5 mm does not exclude CM1

Gross Pathologic & Surgical Features

- Herniated, sclerotic tonsils grooved by opisthion
- Arachnoidal scarring and adhesions at foramen magnum

Microscopic Features

- Tonsillar softening or sclerosis with Purkinje/granular cell loss

CLINICAL ISSUES

Presentation

- Most common signs/symptoms
  - Up to 50% asymptomatic (especially if ≤ 5 mm caudal displacement)
  - Most common symptoms at presentation are headache, neck pain
  - Symptomatic patients present with constellation of findings
    - Sudden death (rare)
    - Suboccipital headache, cranial nerve palsy, ocular disturbances, otoneurologic dysfunction
    - Cord motor or sensory abnormalities, gait disturbance, neuropathic joint
    - Tonsillar herniation > 12 mm nearly always symptomatic; ~ 30% with tonsils 5-10 mm below foramen magnum asymptomatic
    - CM1 patients with syrinx nearly always present with symptoms referable to syrinx; if syrinx extends into medulla, bulbar symptoms predominate
  - Trauma is common precipitating event for symptom onset (24%)
- Clinical profile
  - Clinical CM1 syndrome: Headache, pseudotumor-like episodes, Ménière disease-like syndrome, lower cranial nerve and spinal cord signs

Demographics

- Age
  - 10 months to 65 years; syrinx, congenital CVJ anomalies hasten presentation
- Gender
  - F > M (3:2)
- Epidemiology
  - Incidence: 0.01-0.6% all age groups, 0.9% pediatric patient groups
  - Asymptomatic CM1 discovered incidentally on imaging relatively common; perhaps best described as cerebellar tonsillar ectopia)

Natural History & Prognosis

- Natural history not clearly understood
  - Many patients asymptomatic, CM1 discovered incidentally
  - Increasing ectopia → ↑ risk of syrinx
- Children respond better to treatment than adults

DIAGNOSTIC CHECKLIST

Consider

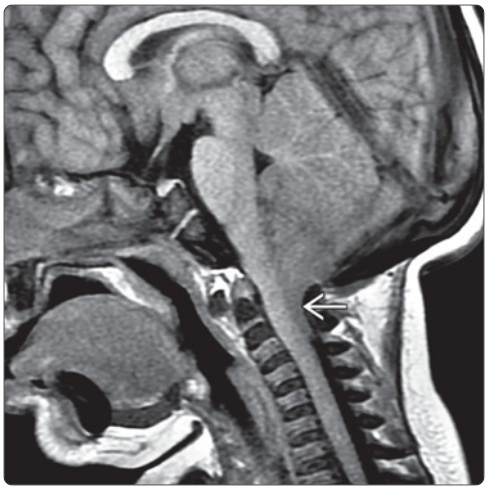
- Degree of tonsillar correlates with clinical severity
- Unless tonsils > 5 mm and pointed ± "crowded posterior fossa" probably not clinically significant

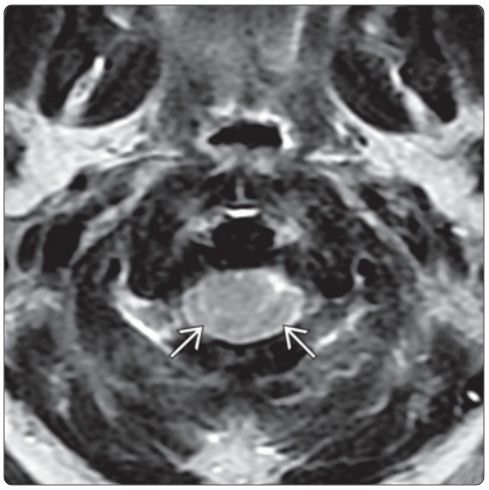
Image Interpretation Pearls

- Don't use 5 mm cut-off point alone to diagnosis CM1 (with pathological and clinical implications)

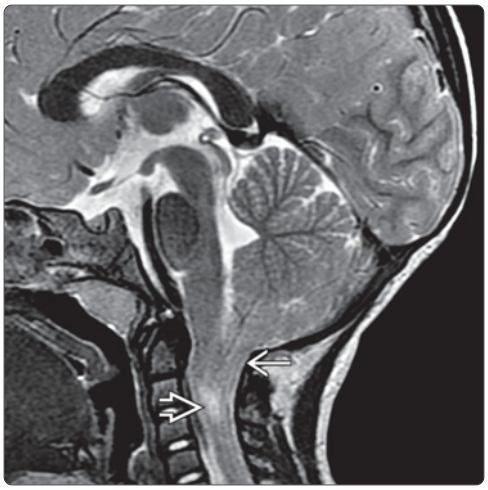
SELECTED REFERENCES

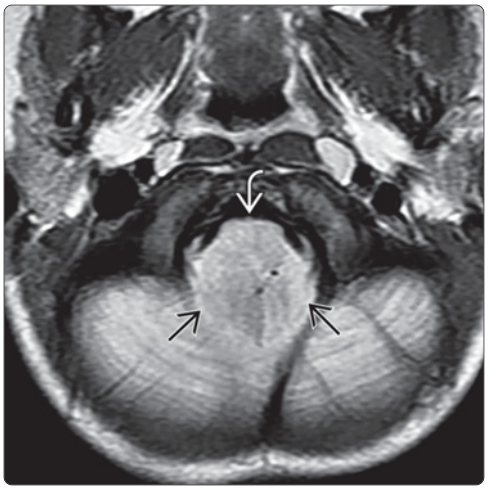
1. Alperin N et al: Imaging-Based Features of Headaches in Chiari Malformation Type I. Neurosurgery. ePub, 2015
2. Bond AE et al: Changes in cerebrospinal fluid flow assessed using intraoperative MRI during posterior fossa decompression for Chiari malformation. J Neurosurg. 1-8, 2015
3. Quon JL et al: Multimodal evaluation of CSF dynamics following extradural decompression for Chiari malformation Type I. J Neurosurg Spine. 1-9, 2015
4. Roller LA et al: Demographic confounders in volumetric MRI analysis: is the posterior fossa really small in the adult Chiari 1 malformation? AJR Am J Roentgenol. 204(4):835-41, 2015
5. Strahle J et al: Syrinx location and size according to etiology: identification of Chiari-associated syrinx. J Neurosurg Pediatr. 1-9, 2015
6. Godzik J et al: Relationship of syrinx size and tonsillar descent to spinal deformity in Chiari malformation Type I with associated syringomyelia. J Neurosurg Pediatr. 13(4):368-74, 2014
7. Lee S et al: Surgical outcome of Chiari I malformation in children: clinico-radiological factors and technical aspects. Childs Nerv Syst. 30(4):613-23, 2014
8. McVige JW et al: Imaging of Chiari type I malformation and syringohydromyelia. Neurol Clin. 32(1):95-126, 2014
9. Moore HE et al: Magnetic resonance imaging features of complex Chiari malformation variant of Chiari 1 malformation. Pediatr Radiol. 44(11):1403-11, 2014



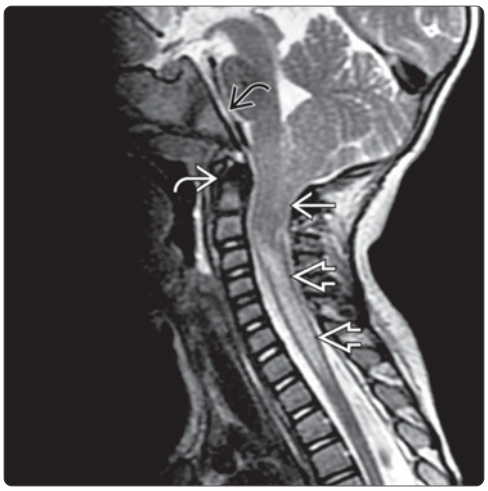


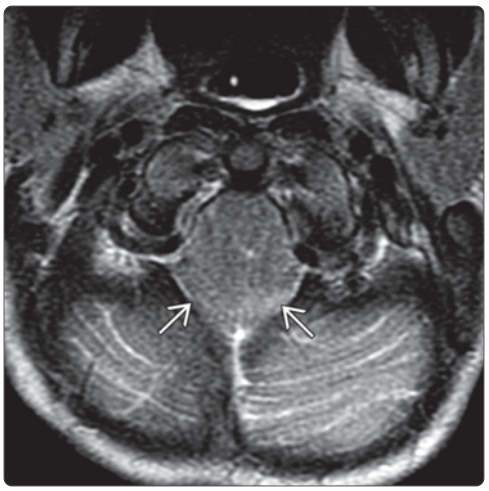
(Left) *Sagittal T1WI MR (osteopetrosis) demonstrates severe cerebellar tonsillar ectopia, with extension of the elongated cerebellar tonsils into the upper cervical canal to the C2-C3 level. Hypointense marrow signal reflects diffuse sclerosis.* **(Right)** *Axial T2WI MR (osteopetrosis) reveals characteristic crowding of the foramen magnum related to CM1, with extension of the ectopic cerebellar tonsils into the upper cervical canal.*





(Left) *Sagittal T2WI MR (asymptomatic CM1) demonstrates severe cerebellar tonsillar ectopia. The tonsils produce deformation of the upper cervical spinal cord and abnormal cord T2 prolongation reflecting edema and potentially an early presyrinx state.* **(Right)** *Axial T2WI MR (asymptomatic CM1) reveals caudal extension of ectopic cerebellar tonsils into the foramen magnum, completely effacing the basilar cisterns and displacing the adjacent spinal cord.*





(Left) *Sagittal T2WI MR depicts marked cerebellar tonsillar ectopia with normal tectum and 4th ventricular position. The clivus is mildly foreshortened and dens retroflexed. There is central intramedullary edema in the cervical spinal cord without frank syringomyelia, a finding that has been described as a "presyrinx" state.* **(Right)** *Axial T2WI MR confirms displacement of the ectopic cerebellar tonsils through the crowded foramen magnum, producing foramen magnum crowding.*

Chiari 2

KEY FACTS

TERMINOLOGY

- Complex hindbrain malformation
- Virtually 100% associated with neural tube closure defect (NTD), usually lumbar myelomeningocele (MMC)

IMAGING

- Crowded posterior fossa, widened tentorial incisura, tectal beaking, inferior vermian displacement
- Cascade or waterfall of cerebellum/brainstem downward
  - Uvula/nodulus/pyramid of vermis → sclerotic peg
  - Cervicomedullary kink (70%)
  - Towering cerebellum → compresses midbrain, associated beaked tectum
  - 4th ventricle elongated with no posterior point (fastigium)
- Lacunar skull: Focal calvarial thinning with scooped-out appearance

TOP DIFFERENTIAL DIAGNOSES

- Chiari 1 malformation
- Chiari 3 malformation
- Intracranial CSF hypotension
- Severe, chronic shunted hydrocephalus (congenital)

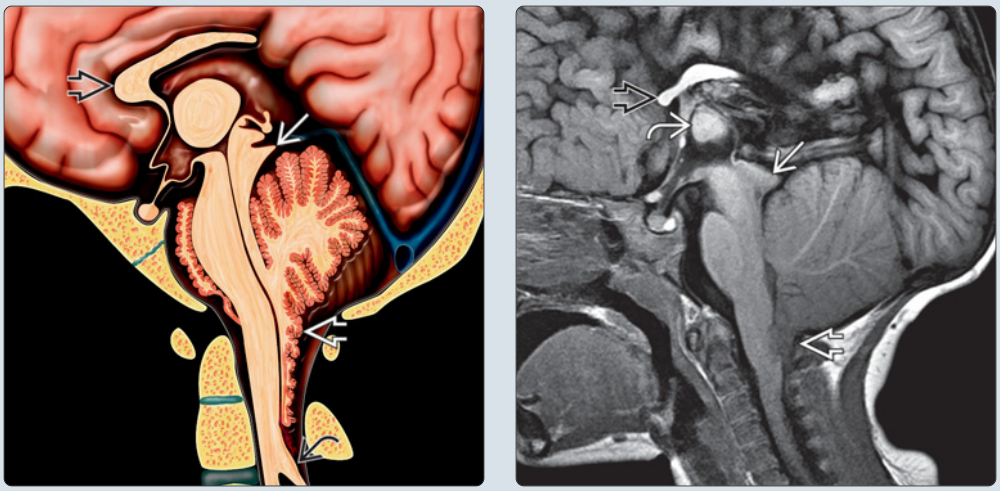
PATHOLOGY

- Secondary to sequelae of CSF leakage through open spinal dysraphism during gestation (4th fetal week)
- Methylenetetrahydrofolate reductase (*MTHFR*) mutations → abnormal folate metabolism
- Spine- and brain/skull-associated anomalies common

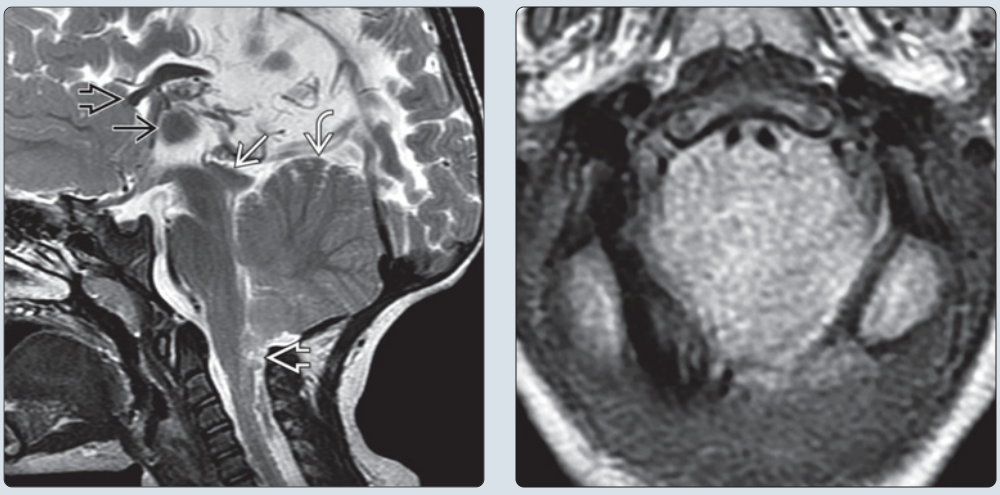
DIAGNOSTIC CHECKLIST

- Towering cerebellum, downward vermian displacement, ± brainstem compression diagnostic for Chiari 2 especially if MMC present

(Left) *Sagittal graphic of the posterior fossa and upper cervical spine demonstrates characteristic findings of Chiari 2 malformation, including callosal dysgenesis, tectal beaking, small posterior fossa, vermian ectopia, and medullary kinking.* **(Right)** *Sagittal T1WI MR reveals characteristic Chiari 2 malformation findings. Note the tectal beaking, vermian displacement through the foramen magnum, large massa intermedia, and dysplastic corpus callosum.*



(Left) *Sagittal T2WI MR confirms characteristic findings of Chiari 2 malformation, including tectal beaking, vermian displacement through the foramen magnum, "towering" cerebellum, large massa intermedia, and dysplastic corpus callosum.* **(Right)** *Axial T2WI MR shows characteristic posterior fossa crowding at the foramen magnum, reflecting small dimensions of the posterior fossa combined with cerebellar ectopia and vermian displacement through the foramen magnum.*



TERMINOLOGY

Abbreviations

- Chiari 2 malformation (CM2)

Synonyms

- Chiari type II

Definitions

- Complex hindbrain malformation
  - Virtually 100% associated with neural tube closure defect (NTD), usually lumbar myelomeningocele (MMC)
    - Rare reports in closed spinal dysraphism (probably misinterpreted Chiari 1)

IMAGING

General Features

- Best diagnostic clue
  - Downward herniation of cerebellar vermis plus myelomeningocele
- Location
  - Posterior fossa (PF), upper cervical spine; syrinx may involve entire cord
- Size
  - Posterior fossa smaller than normal
- Morphology
  - Cerebellum "wraps" around medulla and "towers" through incisura, with "beaked" tectum and heart-shaped midbrain

CT Findings

- NECT
  - Crowded posterior fossa, widened tentorial incisura, tectal beaking, and inferior vermian displacement
- Bone CT
  - Small PF
    - Low-lying tentorium/torcular inserts near foramen magnum
    - Large, funnel-shaped foramen magnum with "notched" opisthion
    - "Scalloped" posterior petrous pyramids, clivus
  - Posterior C1 arch anomalies (66%), enlarged cervical canal
  - Lacunar skull: Focal calvarial thinning with scooped-out appearance
    - Mostly resolved by 6 months, but some scalloping of inner table often persists into adulthood

MR Findings

- T1WI
  - Cascade or waterfall of cerebellum/brainstem downward
    - Uvula/nodulus/pyramid of vermis → sclerotic peg
    - Cervicomedullary kink (70%)
    - Towering cerebellum → compresses midbrain, associated beaked tectum
    - 4th ventricle elongated with no posterior point (fastigium)
  - Open spinal dysraphism, MMC ~ 100% (lumbar > > cervical)
  - Hydrosyringomyelia (20-90%)
- T2WI
  - Similar to T1WI + hyperintense, gliotic cerebellar tissue
  - ± 4th ventricular lesions (rare)
    - Roof of 4th ventricle adjacent/within choroid plexus
    - Glial or arachnoidal cysts, glial or choroidal nodules, subependymoma
- MR cine
  - Phase contrast cine MR → restricted CSF flow through foramen magnum
- Diffusion tensor imaging (DTI)
  - Fractional anisotropy (FA) map and quantitative analysis defines callosal dysgenesis, confirms abnormal white matter architecture

Ultrasonographic Findings

- Grayscale ultrasound
  - Fetal obstetrical ultrasound (US) pivotal for early diagnosis
    - MMC may be identified as early as 10 weeks
    - Characteristic brain findings (lemon and banana signs) seen as early as 12 weeks

Imaging Recommendations

- Best imaging tool
  - Multiplanar MR for initial brain, spine evaluation
  - Follow-up brain CT or MR to assess hydrocephalus
  - Cervical spine MR for progressive brainstem or spinal symptoms

DIFFERENTIAL DIAGNOSIS

Chiari 1

- No association with myelomeningocele
- Tonsillar herniation (not vermis)

Chiari 3

- Brainstem, cerebellum herniating through C1-C2 spinal dysraphism

Intracranial Hypotension

- Symptomatic expression of low CSF pressure; distinguishable by clinical onset and symptoms
- Slumping posterior fossa with pons compressed against clivus, dural thickening/enhancement

Severe, Chronic Shunted Hydrocephalus (Congenital)

- May cause collapsed brain, upwardly herniated cerebellum

PATHOLOGY

General Features

- Etiology
  - Secondary to sequelae of CSF leakage through open spinal dysraphism during gestation (4th fetal week)
    - Abnormal neurulation → CSF escapes through NTD → failure to maintain 4th ventricular distention → hypoplastic PF chondrocranium → displaced/distorted PF contents
    - Exceedingly rare cases of closed spinal dysraphism with Chiari 2 malformation may contradict this theory
  - Alternative theory proposes association between Chiari 2 malformation and myelomeningocele is due to rostral and caudal neural tube dysgenesis

- Genetics
  - Methylenetetrahydrofolate reductase (*MTHFR*) mutations associated with abnormal folate metabolism
    - *MTHFR* mutations **plus** folate deficiency → ↑ risk NTD → Chiari 2
    - 4-8% risk of 2nd affected child
- Associated abnormalities
  - Spine
    - Open dysraphism (MMC) ~ 100% (lumbar > > cervical)
    - Posterior arch C1 anomalies (66%)
    - Syringohydromyelia (20-90%)
    - Diastematomyelia (5%)
    - Klippel-Feil syndrome
    - Cervical myelocystocele
  - Brain/skull
    - Corpus callosum (CC) dysgenesis (90%), aqueductal stenosis, rhombencephalosynapsis, gray matter malformations, absent septum pellucidum, fused forniceal columns
    - Lacunar skull (Lückenschädel)
- Hydrocephalus and severity of brain malformation relate to size of PF, degree of caudal hindbrain descent

Gross Pathologic & Surgical Features

- Small PF → contents shift down into cervical spinal canal
  - Cerebellar hemispheres/tonsils "wrap" around medulla
  - Pons/cranial nerve roots often elongated
  - Compressed/elongated/low 4th ventricle → pouch in cervical canal
  - Medullary kink
  - ± syringohydromyelia

Microscopic Features

- Purkinje cell loss, sclerosis within herniated tissues

CLINICAL ISSUES

Presentation

- Most common signs/symptoms
  - Neonate: MMC, enlarging head circumference ± hydrocephalus symptoms
  - Older child/adult: Clinical hydrocephalus, symptoms referable to tethered cord (MMC repair)
  - All age groups: Varying degrees of lower extremity paralysis/sphincter dysfunction/bulbar signs
- Clinical profile
  - Usually presents within context of known MMC
    - Infants: Enlarging head circumference
    - Child/adult: Known Chiari 2 malformation, signs of hydrocephalus/shunt failure ± bulbar symptoms
- Laboratory
  - Fetal screening: ↑ alpha-fetoprotein

Demographics

- Age
  - Usually presents at birth with MMC ± hydrocephalus
- Gender
  - M = F
- Epidemiology
  - Incidence: 0.44 per 1,000 births, ↓ with folate replacement therapy

Natural History & Prognosis

- Most common cause of death in MMC
  - Brainstem compression/hydrocephalus, intrinsic brainstem "wiring" defects
- Progression of spinal neurological deficits is rare; suspect hydrocephalus, associated undiagnosed spinal deformity (diastematomyelia), tethered cord
- Cerebellar tonsil/vermian ectopia may "improve" (ascend) following postnatal repair

Treatment

- Folate supplement for pregnant mothers (preconception → 6 weeks post conception) significantly decreases MMC risk
- Surgical management
  - Chiari decompression with resection of posterior foramen magnum, C1 ring
  - CSF diversion/shunting
  - Fetal MMC repair in selected patients may ameliorate Chiari 2 severity

DIAGNOSTIC CHECKLIST

Consider

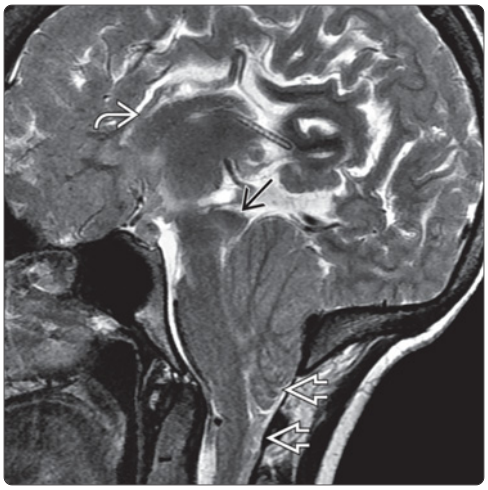
- Brain/spinal axis MR to detect presence of Chiari 2, assess severity, look for complications

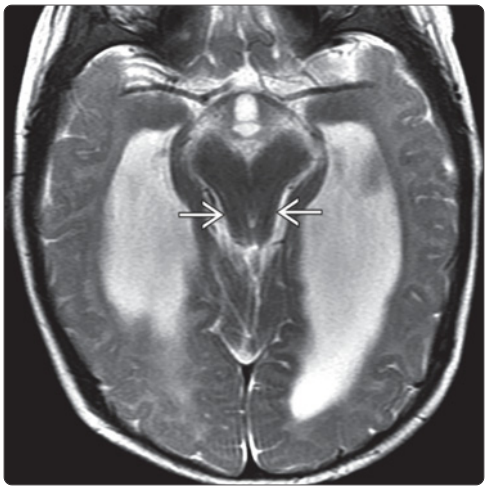
Image Interpretation Pearls

- Low torcular herophili indicates small posterior fossa
- CT or MR showing towering cerebellum, downward vermian displacement, ± brainstem compression diagnostic of Chiari 2

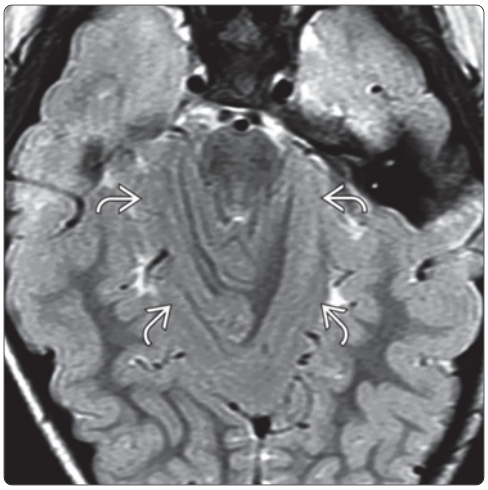
SELECTED REFERENCES

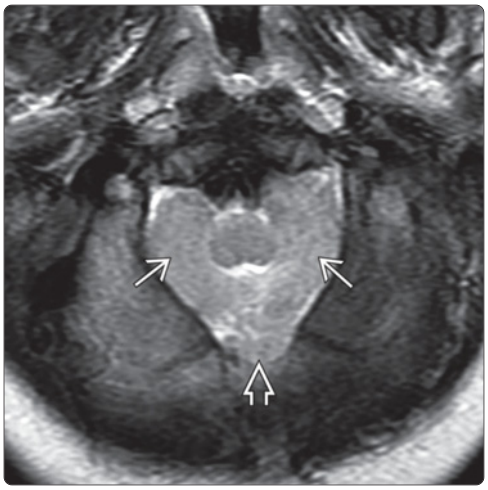
1. Cesmebasi A et al: The Chiari malformations: A review with emphasis on anatomical traits. Clin Anat. 28(2):184-194, 2015
2. Akbari SH et al: Surgical management of symptomatic Chiari II malformation in infants and children. Childs Nerv Syst. Epub ahead of print, 2013
3. Messing-Jünger M et al: Primary and secondary management of the Chiari II malformation in children with myelomeningocele. Childs Nerv Syst. 29(9):1553-62, 2013
4. Sweeney KJ et al: Spinal level of myelomeningocele lesion as a contributing factor in posterior fossa volume, intracranial cerebellar volume, and cerebellar ectopia. J Neurosurg Pediatr. 11(2):154-9, 2013
5. Citton V et al: Chiari 2 without spinal dysraphism: does it blow a hole in the pathogenesis? J Child Neurol. 27(4):536-9, 2012
6. Geerdink N et al: Essential features of Chiari II malformation in MR imaging: an interobserver reliability study--part 1. Childs Nerv Syst. 28(7):977-85, 2012
7. Juranek J et al: The cerebellum in children with spina bifida and Chiari II malformation: Quantitative volumetrics by region. Cerebellum. 9(2):240-8, 2010
8. Luigetti M et al: Improvement of obstructive sleep apneas caused by hydrocephalus associated with Chiari malformation Type II following surgery. J Neurosurg Pediatr. 6(4):336-9, 2010
9. Morota N et al: Postnatal ascent of the cerebellar tonsils in Chiari malformation Type II following surgical repair of myelomeningocele. J Neurosurg Pediatr. 2(3):188-93, 2008
10. Vinck A et al: Arnold-Chiari-II malformation and cognitive functioning in spina bifida. J Neurol Neurosurg Psychiatry. 77(9):1083-6, 2006



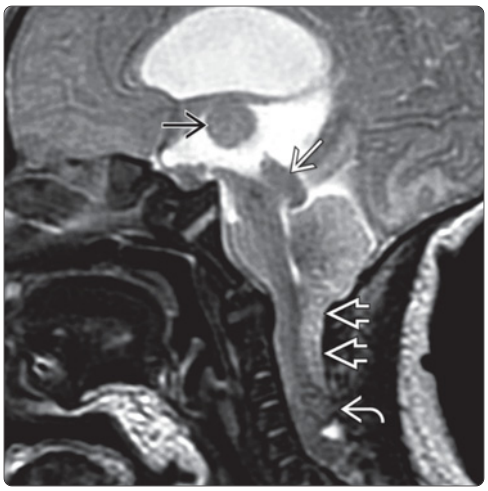


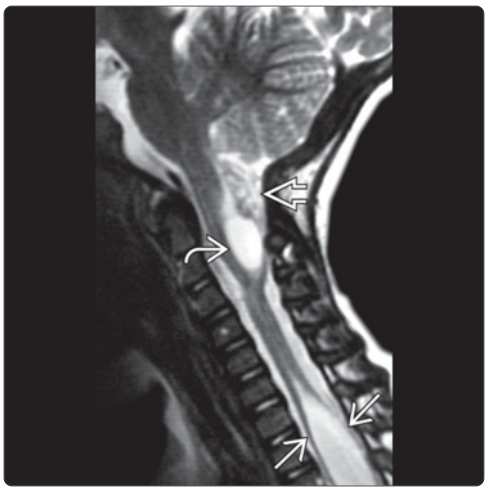
(Left) *Sagittal T2WI MR of the brain shows characteristic Chiari 2 findings, with very small posterior fossa size, prominent tectal beak, and vermian/tonsillar extension through the foramen magnum. The corpus callosum is severely dysplastic and the ventricles small following CSF shunting.* **(Right)** *Axial T2WI MR depicts enlargement of the occipital horns of the lateral ventricles (colpocephaly) related to callosal dysgenesis in conjunction with beaked tectum.*





(Left) *Axial T2WI MR at the posterior fossa level demonstrates the classic axial image manifestation of the towering cerebellum extending through the wide tentorial incisura.* **(Right)** *Axial T2WI MR performed at the foramen magnum level depicts characteristic crowding of the inferior posterior fossa. Both of the cerebellar tonsils, as well as vermis, are inferiorly displaced into the foramen magnum.*





(Left) *Sagittal T2WI MR depicts marked vermian ectopia and prominent medullary kink positioned lower than typically seen at the C4 level. Note also the dysplastic beaked tectum and prominent massa intermedia.* **(Right)** *Sagittal T2WI MR shows crowded posterior fossa with vermian ectopia, large cervicothoracic cord syrinx as well as sizable focal cervicomedullary syrinx (syringobulbia). Note the hyperintense gliotic changes of scarred vermis.*

Chiari 3

KEY FACTS

TERMINOLOGY

- Chiari 3 malformation (CM3)
- Synonyms: Chiari III, rhombencephalocele

IMAGING

- Low occipital or high cervical meningoencephalocele containing cerebellum ± brainstem, meninges, vessels, CSF
- Midline bone defect within supraoccipital bone, opisthion

TOP DIFFERENTIAL DIAGNOSES

- Isolated occipital encephalocele
- Other occipital encephaloceles
  - Iniencephaly
  - Syndromic occipital encephalocele

PATHOLOGY

- Severity classified by sac contents
- Cephalocele contents: Meninges, cerebellum, brainstem ± cervical cord, occipital poles, vasculature
  - Disorganized (neuronal migration anomalies, cortical dysplasias) and gliotic brain tissue
  - Lining of sac may show gray matter heterotopias
- Associated abnormalities: Corpus callosum anomalies, gray matter heterotopia, syringohydromyelia, tethered cord

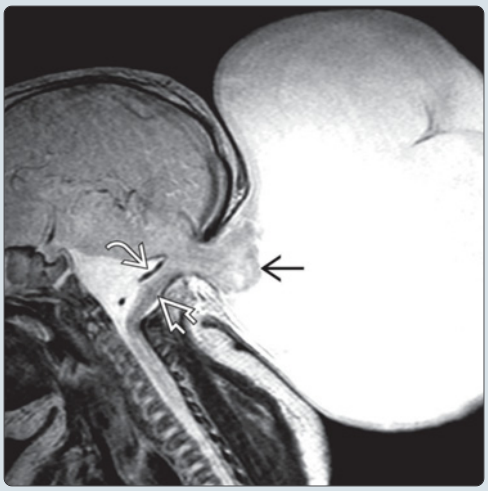
CLINICAL ISSUES

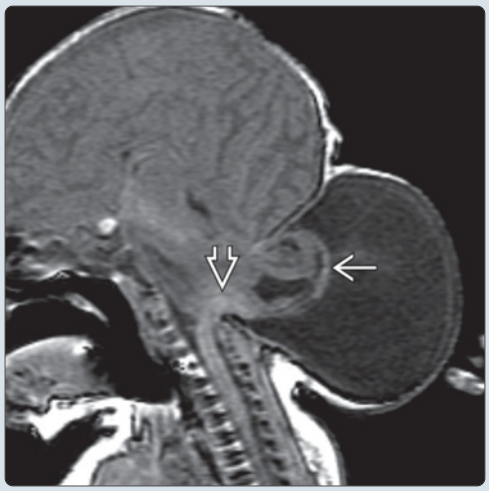
- Microcephaly, severe developmental delay, spasticity, hypotonia, seizures
- Mechanical brainstem traction, respiratory deterioration, lower cranial nerve dysfunction

DIAGNOSTIC CHECKLIST

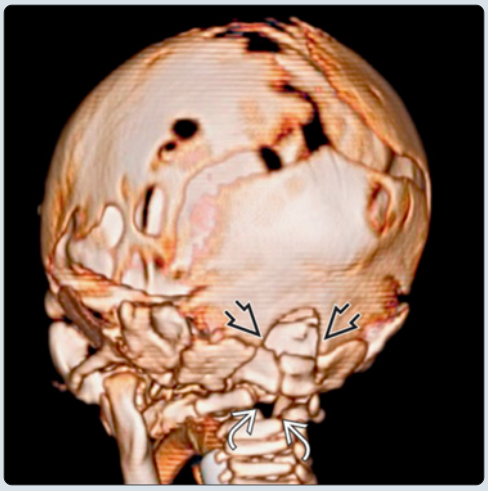
- Occipitocervical cephalocele containing cerebellum ± brainstem in conjunction with C1-C2 spina bifida = Chiari 3 malformation

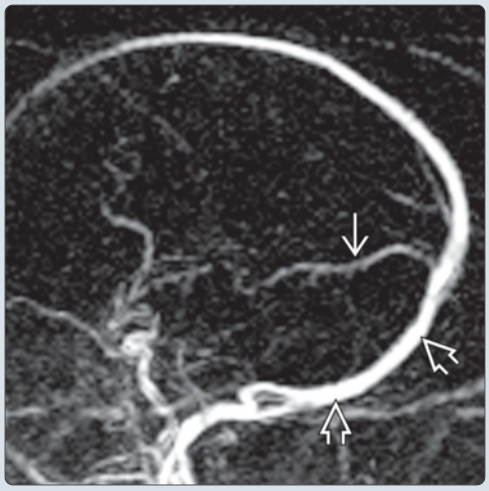
(Left) *Sagittal T2WI MR reveals a large defect in the ventral chondral portion of the supraoccipital bone and opisthion of foramen magnum. Gliotic cerebellar tissue protrudes into a large sac. Note the displacement of the brainstem and basilar artery.* **(Right)** *Sagittal T1WI MR shows a large meningoencephalocele composed of meninges, CSF, cerebellum, brainstem, and upper cervical spinal cord herniated through a bone defect in the lower occiput and upper cervical spine.*





(Left) *Bone CT 3D shaded surface rendering of the posterior calvaria/upper cervical spine in a Chiari 3 malformation (CM3) patient shows a large defect of the ventral chondral and squamous supraoccipital bones in conjunction with upper cervical spina bifida.* **(Right)** *Sagittal MRV demonstrates typical venous abnormalities of Chiari 3. The straight sinus and vein of Galen is severely hypoplastic. Large occipital sinuses rather than transverse sinuses are present.*





TERMINOLOGY

Synonyms

- Chiari III, rhombencephalocele

Definitions

- Combined cephalocele with myelocele herniating through high cervical ± low occipital dysraphic defect

IMAGING

General Features

- Best diagnostic clue
  - Skin-covered upper cervical meningoencephalocele containing cerebellum

CT Findings

- NECT
  - Midline posterior cephalocele containing cerebellum
  - Small posterior cranial fossa ± scalloped clivus, lacunar skull
- Bone CT
  - Opisthion, upper cervical osseous dysraphic bone defect
- CTA
  - Basilar artery "pulled" into defect along with brainstem into cephalocele sac
  - ± veins/dural sinuses within cephalocele sac
  - Anomalous &/or ptotic veins, dural sinuses

MR Findings

- T1WI
  - High cervical cephalocele sac containing meninges and cerebellum ± brainstem, upper cervical cord
  - Cisterns, 4th ventricle, dural sinuses may extend into cephalocele (50%)
- T2WI
  - Tissues in cephalocele sac may be bright (gliosis), strand-like (necrotic), or hypointense (hemorrhagic)

Imaging Recommendations

- Best imaging tool
  - Multiplanar brain MR with MRV to characterize occipitocervical encephalocele, vessels
  - Multiplanar bone CT to evaluate osseous defects

DIFFERENTIAL DIAGNOSIS

Isolated Occipital Encephalocele

- Spares foramen magnum, lacks intracranial Chiari 2 findings

Other Occipital Encephaloceles

- Iniencephaly
- Syndromic occipital encephalocele
  - Meckel-Gruber, Goldenhar-Gorlin, MURCS (müllerian, renal, cervical-spine), Walker-Warburg, amniotic band

PATHOLOGY

General Features

- Genetics
  - 677C → T mutation on methylenetetrahydrofolate reductase (*MTHFR*) gene (≤ 50%)
- Associated abnormalities
  - Corpus callosum anomalies, gray matter heterotopia, syringohydromyelia, tethered cord
  - Previously described in combination with intracranial CM2 manifestations
    - Now thought that tectum, lower brainstem findings actually reflect distortion related to cerebellar displacement into sac

Gross Pathologic & Surgical Features

- Cephalocele contents: Meninges, cerebellum, brainstem ± cervical cord, ± occipital poles, ± vasculature

Microscopic Features

- Disorganized (neuronal migration anomalies, cortical dysplasias, gliotic) brain tissue within sac

CLINICAL ISSUES

Presentation

- Most common signs/symptoms
  - Occipital/upper cervical cephalocele, microcephaly
  - Discovered by fetal ultrasound/MR or surprise at birth
- Other signs/symptoms
  - Mechanical brainstem traction, respiratory deterioration, lower cranial nerve dysfunction
- Clinical profile
  - Severe developmental delay, spasticity, hypotonia, seizures

Demographics

- Age
  - Newborn
- Gender
  - F > M (as in all NTDs) in most series
- Epidemiology
  - Rare; 1-4.5% of all Chiari malformations

Natural History & Prognosis

- Dependent on amount, type of herniated tissue
- Prognosis usually dismal, with severe disability and early death

Treatment

- Surgical resection, encephalocele repair
  - Resect or repair sac (most structures in sac are nonfunctioning)
  - If amount CNS tissue in sac > intracranial → not surgical candidate
- Cerebrospinal fluid diversion for hydrocephalus

DIAGNOSTIC CHECKLIST

Consider

- Chiari 3 in newborn presenting with low occipital encephalocele

SELECTED REFERENCES

1. Cesmebasi A et al: The Chiari malformations: A review with emphasis on anatomical traits. Clin Anat. 28(2):184-194, 2015
2. Deans AE et al: Radiology of the Chiari Malformations. In Tubbs RS et al: The Chiari Malformations. New York: Springer. 153-69, 2013

Callosal Dysgenesis

KEY FACTS

TERMINOLOGY

- Partial or complete absence of corpus callosum (CC), hippocampal commissure (HC), or anterior commissure (AC); can be isolated or associated with additional cerebral malformations
- Spectrum of congenital CC structural abnormalities
  - Total agenesis (absence from birth of all anatomically defined regions of CC)
  - Partial agenesis (absence from birth of at least 1, but not all, regions of CC)
  - Hypoplasia (thinner CC with normal anteroposterior extent)
  - Hyperplasia (thick CC resulting from decreased postnatal axonal pruning)
  - Dysgenesis (CC present but malformed in some way, including partial ACC and hypoplasia of CC)

IMAGING

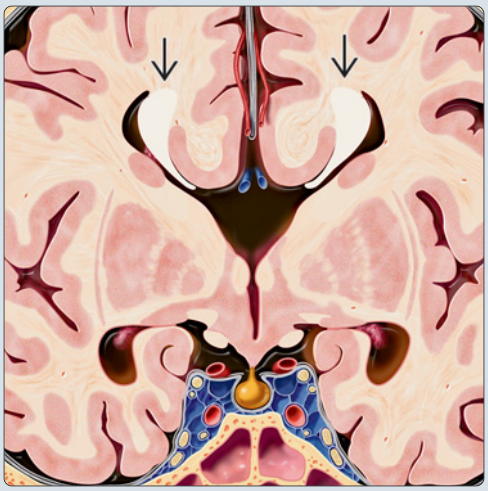
- Absent corpus callosum on sagittal, coronal views
- Atrium/occipital horns often dilated ("colpocephaly")
- DTI: Callosal fiber tracts form Probst bundles instead of crossing, where corpus callosum is absent
- Vertical/posterior course of anterior cerebral artery

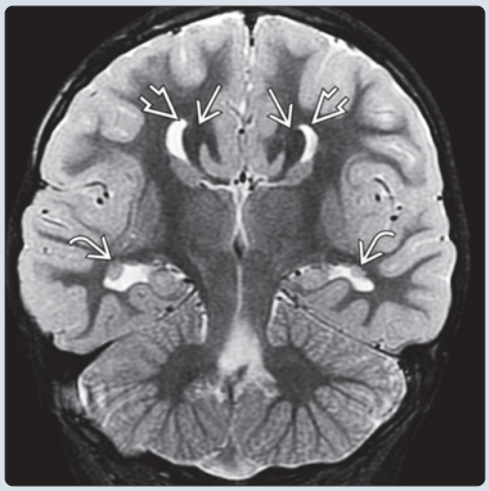
CLINICAL ISSUES

- Any age; classically identified in early childhood, most common malformation found in fetuses
- Seizures, developmental delay, cranial deformity/hypertelorism
- Sporadic/isolated agenesis/dysgenesis corpus callosum: Normal/near normal at 3 years (75%), but subtle cognitive defects apparent with increasing complexity of school tasks
- Agenesis/dysgenesis corpus callosum with associated/syndromic anomalies = worst

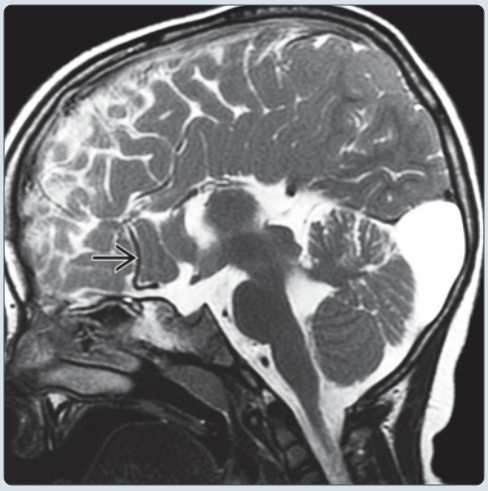
DIAGNOSTIC CHECKLIST

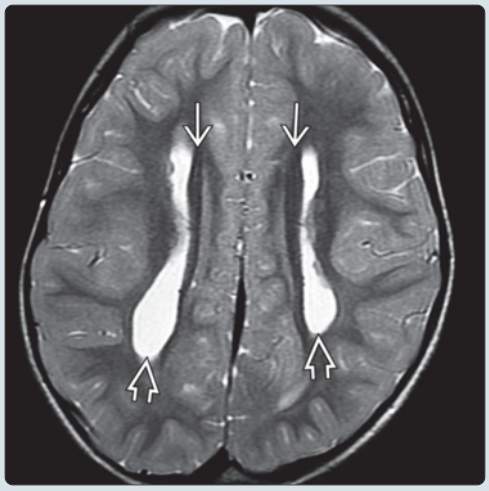
- Look for absent/incomplete corpus callosum rather than indirect signs
- Fully assess for associated lesions





(Left) *Coronal graphic shows a lack of transverse corpus callosum and separate lateral ventricles. The interhemispheric fissure extends to the 3rd ventricle. The bundles of Probst ⇨ contain the parasagittally rerouted callosal fibers.* **(Right)** *Coronal T2WI with callosal dysgenesis shows Viking helmet or moose head appearance of widely separated lateral ventricles ⇨. The very hypointense white matter tracts medial to the lateral ventricles are the Probst bundles ⇨. Note the heterotopic GM ⇨.*





(Left) *Sagittal T2WI in the same patient shows absence of the corpus callosum, radially-oriented gyri converging on a high-riding 3rd ventricle. Note the azygous anterior cerebral artery (ACA) ⇨. The anterior commissure is also absent.* **(Right)** *Axial T2WI in the same case shows the characteristic parallel, nonconverging lateral ventricles ⇨ seen in corpus callosum agenesis. Heavily myelinated Probst bundles ⇨ are seen just medial to the lateral ventricles.*

TERMINOLOGY

Abbreviations

- Agenesis/dysgenesis corpus callosum (ACC)

Synonyms

- Callosal agenesis/dysgenesis, commissural agenesis/dysgenesis

Definitions

- Partial or complete absence of corpus callosum (CC), hippocampal commissure (HC), or anterior commissure (AC); can be isolated or associated with additional cerebral malformations
- Spectrum of congenital CC structural abnormalities
  - Total agenesis (absence from birth of all anatomically defined regions of CC)
  - Partial agenesis (absence from birth of at least 1, but not all, regions of CC)
  - Hypoplasia (thinner CC with normal anteroposterior extent)
  - Hyperplasia (thick CC resulting from decreased postnatal axonal pruning)
  - Dysgenesis (CC present but malformed in some way, including partial ACC and hypoplasia of CC)

IMAGING

General Features

- Best diagnostic clue
  - Partially or completely absent CC on midline sagittal and coronal planes
  - Lateral ventricles separate and parallel (axial), bull's head, trident, Viking helmet, or moose head appearances (coronal)
- Size
  - When present, CC remnants vary in size, extent, shape
    - Prior to myelin maturation, may be difficult to define (T2WI is better)
- Morphology
  - Commissural plate, clockwise
    - AC
    - Lamina rostralis and rostrum
    - Genu, body and isthmus, splenium
    - HC below CC, largest posterior to septum pellucidum

CT Findings

- NECT
  - On axial CT, lateral ventricles key to diagnosis
    - Parallel and separate
    - Atrium/occipital horns dilated ("colpocephaly")
- CTA
  - Anterior cerebral arteries (ACAs) course directly upward in interhemispheric fissure

MR Findings

- T1WI
  - Sagittal
    - Absent or incomplete commissures, expanded 3rd ventricular roof
    - Abnormal cingulate gyrus: Radiating sulcal pattern
    - AC may be absent, small, or normal
  - Coronal
    - Interhemispheric fissure extends down to 3rd ventricular roof
    - Probst bundles: Medial parasagittal white matter tracts, brighter than other myelin on T1WI, indent lateral ventricles ("bull's head," etc.)
    - Bifid temporal horns and rounded hippocampi
  - Axial
    - Parallel separate lateral ventricles, colpocephaly
- T2WI
  - Same morphology as on T1WI
    - Probst bundles darker than rest of white matter
  - Variants and associated malformations
    - High-riding 3rd ventricle
    - Partial agenesis usually affects posterior CC and HC
    - Multiple interhemispheric cysts (meningeal dysplasia)
    - Lipomas: Nodular, curvilinear
    - Malformations of cortical development (MCD): Polymicrogyria-like cortical malformation (often along midline cysts), subcortical or periventricular nodular heterotopia
    - Malformation of eyes, hindbrain (Dandy-Walker), hypothalamus-pituitary, cord, heart
- DWI
  - DTI: Callosal fiber tracts form Probst bundles instead of crossing, where CC is absent
  - Callosal remnants may contain axons from any part of cerebrum
- MRA
  - Vertical/posterior course of ACA (no genu to sweep around), ± azygous ACA
- MRV
  - Occasional midline venous anomalies, persistent falcine sinus

Ultrasonographic Findings

- Grayscale ultrasound
  - Coronal
    - Absent CC, bull's head lateral ventricles, separated lateral ventricles, colpocephaly
  - Sagittal
    - Radially arranged gyri "point to" 3rd ventricle
- Color Doppler
  - Abnormal posterior ACA course

Imaging Recommendations

- Best imaging tool
  - MR
- Protocol advice
  - Multiplanar MR (look for associated malformations)
  - If MR unavailable, multiplanar CT will diagnose ACC
  - In fetuses, use ultrafast single-shot T2WI in 3 planes

DIFFERENTIAL DIAGNOSIS

Destruction of Corpus Callosum

- Surgery (callosotomy), trauma
- Hypoxic-ischemic encephalopathy, infarcts, hemorrhages
- Metabolic (Marchiafava-Bignami) with necrosis, longitudinal splitting of CC

Stretched Corpus Callosum

- Thinned CC (e.g., hydrocephalus), but all parts present

Hypoplastic Corpus Callosum

- CC thin, but all parts present

Immature Corpus Callosum

- Premyelinated CC may be difficult to confirm; look for cingulate gyrus

Thick Corpus Callosum ("Mega-Corpus Callosum")

- Excessively thick CC can be isolated or occur with brain malformations, congenital metabolic diseases
  - Probably due to delayed retraction of transitory collateral axons

PATHOLOGY

General Features

- Etiology
  - Axons fail to form
    - Rare: CRASH syndrome/*L1CAM* gene defect, "cobblestone" lissencephaly
  - Axons not guided to midline (mutations in adhesion molecules)
  - Axons reach midline but fail to cross (absence or malfunction of midsagittal guiding substrate)
    - Turn and form large, aberrant, parasagittal Probst bundles
  - Miscellaneous
    - Toxic: Fetal alcohol exposure may affect *L1CAM*
    - Infection: In utero cytomegalovirus (CMV)
    - Inborn errors of metabolism: Nonketotic hyperglycinemia, pyruvate dehydrogenase deficiency, maternal phenylketonuria (PKU), Zellweger
- Genetics
  - Genetics of associated/syndromic CC anomalies
    - Most common abnormality seen as part of CNS malformations: > 130 syndromes
    - Chiari 2, frontonasal dysplasia, syndromic craniosynostoses, MCD, tubulin mutations, etc.
    - Aicardi syndrome: X-linked ACC, polymicrogyria and heterotopia, infantile spasms, retinal lacunae, developmental delay
- Associated abnormalities
  - MCD: Heterotopia, lissencephaly, polymicrogyria, etc.
  - Ocular/hypothalamic-pituitary/cord/facial anomalies
  - Heart, limbs
  - ACC may be malformation in itself or feature of many malformative syndromes

Staging, Grading, & Classification

- May be isolated or part of syndrome; complete or partial
- May have interhemispheric dysplasia: Meningeal cysts, lipomas
- May be part of syndrome (> 130)

Gross Pathologic & Surgical Features

- Leaves of septum pellucidum laterally displaced, contain Probst bundles
- Probst bundles contain parasagittal callosal bundle
  - Only form if callosal neurons present
  - Variable-sized bundles smaller than normal CC
- Associated dysgenetic brain lesions

CLINICAL ISSUES

Presentation

- Most common signs/symptoms
  - Seizures, developmental delay, cranial deformity-hypertelorism
  - Hypopituitarism-hypothalamic malfunction
  - Autism spectrum disorders
- Clinical profile
  - None specific

Demographics

- Age
  - Any age, classically identified in early childhood, most common malformation found in fetuses
- Gender
  - M > F, if isolated finding
- Epidemiology
  - 0.5-70 per 10,000 live births
  - 4% of CNS malformations
  - Can be isolated (often males) or part of other CNS malformations

Natural History & Prognosis

- Sporadic/isolated ACC: Normal/near normal at 3 years (75%), but subtle cognitive defects apparent with increasing complexity of school tasks
- ACC with associated/syndromic anomalies = worst

DIAGNOSTIC CHECKLIST

Consider

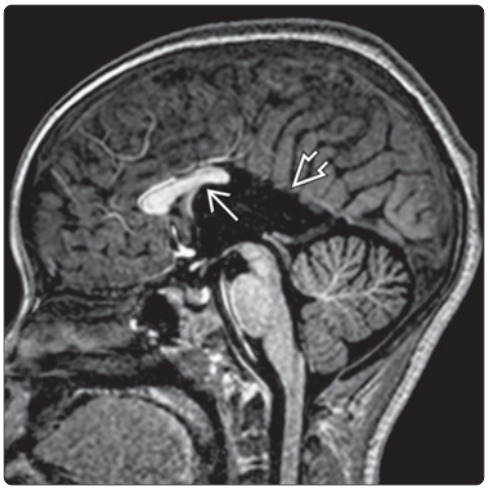
- Syndromic associations common

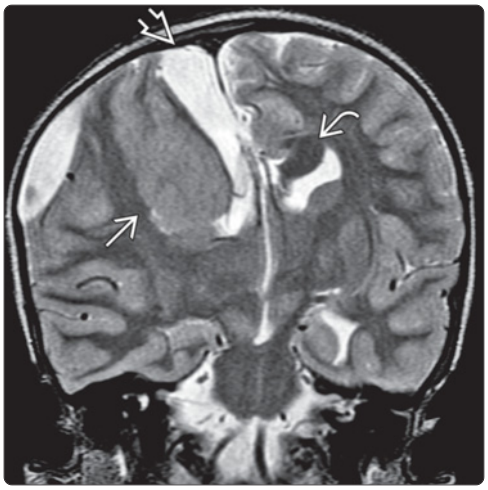
Image Interpretation Pearls

- Look for absent/incomplete CC rather than indirect signs
- Fully assess for associated lesions

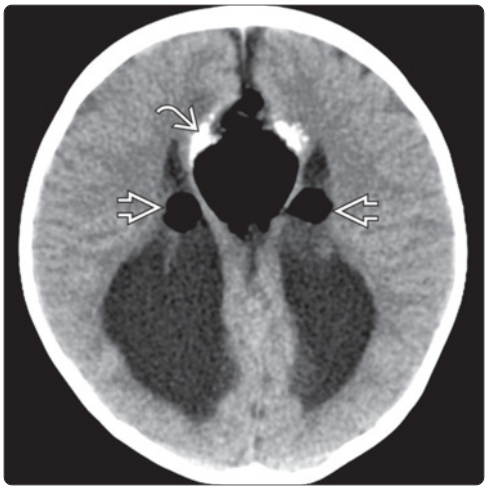
SELECTED REFERENCES

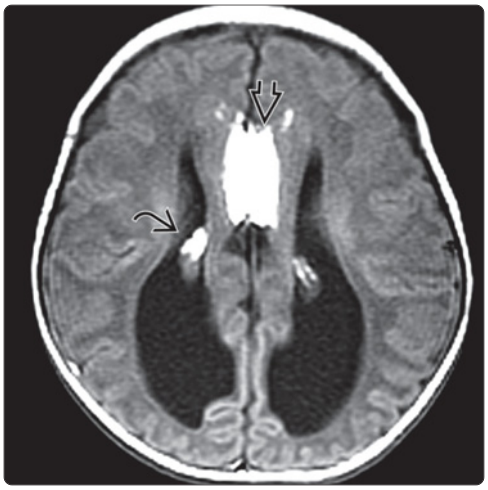
1. Craven I et al: Antenatal diagnosis of agenesis of the corpus callosum. Clin Radiol. 70(3):248-53, 2015
2. Edwards TJ et al: Clinical, genetic and imaging findings identify new causes for corpus callosum development syndromes. Brain. 137(Pt 6):1579-1613, 2014
3. Palmer EE et al: Agenesis of the corpus callosum: a clinical approach to diagnosis. Am J Med Genet C Semin Med Genet. 166C(2):184-97, 2014
4. Lau YC et al: Autism traits in individuals with agenesis of the corpus callosum. J Autism Dev Disord. 43(5):1106-18, 2013
5. Owen JP et al: The structural connectome of the human brain in agenesis of the corpus callosum. Neuroimage. 70:340-55, 2013
6. Santo S et al: Counseling in fetal medicine: agenesis of the corpus callosum. Ultrasound Obstet Gynecol. 40(5):513-21, 2012
7. Vasudevan C et al: Long-term outcome of antenatally diagnosed agenesis of corpus callosum and cerebellar malformations. Semin Fetal Neonatal Med. 17(5):295-300, 2012
8. Hopkins B et al: Neuroimaging aspects of Aicardi syndrome. Am J Med Genet A. 146A(22):2871-8, 2008
9. Lee SK et al: Diffusion tensor MR imaging visualizes the altered hemispheric fiber connection in callosal dysgenesis. AJNR Am J Neuroradiol. 25(1):25-8, 2004
10. Küker W et al: Malformations of the midline commissures: MRI findings in different forms of callosal dysgenesis. Eur Radiol. 13(3):598-604, 2003



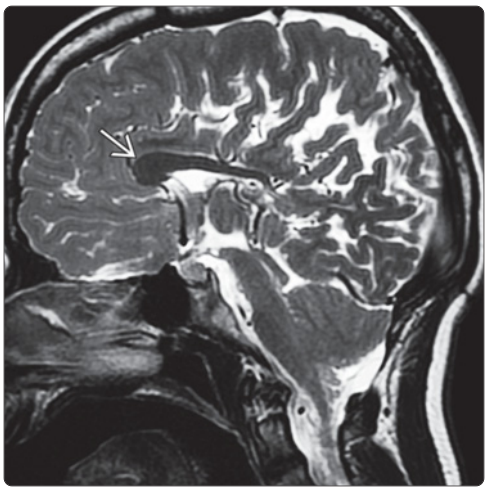


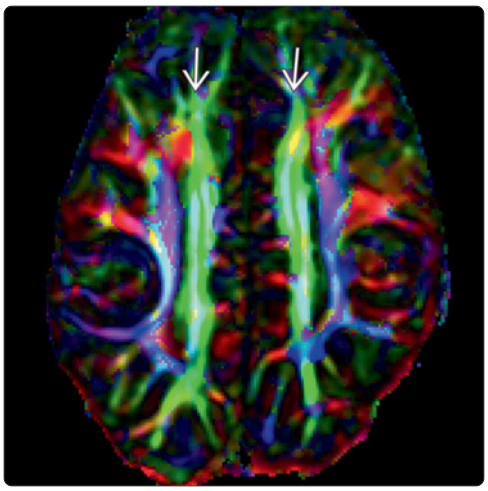
(Left) *Sagittal T1WI MR shows pure partial agenesis/dysgenesis corpus callosum (ACC). The posterior portion of the corpus callosum is missing, but the junction with the fornix seems preserved. Posterior coronals would show Probst bundles, whereas anterior images would appear normal.* **(Right)** *Coronal T2WI MR shows ACC with (shunted) interhemispheric meningeal cysts. Note the massive nodular heterotopia on the patient's right. A Probst bundle has formed on the left but not on the right.*





(Left) *Axial NECT with widened windows shows ACC with colpocephaly, calcified midline lipoma that extends through choroid fissures into lateral ventricles.* **(Right)** *Axial T1WI MR in ACC shows parallel ventricles, colpocephaly, and a midline lipoma. Note that the lipoma protrudes through the choroid fissure into the lateral ventricles.*





(Left) *Sagittal T1WI MR in a 19-year-old female with Chiari 2 is shown. ACC in Chiari 2 is always partial; Probst bundles are never seen. Note the multiple supra- and infratentorial Chiari 2 features.* **(Right)** *Axial DTI of a child with complete callosal agenesis shows Probst bundles as green uncrossed callosal fibers coursing front to back.*

Lipoma

KEY FACTS

TERMINOLOGY

- Intracranial lipoma (ICL)
- Mass of mature nonneoplastic adipose tissue
- CNS lipomas are congenital malformations, not true neoplasms

IMAGING

- Well-delineated lobulated extraaxial mass with fat attenuation/intensity
- 80% supratentorial
  - 40-50% interhemispheric fissure (over corpus callosum; may extend into lateral ventricles, choroid plexus)
  - 15-20% suprasellar (attached to infundibulum, hypothalamus)
  - 10-15% tectal region (usually inferior colliculus/superior vermis)
- 20% infratentorial
- Cerebellopontine angle (may extend into internal auditory canal, vestibule)
- Lobulated pial-based fatty mass that may encase vessels and cranial nerves
- CT: -50 to -100 Hounsfield units (HU) (fat density)
- Ca++ varies from none to extensive
- Standard SE MR: Hyperintense on T1WI
- Becomes hypointense with fat suppression

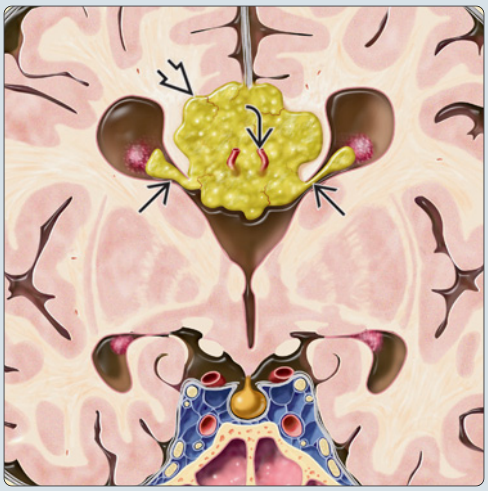
TOP DIFFERENTIAL DIAGNOSES

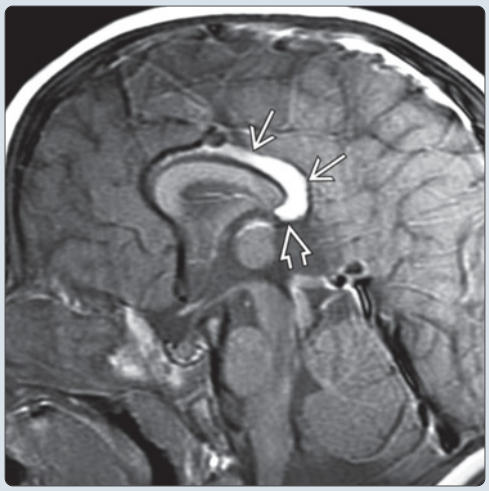
- Teratoma
  - Locations similar to lipoma
  - Tissue from all 3 embryonic germ layers

DIAGNOSTIC CHECKLIST

- When in doubt, use fat-saturation sequence
- Could high signal on T1WI be due to other substances with short T1 (e.g., subacute hemorrhage)
- Beware: Lipoma can mimic intracranial air on NECT (use bone windows to distinguish)

(Left) *Coronal graphic shows callosal agenesis with a bulky tubulonodular interhemispheric lipoma that encases the arteries and extends into the lateral ventricles.* **(Right)** *Sagittal T1WI MR shows a rather thin curvilinear interhemispheric lipoma in a 9 month old. Note that the hyperintense lipoma is thicker posteriorly than anteriorly. It wraps around the back of the corpus callosum and extends beneath the corpus into the velum interpositum.*





(Left) *Sagittal T1WI MR in a neonate shows a large, tubulonodular, interhemispheric lipoma dorsal to a wedge-shaped callosal remnant. The brain is otherwise normal.* **(Right)** *Axial T2WI FS MR in the same patient shows the lipoma as hypointense and lying between the 2 cerebral hemispheres. The lipoma extends through the choroidal fissures into the lateral ventricles where it is in the stroma of the choroid plexuses.*