CURRENT NEUROSURGICAL PRACTICE

Cerebral Vascular Disease in Children and Adolescents

Edited by

Michael S. B. Edwards

Harold J. Hoffman

Cerebral Vascular Disease in Children and Adolescents

Edited by

Michael S. B. Edwards, M.D.

Professor
Departments of Neurological Surgery and Pediatrics
Director, Division of Pediatric Neurosurgery
School of Medicine
University of California, San Francisco
San Francisco, California

Harold J. Hoffman, M.D., F.R.C.S.C.

Professor
Department of Surgery (Neurosurgery)
University of Toronto
Chief of Neurosurgery
The Hospital for Sick Children
Toronto, Ontario
Canada

Current Neurosurgical Practice
Charles B. Wilson, M.D., Series Editor

WILLIAMS & WILKINS
Baltimore • Hong Kong • London • Sydney

Editor: Carol-Lynn Brown
Associate Editor: Victoria M. Vaughn
Copy Editors: Susan Vaupel, Stephen Siegforth
Design: JoAnne Janowiak
Production: Theda Harris, Barbara Felton
Illustration Planning: Wayne Hubbel

Williams & Wilkins
428 East Preston Street
Baltimore, MD 21202, U.S.A.

Accurate indications, adverse reactions, and dosage schedules for drugs are provided in this book but it is possible that they may change. The reader is urged to review the package information data of the manufacturers of the medications mentioned.

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data

Cerebral vascular disease in children and adolescents.

(Current neurosurgical practice)
Includes index.
1. Cerebral vascular disease in children.
I. Edwards, Michael S. B., 1945 II. Hoffman, Harold J.,
1932– . III. Series.
RJ496.C45C47 1988 618.92'81 87-33990
ISBN 0-683-02747-6

88 89 90 91 92
10 9 8 7 6 5 4 3 2 1

Foreword

Medical writing, and neurosurgical writing in particular, has in the past produced only scattered information on the problems of cerebral vascular disease in the younger patient. This volume, ably edited by Michael Edwards and Harold Hoffman, remedies this major hiatus. Each chapter is written in a clear and well-organized manner, making for easy reference and rapid assimilation. The authors have been selected on the basis of their acknowledged expertise in their particular fields and the results indicate a wide and well-informed research.

Beginning with beautifully illustrated chapters on the embryology and anatomy of the cerebral vascular system and proceeding through radiologic investigation to the latest forms of therapy, including focused gamma-beam irradiation and heavy charged-particle Bragg peak radiosurgery, the reader should have no difficulty in obtaining the information that is sought. The mass of illustrations excites immediate interest and a full bibliography guides the reader to further study.

Although too complex for the casual reader, this text should be required reading for all those individuals concerned with the nervous system in the pediatric patient. One's only regret is that this superb effort was not forthcoming sooner!

E. Bruce Hendrick
May 1988

Note

As the editor of this series on current neurosurgical practice, I have responsibility for selecting topics that are appropriate and timely for the intended audience. I chose cerebral vascular disease in children and adolescents as the topic of this volume because I could find no publication that reviewed the subject under one cover. Despite a substantial literature on cerebral vascular disease specifically in adults, there appeared to be no definitive contemporary monograph on vascular disease in the pediatric population. Having defined the subject, I asked Michael Edwards and Harold Hoffman to bring together the authors whom they considered experts in the various aspects of pediatric vascular disease. This monograph is the result of their efforts, and I am very pleased with the final product.

CHARLES B. WILSON, M.D.
April 1988

Preface

New techniques in diagnosis and management have altered the treatment and prognosis for many vascular disorders that affect the central nervous system in children and adolescents. This book has been designed to provide a comprehensive review of these developments for neurologists, neurosurgeons, neuroradiologists, neuropathologists, pediatricians, and practitioners in allied fields concerned with the diagnosis and treatment of cerebral vascular diseases in the pediatric population.

Beginning with descriptions of the embryology, anatomy, and pathology of the vascular system, this volume focuses on the most current diagnostic and therapeutic methodologies applicable specifically for cerebral vascular disorders in children, and summarizes relevant ongoing research in these fields. Its chapters detail advances in neuroradiologic and operative techniques, anesthetic management, and evaluations of cerebral blood flow. Aneurysms, arteriovenous malformations, and related syndromes, and problems such as spontaneous dissection, traumatic vascular lesions, cerebral ischemia, and stroke—which are seldom reviewed specifically in their relation to the pediatric patient—are discussed individually and in depth. Current practice in the management of pediatric cerebral vascular disorders of cardiac origin and those related to coagulation disorders or cancer receives particular attention also, as does the management of stroke and hemorrhage in the premature and term neonate.

Unique to this volume is its emphasis on the differences in diagnosis, management and outcome that must be considered in treating children, as opposed to the adult population. We are indebted to the authors of these chapters, who have contributed their knowledge and expertise toward a cogent view of cerebral vascular disease in children and adolescents.

MICHAEL S. B. EDWARDS
HAROLD J. HOFFMAN
April 1988

Acknowledgments

To Linda Edwards, Brent, and Rebecca, and to JoAnn Hoffman, Richard, Rhonda, Andrew, and Katy, who have been so generously supportive and understanding of our time committed to this book.

We are grateful to Dr. Charles Wilson for his support and encouragement of the subspecialty of pediatric neurosurgery; to Heidi Pischler for her invaluable help weathering the maelstrom of manuscripts in Toronto; to Cindy Huff for her attention to perfection; and to Susan Eastwood for her thoughtfulness, creativity, collaboration, and support, without which this book would not have been possible.

MICHAEL S. B. EDWARDS
HAROLD J. HOFFMAN
April 1988

Contributors

Michael J. Aminoff, M.D., F.R.C.P., Professor, Department of Neurology and Director of Clinical Neurophysiology, School of Medicine, University of California, San Francisco, San Francisco, California

Brian T. Andrews, M.D., Assistant Professor, Department of Neurological Surgery, School of Medicine, University of California, San Francisco, San Francisco, California

Alex Berenstein, M.D., Professor, Department of Radiology and Director, Surgical Neuroangiography Section, New York University Medical Center and Bellevue Hospital Medical Center, New York, New York

Bruce O. Berg, M.D., Professor, Departments of Neurology and Pediatrics and Director of Child Neurology, School of Medicine, University of California, San Francisco, San Francisco, California

Stephen M. Bloomfield, M.D., Clinical Instructor and Fellow, Division of Neurosurgery, Department of Surgery, School of Medicine, University of California, Irvine, Irvine, California

Derek A. Bruce, M.B., Ch.B., Director of the International Pediatric Neurosurgical Institute, Humana Advanced Surgical Institutes, Dallas, Texas

Sylvester Chuang, M.D., C.M., F.R.C.P.C., D.A.B.R., C.S.P.Q., Associate Professor, Department of Radiology, University of Toronto and Head, Division of Special Procedures, Department of Radiology, The Hospital for Sick Children, Toronto, Ontario, Canada

Kerry R. Crone, M.D., Assistant Professor, Department of Pediatric Neurosurgery, Children's Hospital Medical Center and Mayfield Neurological Institute, Cincinnati, Ohio

Charles G. Drake, M.D., M.Sc., M.S., F.R.C.S.C., F.A.C.S., Professor, Department of Surgery, Division of Neurosurgery, The University of Western Ontario, London, Ontario, Canada

Michael S. B. Edwards, M.D., Professor, Departments of Neurological Surgery and Pediatrics and Director, Division of Pediatric Neurosurgery, School of Medicine, University of California, San Francisco, San Francisco, California

William K. Ehrenfeld, M.D., Professor, Department of Surgery, School of Medicine, University of California, San Francisco, San Francisco, California

Jacob I. Fabrikant, M.D., Ph.D., Professor, Department of Radiology, School of Medicine, University of California, San Francisco and University of California, Berkeley, Donner Laboratory and Donner Pavilion, Lawrence Berkeley Laboratory, Berkeley, California

Dennis M. Fisher, M.D., Associate Professor, Departments of Anesthesia and Pediatrics, School of Medicine, University of California, San Francisco, San Francisco, California

Kenneth A. Frankel, Ph.D., Staff Scientist, Donner Laboratory and Donner Pavilion, Lawrence Berkeley Laboratory, University of California, Berkeley, Berkeley, California

Robert M. Freedom, M.D., F.R.C.P.C., F.A.C.C., Professor, Departments of Cardiology, Paediatrics, and Pathology, University of Toronto and Chief of Cardiology, The Hospital for Sick Children, Toronto, Ontario, Canada

Robert W. Griebel, M.D., F.R.C.S.C., Associate Professor, Department of Neurosurgery, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

E. Bruce Hendrick, M.D., B.Sc.(Med), F.R.C.S.C., Professor of Surgery, University of Toronto and Deputy Chief Surgeon, Division of Neurological Surgery, The Hospital for Sick Children, Toronto, Ontario, Canada

Alan Hill, M.D., Ph.D., Professor, Department of Paediatrics and Head, Division of Paediatric Neurology, University of British Columbia, British Columbia's Children's Hospital, Vancouver, British Columbia, Canada

Harold J. Hoffman, M.D., B.Sc.(Med), F.R.C.S.C., F.A.C.S., Professor, Department of Surgery (Neurosurgery), University of Toronto and Chief of Neurosurgery, The Hospital for Sick Children, Toronto, Ontario, Canada

Yoshio Hosobuchi, M.D., Professor, Department of Neurological Surgery, School of Medicine, University of California, San Francisco, San Francisco, California

Roger J. Hudgins, M.D., Attending Pediatric Neurosurgeon, Scottish Rite Children's Hospital, Atlanta, Georgia

Robin P. Humphreys, M.D., F.R.C.S.C., F.A.C.S., Associate Professor, Departments of Surgery (Neurosurgery) and Anatomy, University of Toronto and Staff Surgeon, Division of Neurosurgery, The Hospital for Sick Children, Toronto, Ontario, Canada

Richard P. Levy, M.D., Staff Scientist, Donner Laboratory and Donner Pavilion, Lawrence Berkeley Laboratory, University of California, Berkeley, Berkeley, California

Steven Linder, M.D., Associate Clinical Professor of Pediatric Neurology, Department of Pediatrics, University of Texas Southwestern Medical School and Health Science Center, Dallas, Texas

Christer Lindquist, M.D., Ph.D., Associate Professor of Neurosurgery, Department of Neurosurgery, Karolinska Hospital, Stockholm, Sweden

Neil A. Martin, M.D., Assistant Professor, Division of Neurological Surgery, Department of Surgery, University of California School of Medicine, Los Angeles, Los Angeles, California

David G. McLone, M.D., Ph.D., Professor and Chairman, Division of Pediatric Neurosurgery, Northwestern University Medical School and The Children's Memorial Hospital, Chicago, Illinois

Thomas P. Naidich, M.D., Professor of Radiology, Northwestern University Medical School, Chicago, Illinois, and Director of Neuroradiology, Baptist Hospital of Miami, Miami, Florida

Shigeru Nemoto, M.D., Lecturer, Department of Neurosurgery, Tokyo University and Chief, Division of Neurosurgery, Showa General Hospital, Tokyo, Japan

Roger J. Packer, M.D., Associate Professor, Departments of Neurology and Pediatrics, University of Pennsylvania School of Medicine and Director, Neuro-Oncology Program, The Children's Hospital of Philadelphia, Philadelphia, Pennsylvania

Sydney J. Peerless, M.D., F.R.C.S.C., C. G. Drake Professor of Neurosurgery and Chairman, Division of Neurosurgery, Department of Clinical Neurological Sciences, The University of Western Ontario, London, Ontario, Canada

Mark H. Phillips, Ph.D., Staff Scientist, Donner Laboratory and Donner Pavilion, Lawrence Berkeley Laboratory, University of California, Berkeley, Berkeley, California

Peter G. Qvarfordt, M.D., Vascular Fellow, Department of Surgery, School of Medicine, University of California, San Francisco, San Francisco, California

Lucy Balian Rorke, M.D., Clinical Professor, Departments of Pathology and Neurology, University of Pennsylvania School of Medicine and Neuropathologist, Children's Hospital of Philadelphia, Philadelphia, Pennsylvania

Scott A. Rosenbloom, M.D., Staff Neuroradiologist, Division of Radiology, The Cleveland Clinic Foundation, Cleveland, Ohio

Duke Samson, M.D., Professor and Chairman, Divison of Neurosurgery, Department of Surgery, University of Texas Southwestern Medical School and Health Science Center, Dallas, Texas

Luis Schut, M.D., Professor of Neurosurgery and Pediatrics, University of Pennsylvania School of Medicine and Chief, Neurosurgical Services, Children's Hospital of Philadelphia, Philadelphia, Pennsylvania

Robert F. Spetzler, M.D., Director and J. N. Harber Chairman of Neurological Surgery, Barrow Neurological Institute of St. Joseph's Hospital and Medical Center, Phoenix, and Professor and Chief, Section of Neurosurgery, University of Arizona School of Medicine, Tucson, Arizona

Ladislau Steiner, M.D., Ph.D., Professor of Neurological Surgery, Department of Neurological Surgery, School of Medicine, University of Virginia, Charlottesville, Virginia

Melita Steiner, M.D., Professor of Neurological Surgery, Department of Neurological Surgery, School of Medicine, University of Virginia, Charlottesville, Virginia

Leslie N. Sutton, M.D., Assistant Professor, Department of Neurosurgery, University of Pennsylvania School of Medicine and Assistant Neurosurgeon, Children's Hospital of Philadelphia, Philadelphia, Pennsylvania

Joan L. Venes, M.D., Associate Professor, Departments of Surgery (Neurosurgery) and Pediatrics, University of Michigan Medical Center, Ann Arbor, Michigan

Joseph J. Volpe, M.D., A. Ernest and Jane G. Stein Professor of Developmental Neurology, Professor, Departments of Pediatrics, Neurology, and Biological Chemistry and Director of Pediatric Neurology, The Edward Mallinckrodt Department of Pediatrics, Washington University School of Medicine, St. Louis, Missouri

Charles B. Wilson, M.D., Tong-Po Kan Professor and Chairman, Department of Neurological Surgery, School of Medicine, University of California, San Francisco, San Francisco, California

Jeffrey H. Wisoff, M.D., Assistant Professor, Department of Neurosurgery, Division of Pediatric Neurosurgery, New York University Medical Center, New York, New York

Contents

CHAPTER ONE

Embryology of the Cerebral Vascular System

David G. McLone, M.D., Ph.D.
Thomas P. Naidich, M.D.

Dandy's monograph on intracranial arterial aneurysms (11), published in 1944, marked a pivotal point in the literature on the embryology of the vascular system of the brain. Earlier descriptions of the arteries of the head (3, 30, 52) had provided little information about the development of the cerebral arterial system and the circle of Willis (circulus arteriosus). Streeter (46) had described the formation of the cranial vasculature, adjustment of vessels to cerebral growth, and development of the dural venous sinuses, and Congdon (8) had defined the formation of the arch of the aorta and of the carotid, vertebral, and basilar arteries, but in general theirs had been the only work providing insight into the embryology of the cerebral vascular system.

In 1948, Padget (34) completed a study of the embryonic development of the cerebral arterial system and particularly the ophthalmic, stapedial, and trigeminal arteries, although she said little about those vessels that penetrate the neural substance. She later described the development of the venous drainage of the human brain (35, 36). Her classification systems, cast in the framework of Streeter's (47–50) developmental horizons (age groups), were the basis for much of the work that followed.

Subsequently, several authors elucidated the nature of the vascular system (19, 23, 24). Stoeter and Drews (44) focused on the embryonic venous system. Light and electron microscopy provided a powerful means for charting the penetration of vessels into the embryonic nervous system (5, 9, 10, 13, 14, 25–27, 29, 37, 54, 57). Within a period of a few years, the capillaries in the human embryonic brain were studied (4), establishment of the internal vasculature of the telencephalon was documented (15), and the capillaries were classified according to size at the ultrastructural level (20, 21). The work of Povlishock et al (38) on the relation between the endothelial cells and pericytes in the embryonic germinal matrix was extended by Allsopp and Gamble (1) to include capillaries of the embryonic cerebral hemispheres. Microangiographic technique (2, 39, 40) provided similarly critical documentation of the developmental architecture of the embryonic capillary system (41, 45).

The phases of prenatal vascular development described in this chapter are based on Padget's classifications (34–36), defined according to the present Carnegie staging system as summarized by O'Rahilly (Table 1.1).* The embryonic period of human development, encompassing the first 8 postovulatory weeks, is divided into 23 Carnegie stages which are delineated in terms of the greatest length (GL) and postovulatory age (POA) of the embryo. As O'Rahilly (32, 33) points out, this staging system has the advantage that relations can be drawn between the development of different organs.

THE CRANIAL ARTERIES

The precise order in which cranial capillaries form in the embryo varies from individual to individual. In general, however, as described by Padget (34), development passes through seven successive phases.

*RO O'Rahilly, personal communication, 1987.

Table 1.1. Developmental Phases of the Cranial Arterial, Venous, and Penetrating Vasculature[a]

Period	Carnegie Stage[b]	GL of embryo (mm)	Post-ovulatory age	Padget's arterial phases[c]	Padget's venous phases[d]	Duckett's phases of penetrating vessels[e]
			days			
EMBRYONIC PERIOD	13	4-6	28		1	
EMBRYONIC PERIOD	13-14			1		
EMBRYONIC PERIOD	14	5-7	32	2	2	
EMBRYONIC PERIOD	15	7-9	33			
EMBRYONIC PERIOD	15-16				3	
EMBRYONIC PERIOD	16	8-11	37	3		
EMBRYONIC PERIOD	17	11-14	41	4		
EMBRYONIC PERIOD	17-18				4	
EMBRYONIC PERIOD	18	13-17	44			
EMBRYONIC PERIOD	18-19			5		
EMBRYONIC PERIOD	19	16-18	48		5	
EMBRYONIC PERIOD	20	18-22	51			
EMBRYONIC PERIOD	20-21			6	6	
EMBRYONIC PERIOD	21	22-24	52			
EMBRYONIC PERIOD	22	23-28	54			
EMBRYONIC PERIOD	23	27-31	57			
			weeks			
EMBRYONIC PERIOD / FETAL PERIOD		20-30	7-8			1
EMBRYONIC PERIOD / FETAL PERIOD		20-40	7-9			2
EMBRYONIC PERIOD / FETAL PERIOD		30-60	8-10			3
FETAL PERIOD		40	9	7	7	
FETAL PERIOD		60-80	10-12		7a	4

GL: greatest length.

[a]Courtesy of R. O'Rahilly, M.D., Ph.D., Carnegie Laboratories of Embryology, California Primate Research Center, University of California, Davis.

[b]Data from O'Rahilly RO: Early human development and the chief sources of information on staged human embryos. *Eur J Obstet Gynecol Reprod Biol* 4:273–280, 1979. Data from O'Rahilly RO: The embryonic period (letter). *Teratology* 34:119, 1986.

[c]Data from Padget DH: The development of the cranial arteries in the human embryo. Carnegie Inst Wash Publ 575, *Contrib Embryol* 32:205–261, 1948.

[d]Data from Padget DH: The development of the cranial venous system in man, from the standpoint of comparative anatomy. Carnegie Inst Wash Publ 611, *Contrib Embryol* 36:79–140, 1957.

[e]Data from Duckett S: The establishment of internal vascularization in the human telencephalon. *Acta Anat* 80:107–113, 1971.

Phase 1. Carnegie Stage 13/14 (4 to 7 mm GL; 28 to 32 days POA). During this phase, the first and second aortic arches begin their involution. The portions of the paired aortas that extend cephalically from the third arch constitute the primitive internal carotid artery on each side (Fig. 1.1). This artery appears to emerge from a vascular plexus and to bifurcate distally into two branches. One branch is the primitive trigeminal artery. The other branch is the cerebral artery, which continues toward Rathke pouch, around which it anastomoses with the opposite cerebral artery. The carotid artery forms two divisions. A cranial division curves in front of the optic vesicle to terminate in the olfactory area. The caudal division of the carotid artery ends in a plexus at the mesencephalon (12). A primitive ophthalmic artery has developed by this time. The basilar artery has not yet formed. Instead, paired longitudinal neural arteries border the hindbrain bilaterally and connect laterally with the primitive hindbrain plexus. These neural arteries receive a dual supply: from the trigeminal division cranially and from the first cervical arterial segments caudally.

Phase 2. Carnegie Stage 14 (5 to 7 mm GL; 32 ± 1 days POA). The internal carotid artery is by now well defined. A ventral pharyngeal artery extends cranially from the aortic sac and contributes to the formation of the external carotid arteries. The basilar artery begins to form (8). The caudal division of each internal carotid artery develops a secondary anastomosis with the cranial end of the ipsilateral longi-

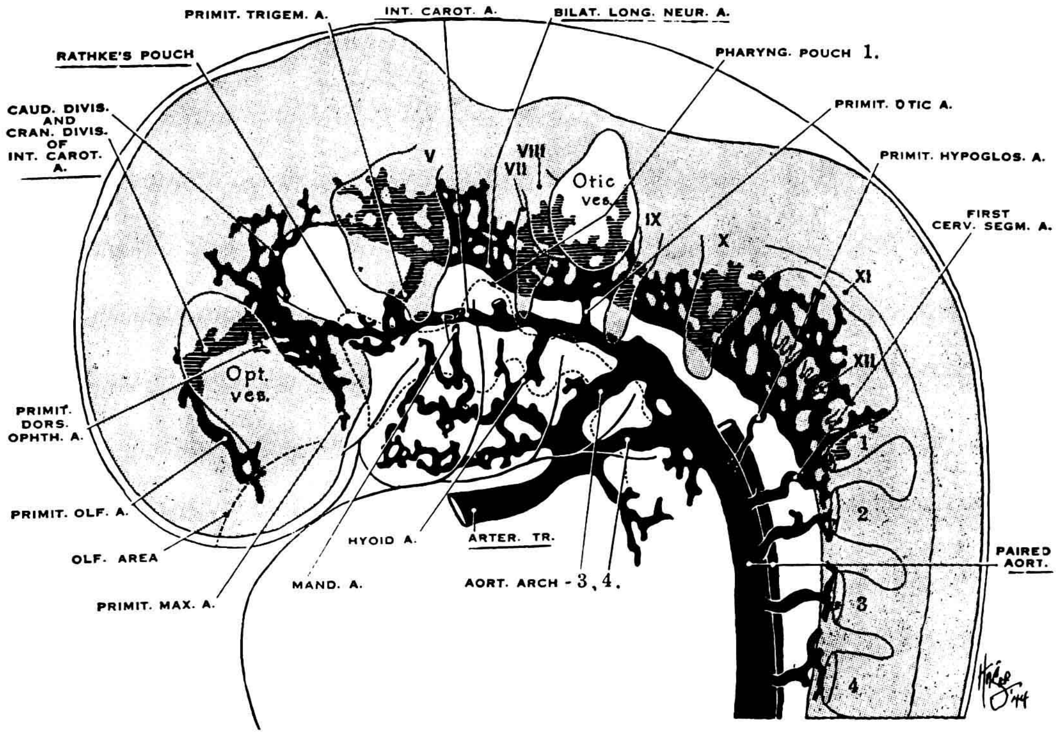

Figure 1.1. *Phase 1.* Cranial arteries in a 4-mm embryo. Following the involution of the first two aortic arches, represented in this phase by mandibular and hyoid arteries, the terminal end of the paired aortas of earlier phases is recognizable as the internal carotid artery originating from the third arch. The forebrain and optic vesicle are supplied by the primitive maxillary branch and the primary cranial division of the carotid; the caudal division courses over the midbrain. (From Padget DH: *Contrib Embryol* 32:205–261, 1948. Drawing by Dorcas H. Padget courtesy of the Department of Embryology, Davis Division, Carnegie Institution of Washington, D.C.)

tudinal neural artery, forming the posterior communicating artery. This new artery soon takes the place of the trigeminal artery as the major source of supply to the longitudinal neural—the future basilar—artery.

Phase 3. Carnegie Stage 16 (8 to 11 mm GL; 37 ± 1 days POA). The most striking development during this phase is the genesis of the vertebral artery (Fig. 1.2). The primary cranial division of the internal carotid artery gives rise to the primitive anterior choroidal artery. Medial twigs form in the path of the future anterior cerebral artery. Vascular twigs also appear at the distal end of the middle cerebral arterial stem. At the caudal end of the posterior communicating artery, the posterior choroidal artery is now visible. Superior cerebellar arteries are forming at the distal end of the basilar artery.

Phase 4. Carnegie Stage 17 (11 to 14 mm GL; 41 ± 1 days POA). The internal carotid artery has by now, in the 6-week-old embryo, formed definite divisions. The most proximal division is the choroidal artery. Next is the middle cerebral artery (MCA). Last is the continuation of the internal carotid artery as the stem of the anterior cerebral artery (Fig. 1.3). This arrangement would appear to be the reverse of that in the adult, in whom the anterior cerebral artery is considered to be the branch and the MCA the major cerebral continuation of the carotid artery. In the embryo, the anterior stem of the anterior cerebral artery joins a plexus of vessels that communicates with the opposite side. This plexus will become the anterior communicating artery.

Phase 5. Carnegie Stage 18/19 (13 to 18 mm GL; 44 to 48 days POA). Descent of

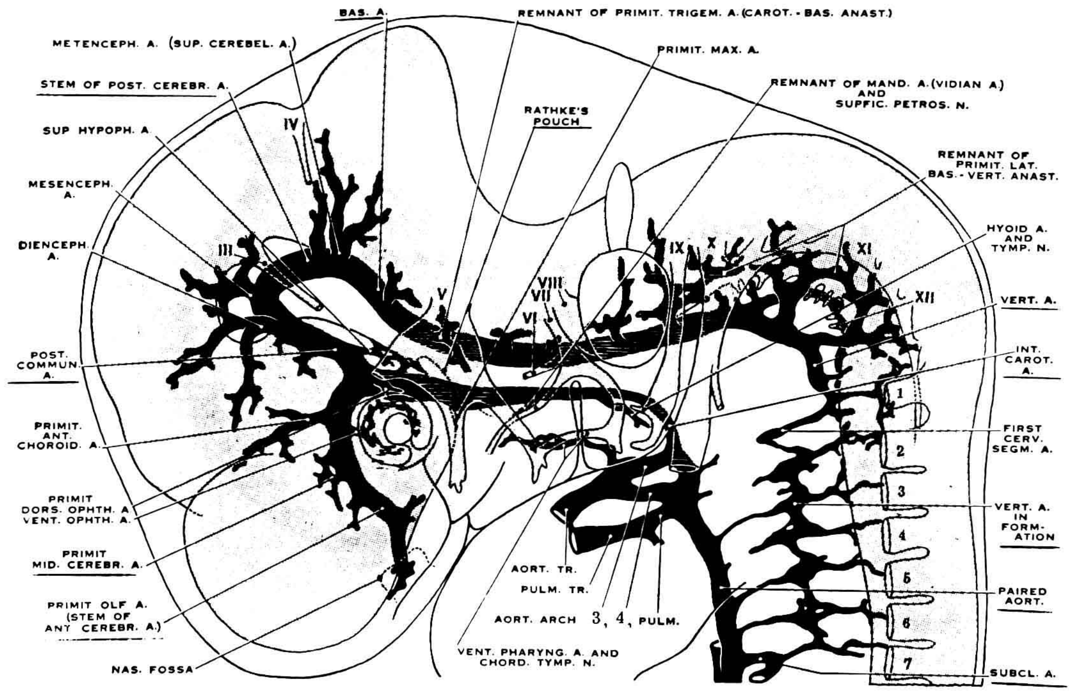

Figure 1.2. *Phase 3*. Cranial arteries of the left side in a 9-mm embryo (*lateral view*). Note formation of the vertebral artery from elements of the upper cervical segmentals, the caudal swing of the cranial nerve VII and its associated hyoid artery, the ventral pharyngeal artery lying against the mandibular end of the chorda tympani, and the two primitive arteries supplying the eye. The primitive olfactory artery cranial division of the internal carotid artery terminates at the nasal cavity. (From Padget DH: *Contrib Embryol* 32:205–261, 1948. Drawing by Dorcas H. Padget courtesy of the Department of Embryology, Davis Division, Carnegie Institution of Washington, D.C.)

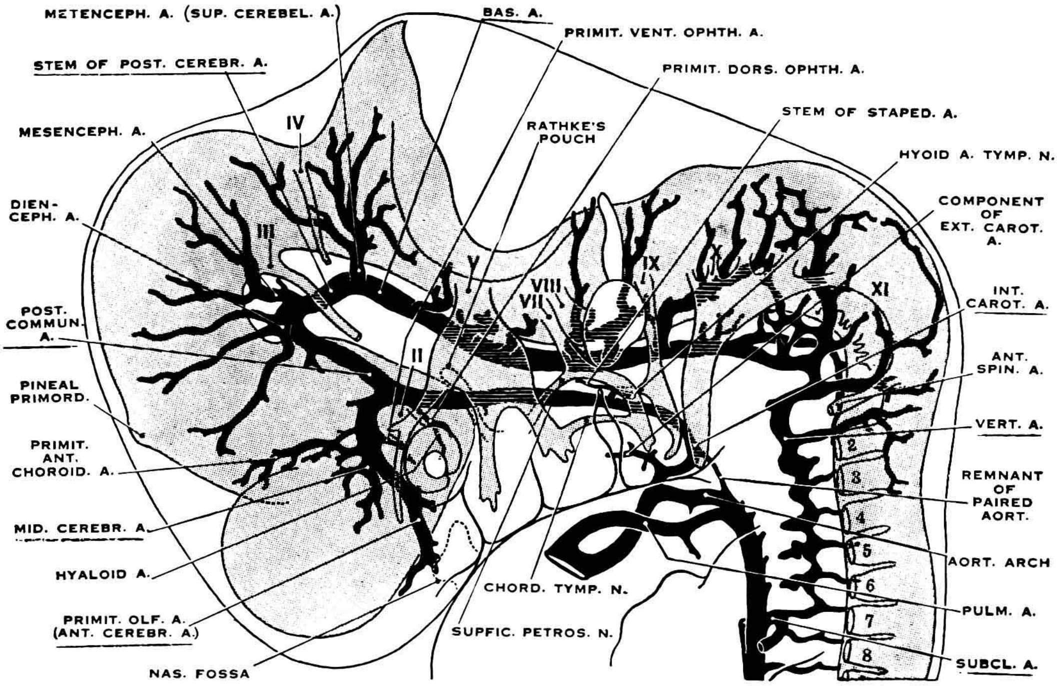

Figure 1.3. *Phase 4*. Cranial arteries in a 12.5-mm embryo. Developments to note are: the new stapedial branch of the hyoid artery, the stem of which has been shifted cranially; the more advanced conformation of the vertebral artery; the emergence of several well-defined cerebral arteries; and elongation and differentiation of the two primitive ophthalmic branches of the internal carotid artery. (From Padget DH: *Contrib Embryol* 32:205–261, 1948. Drawing by Dorcas H. Padget courtesy of the Department of Embryology, Davis Division, Carnegie Institution of Washington, D.C.)

the heart into the thorax elongates the common carotid artery. The definitive adult ophthalmic artery arises from two widely separated portions of the internal carotid artery. The MCA gives rise to several branches that spread over the cerebral hemispheres (Fig. 1.4). Both the anterior and the posterior choroidal arteries terminate in the chordial infolding at the diencephalic roof. The first segment of the posterior cerebral artery is evident at the distal end of the posterior communicating artery. Later, this artery will enlarge rapidly as the hemisphere grows posteriorly to envelop the midbrain. The three principal branches of the basilar system have become clearly identifiable by this phase.

Phase 6. Carnegie Stage 20/21 (18 to 24 mm GL; 51 to 52 days POA). The head of the 7-week-old embryo has recognizable human features and begins to lift away from the chest. As the cerebral hemisphere expands, the circle of Willis becomes complete. The most important arterial development during this phase involves the anterior cerebral and the anterior communicating arteries. Before development of the corpus callosum from the commissural plate, a branch of the anterior cerebral artery supplies the choroid plexus in the region of the foramen of Monro (6). The anterior cerebral artery develops variably; depending on the individual, it may appear as a barely identifiable vessel, a plexus, or a single midline vessel. In chimpanzees, the branch of the anterior cerebral artery may persist in its development, passing around the splenium into the velum interpositum to terminate at the foramen of Monro (34). Some animals may form only

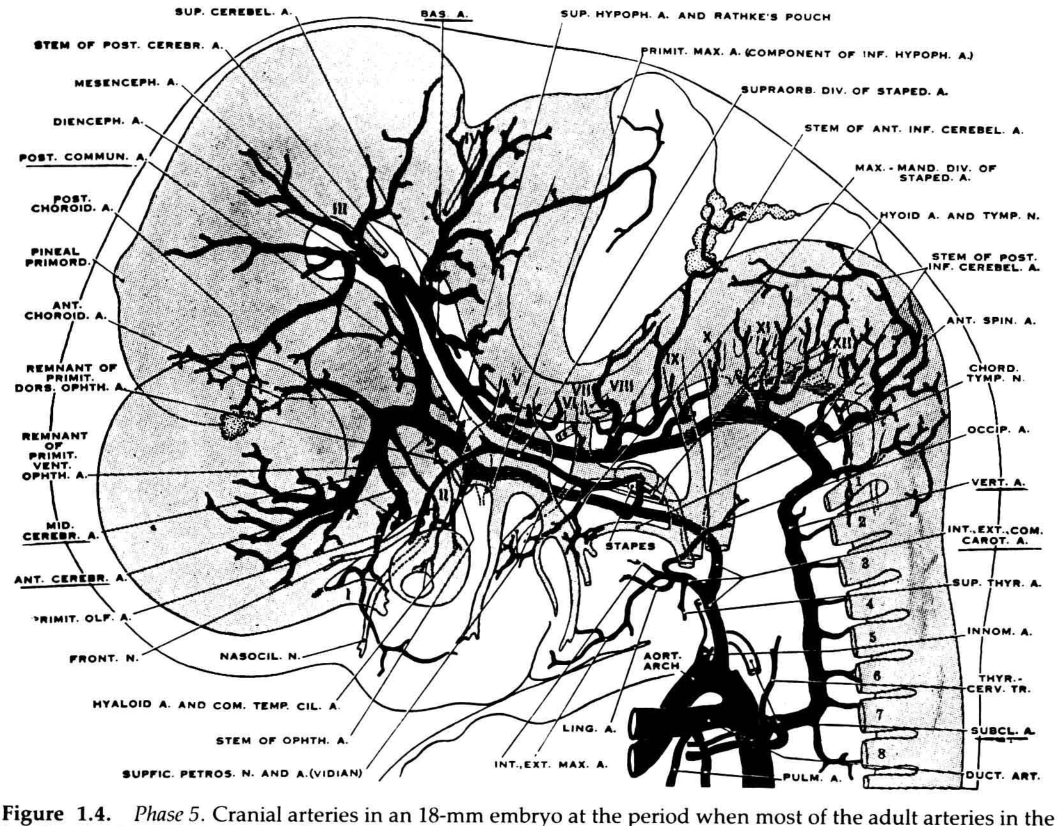

Figure 1.4. *Phase 5.* Cranial arteries in an 18-mm embryo at the period when most of the adult arteries in the head region become recognizable. Note the new adult stem of the ophthalmic artery, which annexes the ocular branches of the primitive ophthalmic arteries. (From Padget DH: *Contrib Embryol* 32:205–261, 1948. Drawing by Dorcas H. Padget courtesy of the Department of Embryology, Davis Division, Carnegie Institution of Washington, D.C.)