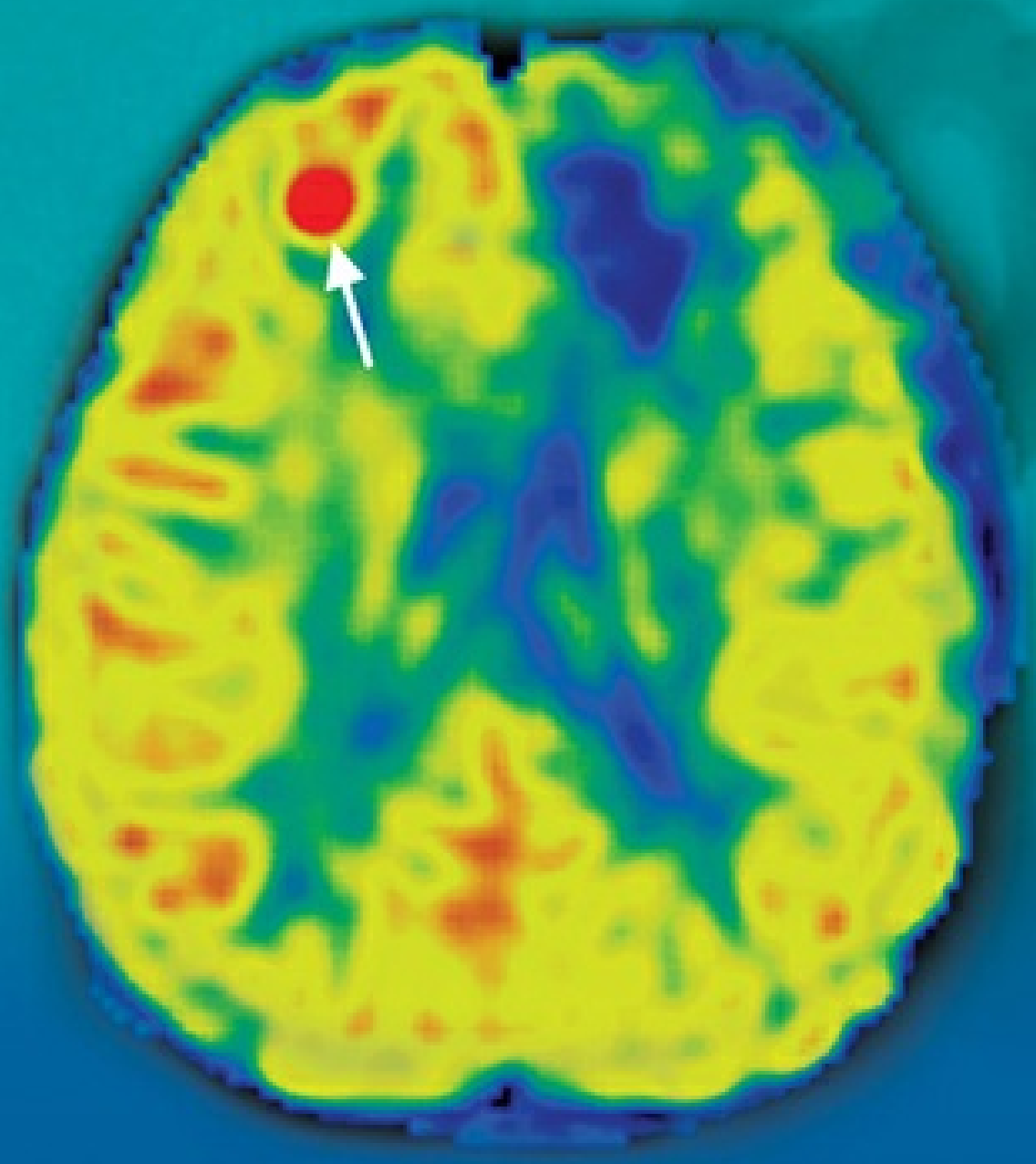
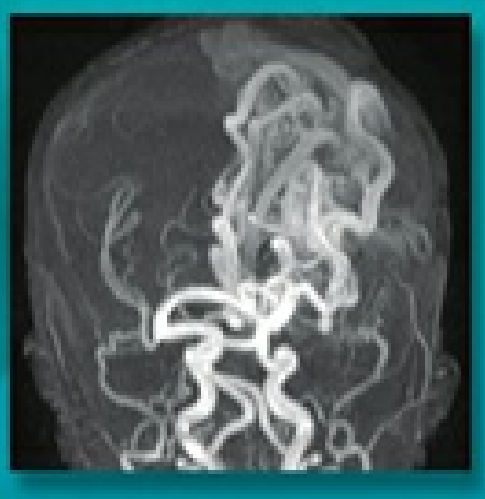
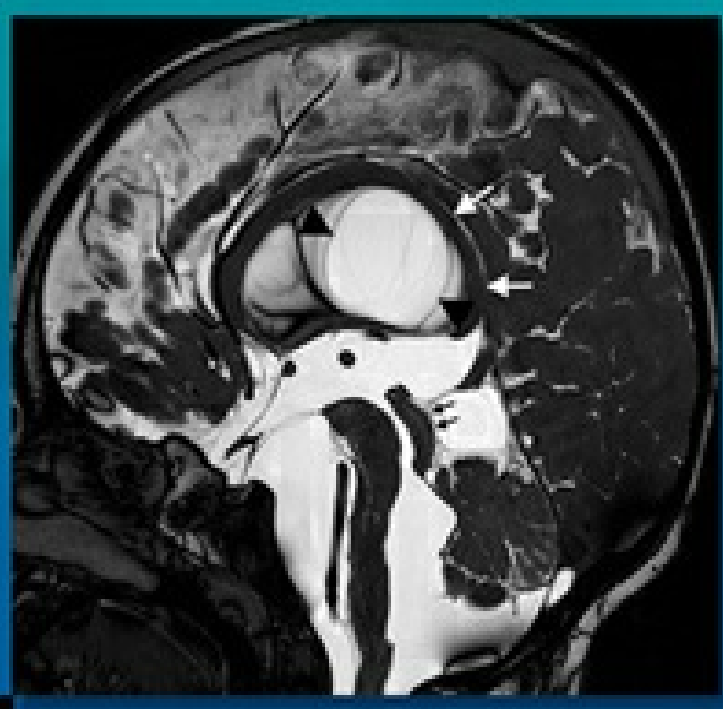
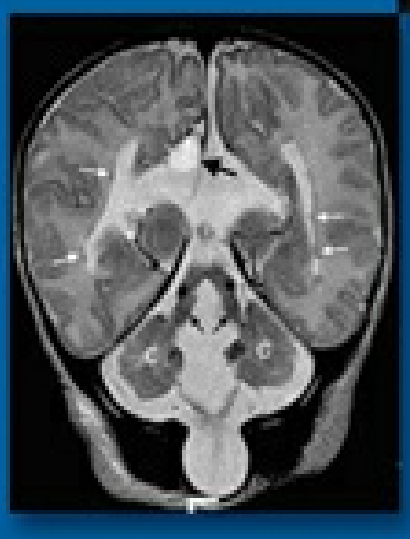
Pediatric Neuroimaging

SIXTH EDITION









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Wolters Kluwer

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To our families,
without whose inspiration
none of this
would have been possible.

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Preface

It is a little hard to believe that this is the sixth edition of *Pediatric Neuroimaging*. However, imaging continues to evolve, as does the sophistication of the imaging machines and techniques used to evaluate the brain, head, neck, and spine of children with abnormal neurodevelopment or neurological function. New diseases continue to be discovered and described, along with improved understanding of normal processes of neurodevelopment (genetics, molecular biology, and biochemistry), what can (and does) go wrong with the developmental processes, and new ways to classify them based upon our knowledge of these factors. Imaging continues to improve; it is faster, and more accurate, allowing assessment, in many cases, of function as well as anatomy. Once again, I have called upon my highly knowledgeable and esteemed colleagues to help in the writing of this book by sharing their experience and knowledge. Charles Raybaud and Jim Barkovich have again written much of it and edited the work of eight other respected authors (Christopher Hess, Duan Xu, Matthew Barkovich, Zoltan Patay, Erin Schwartz, Gilbert Vézina, Gary Hedlund, James Bale, and Steven Hetts), who have generously graced this edition with information and insights from their areas of expertise. As the reader will notice, this is a complete book, which shares the experience and opinions of many dedicated pediatric physicians, some with many decades of experience in many different locations, in addition to some insights from younger colleagues with newer insights. As in the fifth edition, the contributions of the many authors have blended together to give a more informative book, while minimizing confusing differences and maintaining a book that is readable, so that it can be used as a tool for learning, as well as a reference text. In all chapters, the readers will find extensive use of tables to help to organize the disorders and many images to illustrate them.

Chapter 1 on imaging techniques and Chapter 2 on normal developmental features seen by imaging have been updated. In Chapter 1, concepts of imaging children with ultrasound, CT, and MRI are discussed, with discussion of sedation, monitoring, and many recently developed imaging techniques and their role in pediatric neuroimaging. The main focus is on MRI of the brain, blood vessels, and spine, along with suggested protocols for both routine imaging and more sophisticated studies. Techniques for Fetal MRI are also discussed, as well as those for microstructural, physiologic, and metabolic imaging; assessment of blood flow, perfusion, and CSF flow; and sections on MR spectroscopy and functional MRI. Chapter 2 has updated figures of normal development, including new MR images of fetal brain development.

As in prior editions, Chapters 3 to 12 address imaging findings in specific categories of disease. Some of these chapters have been extensively revised to reflect changes in concepts of the disorders; others, with fewer advances, have been updated with a few newly described or newly defined entities in a chapter whose organization remains largely the same, with discussions of new techniques integrated into the discussion of the disease entity accompanied by images of the disease. Images of fetal brains are included when early diagnosis will alter care, mostly illustrating patients with malformations, hydrocephalus, brain injury, occasionally, tumors.

Chapter 3 on metabolic diseases includes new information on diffusivity, spectroscopy, and clinical/genetic manifestations. The mitochondrial disorders section has been significantly updated, now discussing new classification by which respiratory chain complex is affected (when known). However, the field is changing very quickly with new genetic discoveries, so we have not attempted to classify all such disorders according to respiratory chain complex affected, but focused mainly on imaging phenotypes. We have retained the two-section approach, with the initial section having a brief, diagnosis-oriented discussion and the longer second section giving a more detailed explanation of the disorders and their imaging manifestations.

Chapter 4 discusses perinatal and postnatal injuries to the brain and spine and has more up to date information and images of pediatric brain and spine imaging and causes of stroke, perinatal injury (premature and term), and traumatic brain injury (accidental and inflicted). It includes new images and new sections on abusive trauma and brain concussion.

Chapter 5 has again been extensively updated with new concepts of normal development and newly described developmental disorders, in addition to new categories of disease and new concepts of developmental pathways that, when disrupted, cause specific disorders. This chapter remains organized according to the part of the brain primarily involved by the disease process (dorsal forebrain [cerebral cortex and commissures], ventral forebrain [base of the brain], midbrain/hindbrain, craniocervical junction, brain coverings) in order to help the reader to locate the disorder within the text; we hope readers will find this useful. Chapter 6 (Phakomatoses) has been updated with new genetic information, new classifications, many new images, and several new disorders being described.

Chapter 7 has been updated extensively, with many new images, as brain tumor discoveries have exploded over the past several years. However, much of the new Brain Tumor Classification concerns adult tumors; our changes concern new classification of specific pediatric tumors (e.g., medulloblastomas, supratentorial white matter tumors, supratentorial cortical tumors, tumors of central gray matter, etc.) and updated figures and discussions of a broader range of pediatric tumors than has been previously discussed.

Chapter 8 on hydrocephalus has been significantly modified and upgraded to include new theories of development and physiology of the ventricles and other CSF spaces, CSF dynamics, and new methods of assessing hydrocephalus that better explain the effects upon the ventricular system and the underlying brain. Chapters 9 (spine anomalies), 10 (spine tumors), and 12 (disorders of cerebral blood vessels) have all been carefully updated with new data, new theories, and new images that

facilitate the diagnosis and understanding of these disorders. Chapter 11 (infection) has once again been greatly expanded and improved by Drs. Hedlund and Bale, who again have added many new disorders and images, including disorders that were very localized 10 to 15 years ago, outside of North America and Europe, but have become prevalent elsewhere as a result of modern travel. This work will facilitate the diagnosis of these disorders as they spread to new continents, perhaps stopping their spread.

Despite the many changes in this edition, we hope the reader will notice that the philosophy of the book remains the same. A large number of disorders are discussed and illustrated, as it is much easier to recognize a disorder by seeing imaging than by reading about imaging features. The cause of the disorder, the main clinical features, and the underlying pathophysiology are discussed whenever possible because it is easier to remember disorders when the genetic or embryologic or destructive cause is understood, rather than trying to match imaging characteristics to a disease name.

For the convenience of the reader, some topics are discussed more than once in the text. The purpose of this is to avoid forcing the reader to page back through the book, trying to find the previous mention of a disorder. For example, Chiari II malformations are discussed in Chapter 5, under disorders of the craniocervical junction, as a brain malformation and also in Chapter 9 under myelomeningoceles because they are almost always associated. Within Chapter 5, disorders secondary to abnormal pial basement membrane formation are discussed in both the dorsal forebrain section and the midbrain/hindbrain section because both regions are variably involved in the pathologic process, such that they might present as a forebrain or a hindbrain malformation.

We hope that this new edition of *Pediatric Neuroimaging* will serve as a textbook for residents, fellows, and practicing physicians who are interested in diseases of the pediatric brain and spine while, at the same time, serving as a reference book for clinicians seeing patients with these diseases in their daily work.

Preface to the First Edition

New techniques for pediatric brain and spine diagnoses have rapidly developed over the past 10 years. Computed tomography (CT), ultrasound, and magnetic resonance (MR) imaging have opened a new window to the pediatric central nervous system. Through the use of these imaging modalities, an increased understanding of the pathological processes that occur in the pediatric brain has emerged. However, in spite of the wealth of new concepts that have evolved from these new resources, there has been a notable lack of textbooks on the subject, particularly in dealing with CT and MR. In this book, I attempt, at least in part, to fill the gap of knowledge that exists in pediatric neuroimaging.

This book strongly emphasizes CT and MR in pediatric neurodiagnosis. The reasons for this are twofold. First, there are a number of good textbooks available that focus on plain film and sonographic evaluation of the pediatric central nervous system. Second, and more important, I feel that CT and MR, particularly MR, are the best modalities by far for imaging the pediatric brain. In those areas where ultrasound and plain film radiology are important adjuncts or are of primary importance in diagnosis, they have been included. Specifically, this includes the diagnosis of intracranial pathology in premature infants.

Readers will note that this is not an encyclopedic work on diseases of the pediatric central nervous system. Those disease processes that are well covered in other texts, or are extremely uncommon, are deemphasized here. Instead, I have attempted to cover subjects that are encountered in everyday practice. Furthermore, I have emphasized concepts that are crucial to proper imaging techniques and image interpretation. Embryology, normal development, and pathophysiology are explained. Once these basic concepts are understood, interpretation of images is greatly facilitated. Finally, an attempt was made to present the information in a concise and straightforward manner that will make reading this book an enjoyable learning experience.

List of Disorders

3 *Metabolic, Toxic, and Autoimmune/Inflammatory Brain Disorders*

IV. B. Metabolic Disorders Primarily Affecting White Matter

1. White matter diseases initially affecting periventricular cerebral white matter
   a. Metachromatic leukodystrophy
   b. Globoid cell leukodystrophy (Krabbe disease)
   c. Classic X-linked adrenal leukodystrophy/adrenomyeloneuropathy/acyl-CoA-oxidase deficiency
   d. Leukoencephalopathy with vanishing white matter
   e. Giant axonal neuropathy
   f. Phenylketonuria
   g. Maple syrup urine disease
   h. Hyperhomocysteinemia (formerly known as homocystinuria)
   i. Cystathionine beta-synthase deficiency
   j. 5, 10-Methylenetetrahydrofolate reductase deficiency (MTHFRD)
   k. Errors affecting cobalamin (vitamin B_{12}) metabolism
   l. Biotinidase deficiency
   m. Methionine adenosyltransferase deficiency
   n. Oculocerebrorenal syndrome (Lowe syndrome)
   o. Merosin-deficient congenital muscular dystrophy (MDC1A)
   p. Mucolipidosis type IV
   q. Autosomal recessive spastic paraplegia with thin corpus callosum
   r. Sjögren-Larsson syndrome
   s. Brain injury from radiation and chemotherapy
2. White matter disorders with dysmyelination initially affecting subcortical cerebral white matter
   a. Megalencephalic leukoencephalopathy with subcortical cysts (MLC)
   b. Cystic leukoencephalopathy without megalencephaly
   c. Aicardi-Goutières syndrome
   d. Cockayne syndrome
   e. Galactosemia
3. White matter disorders due to hypomyelination (hypomyelinating leukodystrophies)
   a. Pelizaeus-Merzbacher disease
   b. Pelizaeus-Merzbacher-like disease
   c. Leukodystrophies with trichothiodystrophy
   d. 18q-Syndrome and other chromosome 18 mutations
   e. Sialuria
   f. Hypomyelination with congenital cataracts
   g. Fucosidosis
   h. Hypomyelination with atrophy of the basal ganglia and cerebellum (HABC)
4. White matter diseases with nonspecific patterns
   a. Nonketotic hyperglycinemia (glycine encephalopathy)
   b. Dihydropyrimidine dehydrogenase deficiency
   c. 3-Hydroxy-3-methylglutaryl-coenzyme A lyase deficiency
   d. Congenital white matter hypoplasia/familial spastic paraplegia
5. Idiopathic inflammatory, autoimmune, infectious, and toxic disorders affecting white matter
   a. Multiple sclerosis
   b. Neuromyelitis optica (Devic disease)
   c. Acute disseminated encephalomyelitis (ADEM)
   d. Acute hemorrhagic encephalomyelitis
   e. Collagen vascular diseases/systemic lupus erythematosus
   f. Osmotic myelinolysis in childhood
   g. Toxins
   h. Lead encephalopathy
   i. Solvent abuse
   j. Progressive multifocal leukoencephalitis

IV. C. Metabolic Disorders Primarily Involving Gray Matter

1. Gray matter disorders primarily involving the deep gray cerebral nuclei
   a. Pantothenate kinase–associated neuropathy (neurodegeneration with brain iron accumulation 1, formerly Hallervorden-Spatz disease)
   b. Juvenile Huntington disease
   c. Isovaleric acidemia
   d. Succinic semialdehyde dehydrogenase deficiency
   e. Creatine deficiency syndromes
   f. Wernicke encephalopathy
   g. Extrapontine myelinolysis
   h. Hemolytic–uremic syndrome
   i. Sydenham chorea
   j. Chronic liver disease
2. Gray matter disorders primarily involving cortex
   a. Neuronal ceroid lipofuscinosis
   b. Aspartylglucosaminuria
   c. Anti-N-methyl-D-aspartate receptor (NMDAR) encephalitis in children and adolescents
   d. Infantile neuroaxonal dystrophy
   e. Niemann-Pick disease
   f. Rett syndrome
   g. Toxins
   h. Progressive cerebral poliodystrophy (Alpers disease)

IV. D. Metabolic Disorders that Affect both Gray and White Matter

1. Canavan disease (aspartoacylase deficiency, spongiform leukodystrophy)
2. Fibrinoid leukodystrophy (Alexander disease)
3. Mucopolysaccharidoses
   a. Multiple sulfatase deficiency
4. Peroxisomal disorders
   a. Peroxisomal biogenesis disorders
   b. Acyl-CoA-oxidase deficiency
   c. Rhizomelic chondrodysplasia punctata
   d. Nonrhizomelic chondrodysplasia punctata
5. Wilson disease
6. Mitochondrial disorders (respiratory chain disorders)
   a. Mitochondrial encephalomyopathy with lactic acidosis and strokelike episodes (MELAS)
   b. Kearns-Sayre syndrome/progressive external ophthalmoplegia
   c. Mitochondrial neurogastrointestinal encephalomyopathy
   d. Disorders causing Leigh syndrome
   e. Alpers disease
   f. Trichopoliodystrophy (Menkes disease)
   g. Glutaric aciduria type I (glutaryl-CoA-dehydrogenase deficiency)
   h. Glutaric aciduria type II (multiple acyl-CoA-dehydrogenase deficiency)
   i. Neonatal lactic acidosis, complex I/IV deficiency, and fetal cerebral disruption
   j. Friedreich ataxia
   k. Ethylmalonic encephalopathy
   l. Nonspecific mitochondrial disorders
7. Pyruvate dehydrogenase deficiency
8. Disorders of the urea cycle and ammonia
9. Methylmalonic and propionic acidemias
10. GM1 and GM2 (Tay-Sachs and Sandhoff diseases) gangliosidoses
11. Fucosidosis
12. l-2-Hydroxyglutaric aciduria
13. Acute necrotizing encephalitis
14. Hypomyelination with atrophy of the basal ganglia and cerebellum
15. 3-Methylglutaconic aciduria and Barth syndrome
16. Molybdenum cofactor deficiency
17. Isolated sulfite oxidase deficiency
18. Toxin ingestions

IV. E. Metabolic Disorders Primarily Involving the Cerebellum

1. Friedreich ataxia
2. Ataxia-Telangiectasia
3. Late-onset GM2 gangliosidosis
4. Ataxia with oculomotor apraxia, types 1 and 2
5. Autosomal recessive spastic ataxia (of Charlevoix-Saguenay)
6. Mitochondrial disorders causing cerebellar atrophy
   a. Coenzyme Q_{10} deficiency
   b. SANDO syndrome
   c. Infantile-onset spinocerebellar ataxia
7. Infantile olivopontocerebellar atrophy
8. Pontocerebellar hypoplasia
9. Congenital disorders of glycosylation
10. Mevalonic kinase deficiency (Mevalonic aciduria)
11. Progressive encephalopathy with edema, hypsarrhythmia, and optic atrophy (PEHO)
12. Dentatorubral and pallidoluysian atrophy
13. Neuronal ceroid lipofuscinoses
14. Langerhans cell histiocytosis
15. Hypomyelination with atrophy of the basal ganglia and cerebellum (HABC)
16. Spinocerebellar ataxias
17. Cerebrotendinous xanthomatosis
18. Wolfram syndrome
19. Marinesco-Sjögren syndrome
20. X-linked nonprogressive congenital cerebellar hypoplasia
21. Höyeraal-Hreidarsson syndrome
22. Revesz syndrome

4 *Brain and Spine Injuries in Infancy and Childhood*

II. Basic Patterns of Brain Destruction

1. Porencephaly
2. Hydranencephaly
3. Encephalomalacia

III. Hypoxic–ischemic Brain Injury

1. Localized infarctions
   a. Manifestations and causes of infarctions in children
   b. Choice of radiologic study in pediatric stroke
   c. Arterial infarctions
      Presumed perinatal ischemic stroke
      Transient cerebral arteriopathy
   d. Infarction secondary to venous occlusion
2. Diffuse ischemic or inflammatory brain injury
   a. Patterns of diffuse hypoxic–ischemic brain injury
   b. Injury in the premature infant
      Periventricular and intraventricular hemorrhage
      Cerebellar hemorrhage
      Venous infarctions
      White matter injury
      Cerebellar injury
      Imaging findings in premature neonates
      Profound hypotension in premature neonates
   c. Injury in the term infant
      Parasagittal/watershed injury
      Profound hypotension
      Parenchymal and intraventricular hemorrhage in the term neonate
   d. Injury in older infants and children
   e. Ischemia secondary to venous occlusion

IV. CNS Injury in Multiple Pregnancies

V. Neonatal Hypoglycemia

VI. Bilirubin Encephalopathy (Kernicterus)

VII. Brain Injury Associated with Congenital Heart Disease

VIII. Hypernatremic Dehydration

IX. CNS Trauma in Infancy and Childhood

1. Birth trauma
   a. Spinal cord injury
   b. Nerve root and brachial plexus injuries
   c. Head trauma
2. Postnatal trauma
   a. Spinal trauma
      Injuries to young children
      Adolescent injuries
      Torticollis/rotational deformities of C-1 and C-2
      Back pain in children
   b. Head trauma
      Extraparenchymal hematomas
      Subarachnoid hemorrhage
      Injury to the brain parenchyma
      Sequelae of trauma

X. Abusive Trauma (Child Abuse)

XI. Mild Traumatic Brain Injury (Concussion)

5 *Congenital Malformations of the Brain and Skull*

II. Anomalies of Dorsal Prosencephalon Development

1. Anomalies of the cerebral commissures—corpus callosum, anterior commissure, hippocampal commissure, septum pellucidum
2. Malformations of cortical development
   a. Malformations secondary to abnormal cell proliferation and apoptosis
      Microcephaly
      Focal cortical dysplasias
      Megalencephaly, hemimegalencephaly, and dysplastic megalencephaly
   b. Malformations due to neuroependymal abnormalities
      Periventricular heterotopia
   c. Malformations secondary to incomplete transmantle migration
      Focal subcortical heterotopia
      Malformations due to incomplete neuron migration (lissencephalies, pachygyrias, band heterotopia, RELN pathway, and ARX mutations)
      Schizencephaly (incomplete migration due to early transmantle injury)
   d. Malformations secondary to overmigration beyond pial limiting membrane (glial limitans)
      Polymicrogyria
      Cobblestone malformations
      Tubulin mutation

III. Anomalies of Ventral Prosencephalon Development

1. Holoprosencephalies
   a. Alobar holoprosencephaly
   b. Semilobar holoprosencephaly
   c. Lobar holoprosencephaly
   d. Syntelencephaly
2. Arrhinia/arrhinencephaly
3. Septooptic dysplasia
4. Isolated absence of septum pellucidum
5. Anomalies of the hypothalamic–pituitary axis
   a. Pituitary absence, hypoplasia, and duplication
   b. Pituitary dwarfism
   c. Kallmann syndrome (hypogonadotropic hypogonadism)
   d. Hypothalamic dysgenesis and adhesions
6. Anomalies of the eyes
   a. Ocular malformations
   b. Anophthalmia
   c. Microphthalmic malformations
   d. Macrophthalmia
   e. Other congenital ocular anomalies

IV. Anomalies of Midbrain–Hindbrain Development

1. Defects of AP and DV patterning
2. Malformations associated with later generalized developmental disorders that significantly affect the brainstem and cerebellum
   a. Cerebellar aplasia/hypoplasia/patterning defects
   b. Rhombencephalosynapsis
   c. Dandy-Walker continuum
   d. Cerebral malformations (including microcephaly) with cerebellar anomalies
   e. Joubert syndrome and related disorders (molar tooth malformations)
   f. Lhermitte-Duclos syndrome
3. Localized brain malformations that significantly affect the BS and CBL: isolated cerebellar and brain stem malformations
   a. Horizontal gaze palsy with progressive scoliosis
   b. Congenital fibrosis of extraocular muscles
   c. Midbrain clefts
   d. Cerebellar nodular heterotopia with overlying dysgenesis
   e. Cerebellar foliation disorders
   f. Cerebellar duplication
   g. Pontine tegmental cap dysplasia
4. Combined hypoplasia and atrophy in putative prenatal-onset degenerative disorders
   a. Pontocerebellar hypoplasias
   b. Congenital disorders of glycosylation and other metabolic disorders
   c. Cerebellar hemisphere hypoplasia

V. Anomalies of the Craniocervical Junction

1. Chiari I
2. Chiari II
3. Chiari III

VI. Anomalies of the Mesenchyme (Meninges and Skull)

1. Cephaloceles and other calvarial and skull base defects
2. Intracranial lipomas
3. Arachnoid cysts
4. Craniosynostosis syndromes
   a. Nonsyndromic synostosis
   b. Synostosis syndromes
      Apert syndrome
      Saethre-Chotzen syndrome
      Pfeiffer syndrome
      Crouzon syndrome

VII. Specific Chromosomal Anomalies

1. Down syndrome
2. Trisomy 18
3. Trisomy 13
4. Fragile X syndrome

6 *Neurocutaneous Disorders*

I. Neurofibromatosis Type I

II. Neurofibromatosis Type II

III. Other Forms of Neurofibromatosis

IV. Tuberous Sclerosis

V. Sturge-Weber Disease

VI. von Hippel-Lindau Disease

VII. Ataxia–Telangiectasia

VIII. Neurocutaneous Melanosis

IX. Incontinentia Pigmenti

X. Hypomelanosis of Ito

XI. Basal Cell Nevus Syndrome

XII. Cutaneous Hemangioma–Vascular Complex Syndrome (PHACE Syndrome)

XIII. Chédiak-Higashi Syndrome

XIV. Progressive Facial Hemiatrophy (Parry-Romberg Syndrome)

XV. Epidermal Nevus Syndrome

XVI. Encephalocraniocutaneous Lipomatosis

XVII. Other Overgrowth Syndromes

7 *Intracranial, Orbital, and Neck Masses*

II. Techniques of Imaging Pediatric Brain Tumors

III. Imaging Characteristics Used to Identify Brain Tumors

IV. Posterior Fossa Tumors

1. Fourth ventricular tumors
   a. Medulloblastoma
   b. Atypical teratoid/rhabdoid tumor of infancy and childhood
   c. Embryonal tumor with multilayered rosettes
   d. Cerebellar astrocytoma
   e. Rosette-forming glioneuronal tumor
   f. Ependymomas
   g. Choroid plexus tumors of the posterior fossa
2. Brainstem tumors
3. Hemangioblastoma
4. Extraparenchymal tumors
   a. Schwannomas
   b. Dysembryoplastic tumors (epidermoids, dermoids, and enteric cysts)
   c. Teratomas
5. Miscellaneous tumors of the posterior fossa and skull base

V. Sellar and Suprasellar Tumors

a. Craniopharyngioma
b. Suprasellar pilocytic astrocytoma (optic-hypothalamic gliomas)
c. Suprasellar germ cell tumors
d. Pituitary adenomas
e. Other sellar/suprasellar tumors
Hypothalamic hamartomas (hamartomas of the tuber cinereum)
Langerhans cell histiocytosis
Rathke cleft cysts
Lymphocytic hypophysitis

VI. Hemispheric Tumors

1. Tumors primarily located in the white matter
   a. Hemispheric gliomas
      Pilocytic astrocytomas
      Diffuse astrocytomas
      Higrade astrocytomas
      Oligodendrogliomas
      Gliomatosis cerebri
      Diffuse leptomeningeal gliomatosis
   b. Supratentorial ependymomas
   c. Embryonal tumors: tumors with neuroblastic or glioblastic elements
      Hemispheric primitive neuroectodermal tumor
      Hemispheric medulloepitherlioma
      Hemispheric atypical teratoid/rhabdoid tumor
      Astroblastoma
   d. Other hemispheric tumors
      Neuroglial hamatomas (glioneuronal heterotopia)
      Plasma cell granulomatosis (inflammatory pseudotumor)