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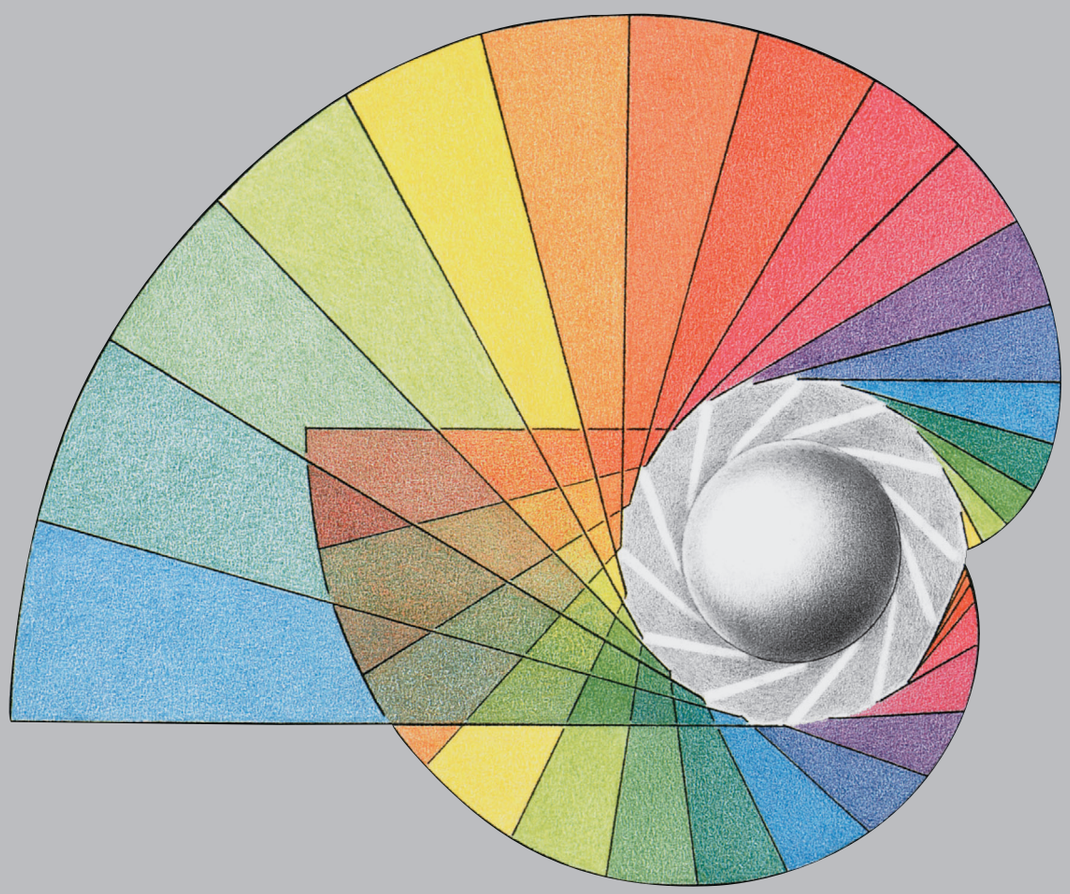
Microneurosurgery

In 4 Volumes

M. G. Yaşargil

IV A

CNS Tumors:
Surgical Anatomy, Neuropathology, Neuroradiology, Neurophysiology, Clinical Considerations, Operability, Treatment Options



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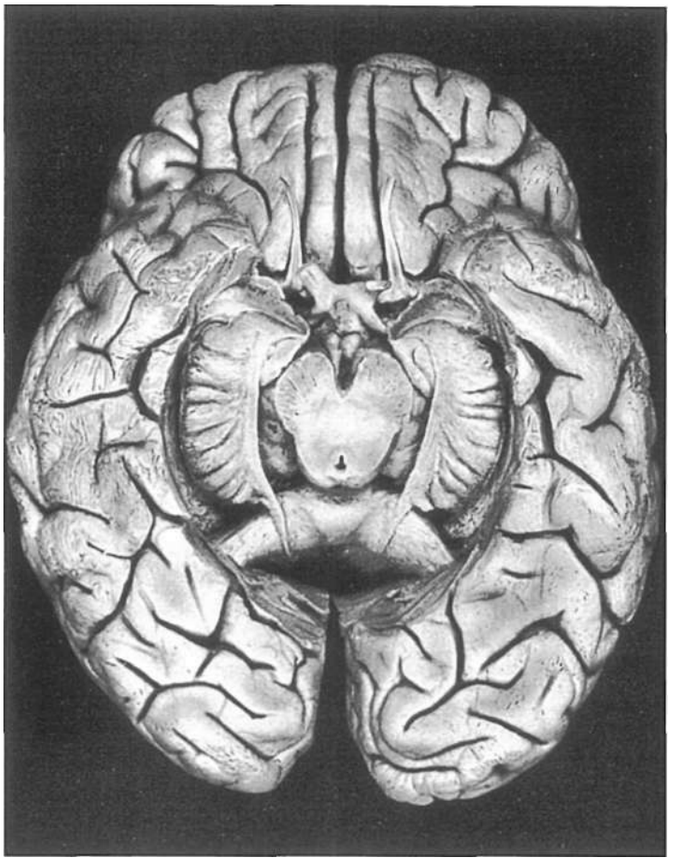

Professor Josef Klingler (1888–1963), Professor of Anatomy at the University of Basel, Switzerland, from whom I learned a unique process for the dissection of the brain and particularly the white matter systems, and thereby gained an inimitable neuroanatomical perspective of these complex structures. Dissection of both Hippocampal formations, by Professor J. Klingler, who always maintained that the Hippocampus was the most complex structure in all of Nature, possessing qualities which are not immediately apparent from its confined anatomical structure.

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M. G. Yaşargil

I

Microsurgical Anatomy of the Basal Cisterns and Vessels of the Brain, Diagnostic Studies, General Operative Techniques and Pathological Considerations of the Intracranial Aneurysms

II

Clinical Considerations, Surgery of the Intracranial Aneurysms and Results

III A

AVM of the Brain, History, Embryology, Pathological Considerations, Hemodynamics, Diagnostic Studies, Microsurgical Anatomy

III B

AVM of the Brain, Clinical Considerations, General and Special Operative Techniques, Surgical Results, Nonoperated Cases, Cavernous and Venous Angiomas, Neuroanesthesia

IV A

CNS Tumors:
Surgical Anatomy, Neuropathology, Neuroradiology, Neurophysiology, Clinical Considerations, Operability, Treatment Options

IV B

Microsurgery of CNS Tumors

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New York

IV A

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M. G. Yaşargil

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Anatomical preparations by A. Lang, U. Türe

Illustrated by P. Roth

1126 illustrations, 58 tables

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In autumn 1993 *M. G. Yaşargil*

Preface

The purpose of Volumes IV A and B is to discuss the reliability of the present basic neuroscientific investigations and to present clinical observations, management strategies, microsurgical approaches, and operative results in over 3400 patients with CNS tumors.

The decision-making process in the treatment of CNS tumors involves the application of knowledge from several associated disciplines. Precision in determining the diagnosis, localization, treatment options, and prognosis of each lesion requires accurate *neuroanatomical, neurophysiological, neuropathological, neuroinvestigational,* and *newoclinical* knowledge. Those involved in the care of CNS tumor patients must be familiar with the important role each of these fields plays in the final determination of a treatment strategy. In addition, we must be aware of the remarkable recent advances being made in these areas.

Neuropathologists, using immunocytochemistry and allied techniques, have been able to offer us an increasingly precise classification of tumors. However, the understanding of fundamental tumor biology is still elusive. In addition, they have not yet provided an accurate method of anticipating the growth and growth pattern, spread, migration, or penetration of an individual tumor, the factors which are most helpful in the determination of tumor operability and intensity of treatment. Clinical observations, on the other hand, indicate that the invasive potentials of benign and malignant extrinsic and intrinsic tumors are limited by anatomical and biological barriers, at least in the initial and intermediate phases of tumor growth. This important fact indicates great changes concerning the therapeutic options (see Chapter 2, Neuropathology).

During the initial period of microsurgery in Zurich (between 1967 and 1975), the diagnosis and the indications for surgery of CNS tumors were based in the classic manner on the complete history, physical examination, and adjuvant studies, including EEG, pneumoencephalography, angiography, and myelography. Within the past 17 years, significant diagnostic advances have been achieved: the visualization techniques of CT scan, functional and dynamic MRI, MR spectroscopy, and other techniques (PET, SPECT, Doppler) have proved to be great innovations in the immediate recognition of CNS tumors and peritumoral changes in both the pre- and postoperative phases. These modalities, combined with microtechniques, have greatly improved the surgical treatment of CNS tumors. Along with these advances, however, there are new problems in diagnosis, indications for treatment, and decisions on the treatment options of these lesions, which are presented and discussed in Neuroradiology (Chapter 3) and Operability (Chapter 5).

The century-old neurophysiological concepts concerning the balance of intracranial and intraspinal volumes (parenchymal mass, blood, cerebrospinal fluid, and tumor) were based only on mechanical forces. Clinical observations, however, combined with modern neuroimaging techniques, demand a more complex concept. This new dynamic concept should not only account for mechanical factors but must allude to the complex biochemical, biological, and immunological interactions between normal tissue and pathological tissue. An understanding of this dynamic normal tissue-lesion imbalance may then explain the changes seen in pathological situations and their resultant consequences (see Chapter 4, Neurophysiology).

Surgical anatomy is another essential issue; it is not only the summary of available knowledge gained from macroscopical, microscopical, and ultramicroscopical investigations of the anatomist or from observations and studies of the neuroradiologist, neurophysiologist, and neurosurgeon. Although three-dimensional morphological and functional anatomical models of the brain are very instructive, they remain segregated models of reality. The individual variations of "morphology-pathomorphology" and "physiology-pathophysiology" are other dimensions, which provoke and challenge the surgeon to continuous imagination and projection of adequate dynamic concepts. Additionally, the reality of a surgical exploration involves a gross amount of still undiscovered, therefore unknown, morphological and functional facts. It would be ideal to have the assistance of the clinical neuroanatomist, neurophysiologist, and computer engineer during the whole perioperative phase. Personally, I am convinced that this will be the case in the near future in the modern, computerized operating room, where the combined morphological and functional anatomical 3-D dynamic models can be examined and checked according to the needs of the given situation with respect to the desires of the surgeon. The ongoing technical developments (i. e., frameless stereotactic localization system with the help of infrared LED devices) require from us accurate anatomical knowledge and new surgical anatomical concepts. The unique construction and functions of the brain require, topographically, a more differentiated concept according to the functional anatomy and sophisticated predilection site of the lesions; to provide the reader with an adequate and systematic picture of the complex brain anatomy, the gyral convolutions, the gyral segments, the sectorial and peduncular organization of the white matter, the topography of the basal ganglia and central nuclei, the pattern of arterial and venous vascularization, pathways of neuronal migration, and pathways of neurotransmitters, I have used not only my own material of sectional specimens and those of the Anatomical Institute of the University of Zurich, but also related, essential, well-known pictures of other authors. It is my intention to give interested colleagues my personal surgical anatomical concepts, which I need and use for my surgical decisions and actions. To facilitate the transformation of surgical anatomical images and their memorization, the figures have often been colored as in Chapter 1, Neuroanatomy.

Our ability to continue to rely on the *old* paradigms of neuroanatomy, neuropathology, neuroradiology, and neurophysiology is questionable. Therefore, conceptually innovative ideas relating to individual surgical anatomy, neuroimaging, neuropathology, and neurophysiology are presented here. A new definition and approach to operability is examined, perhaps giving life to a *new* paradigm for the treatment of CNS tumors.

Advances and limitations in neuroanatomy, neuropathology, neuroimaging, and neurophysiology and their relation to clinical neurosurgery, especially regarding the operability of CNS tumors and the treatment options, are presented and discussed in Chapter 5, Clinical Considerations.

Noninvasive explorations and pure tumorectomies have been performed along the transcisternal, transsulcal, and transfissural pathways without lobectomy or gyrectomy, fully respecting the brain and other vital structures. These microsurgical techniques of "nontraumatization" of the brain or with "very minimal traumatization," are documented in numerous cases with pre- and postoperative three-planar MR images, at the end of Chapters 2, 3, 4, and 5.

I have been asked from visiting colleagues to write this volume and describe the applied microsurgical techniques with perioperative surgical-anatomical perspectives and concepts of the surgeon. Each surgical action comprises not only science, experience, knowledge, and techniques, but also artistic, philosophical, and religious attitudes from a neurosurgeon. We respect that *eros* is the cohesive power which holds the multimodal potentials of the human brain together with its continuous stimulation and drives.

The artistic masters of the Renaissance discovered the perspective of three-dimensionality and immediately began to study the impact of functionality in exact measurement techniques. Up until the twentieth century, orientation depended on the topology of a pictorially ordered world of objects in which relationships are expressed by spatial metaphors. Cubism broke down these forms of perception, dismantling the identity of the figurative into nonidentical aspects that could be projected upon each other. Constructive and concrete art entered into deeper dimensions, searching the elements of functionality. These trends culminated in mathematized art and philosophy, and computerized science and techniques. The masterpieces of constructive and concrete art deal scientifically with modern modular, serial and parallel processes, some relating to the philosophy of monads from G. W. Leibniz (1646–1716), whose genius had already developed an early computer.

The neurophysiologist introduced the concept of a modular and columnar cortical organization of the brain (V. B. Mountcastle, 1957; D. Hubel, T. Wiesel, 1977): computational neurobiology has arrived. The convergence of science, technology, art, and philosophy is obvious. The displayed masterpieces of constructive and concrete art in this volume should be seen symbolically as a prelude to the related topics of the different chapters. It is hoped that the combination of pure art with the art of scientific illustration will enhance the interest of the reader. We should remember that the fortunate cooperation between H. Cushing and W. E. Dandy with the gifted illustrator Max Brödel at Johns Hopkins, Baltimore, opened new perspectives for scientific medicine at the beginning of 20th century.

The presented experiences, observations, ideas, perspectives, and concepts are intended to stimulate open discussions, which will subsequently further advances throughout the entire field of neurosurgery.

Volume IV B is devoted to surgical strategies, tactics, and techniques and to specific types of tumors and their management. It will include detailed descriptions of both surgical approaches and the microtechnical removal of different types of CNS tumors, and is followed by a complete analysis of the operated cases of the senior author.

Initially, Volumes IV A and B had been scheduled to be published at the latest in 1990. My daily clinical work, however, did not permit me to keep my promise. Only one part of the anatomy chapter, namely the "cerebral sulci," could be accomplished and was investigated by Dr. M. Ono and Dr. S. Kubik. The decision was made to publish this homogeneous part in advance as *Atlas of the Cerebral Sulci* (Stuttgart: Thieme, 1990) to be followed later by these volumes. The unforeseen separation of sulcal anatomy, requires therefore, frequent references to the figures in this abovementioned atlas.

In autumn 1993 *M. G. Yaşargil*

La naissance de Pallas Athénée-Minerve / Geburt der Pallas Athena-Minerva, in: Michael Meier, Atlanta Fugiens, hoc est, Emblemata Nova de Secretis Naturae, Oppenheim, 1618.

The very first neurosurgeon of Greek mythology was Hephaestos, god of fire and surgery. The patient here is Zeus. Since giving birth was the only true mark of divinity in ancient beliefs, the first male gods to claim any sort of supremacy had to also claim the ability to give birth. Lacking any birth organ, many male gods in the different mythologies tried to give birth from various parts of their bodies. Hellenic Greeks pretended their new father Zeus gave birth to the goddess Athena from his head. The real mother of Athena was Methis. *Methis* means "female imagination." She was a source of the feminine art of healing and her name is related to the word "medicine." She was the mythological mother of Athena and was assimilated into the Zeus cult by the claim that Zeus impregnated her, then swallowed her after she had transformed herself into a bee, so that her "imagination principle" became part of himself. This "female imagination principle" must have been too heavy for Zeus' brain, for he suffered terrible headaches. Hermes called Hephaestos to perform the first neurosurgical procedure in Greek mythology, that of assisting Zeus to give birth to Athena through his head. In the background is Aphrodite with Ares (god of war). Their children are named Harmonia and the twins, Phobos (Panic) and Deimos (Fear), names which, interestingly, are related to the psychology of surgical actions.

Abbreviations Used

ACA	Anterior cerebral artery
ACTH	Adrenocorticotropic hormone
ADH	Antidiuretic hormone
ATP	Adenosine triphosphate
AV3V	Anteroventral third ventricle
AV	Anterior ventral
AVM	Arteriovenous malformation
AVP	Arginine vasopressin
BUDR	5-bromodeoxyuridine
CBF	Cerebral blood flow
CNS	Central nervous system
CPP	Cerebral perfusion pressure
CSF	Cerebrospinal fluid
CT	Computed tomography
DM	Double minute
DNA	Deoxyribonucleic acid
DSA	Digital subtraction angiography
ECF	Extracellular fluid
EEG	Electroencephalogram
EMG	Electromyogram
EPG	Electropneumogram
GABA	Gamma-aminobutyric acid
Gd-DTPA	Gadolinium diethylenetriaminepentaacetic acid
GH	Growth hormone
HSR	Homogeneously staining region
ICA	Internal carotid artery
ICP	Intracranial pressure
ISF	Interstitial fluid
LH	Luteinizing hormone
LHRH	Luteinizing hormone releasing hormone
LTO	Lateral temporo-occipital
MCA	Middle cerebral artery
MEG	Magnetic encephalography
MGB	Medial geniculate body
MR	Magnetic resonance
MRA	Magnetic resonance angiography
MRI	Magnetic resonance imaging
MTO	Middle temporo-occipital
NOR	Nucleolar organizer region
PCA	Posterior cerebral artery
PET	Positron emission tomography
PNET	Primitive neuroectodermal tumor
PNS	Peripheral nervous system
PVI	Peripheral vascular insufficiency
rCBF	Regional cerebral blood flow
REM	Rapid eye movement
RNA	Ribonucleic acid
SCA	Superior cerebellar artery
SON	Supraoptic nucleus
TGF	Transforming growth factor
TRH	Thyrotropin-releasing hormone
VA	Ventral anterior
VL	Ventrolateral
VMD	Ventromedial dorsal
VMN	Ventromedial nucleus
VPL	Ventroposterolateral
VPM	Ventroposteromedial

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Introduction

Hippocrates (circa 375–460 B. C.) stated "*Askin peri ta nosimata dio: ofelin i mi vlaptin"* which, roughly translated, means: In cases of disease there are two ways to provide: to help, or at least cause no damage. "*Nil nocere"* is the Latin tenant "do not harm."

These age-old principles we should all respect. Physicians are taught as students to ask: "What is wrong? How can I help?," and: "What is the likely outcome?" These questions must be engraved in our approach to each and every patient.

Great advances in the natural sciences and associated techniques in the 18th and 19th centuries made possible the establishment of the field of neuroscience. Over the last one hundred years this field has developed into a large number of closely associated disciplines.

The discipline of neurosurgery is no longer considered in isolation with regard to the treatment decisions concerning CNS neoplasms. Our successes and our failures are no longer ours to bear completely alone. By means of the accelerated developments in the fields listed in Table **1**, almost every recent decade has brought new diagnostic tools and therapeutic aids (Table 2).

Table **1** Neuroscience disciplines

Neuroanatomy	Neurology
Neuroembryology	Neuropsychology + Behavioral neurology
Neurophysiology	Neuroanesthesia
Neuropathology	Neurosurgery
Neuroradiology	Neurootosurgery
Neuronuclear medicine	Neuroradiotherapy
Neurobiochemistry	Neurochemotherapy
Neuropharmacology	Neuroimmunology
Neurobioengineering	Neurogenetics

Table **2** Developments in neurodiagnosis

1. Before 1900	History, neurological examination, ophthalmoscope
2. 1900–1930	X-Ray, PEG, myelography, audiometry, examination of CSF
3. 1930–1970	EEG, cerebral and spinal angiography, stereoangiography, echography, radioisotope studies
4. 1970–1990	Ultrasound (Doppler), CT, MRI, DSA, superselective angiography, MRA, PET, MEG, dynamic 3D-MRI and MR angiography.

The pioneers of neurology and neurosurgery were forced to rely only upon careful history-taking and astute clinical observations gleaned from palpation, percussion, and auscultation, to reach a diagnosis. The first neurological diagnostic instruments were patellar hammers, pins, and smelling bottles, followed later by ophthalmoscopes, perimetry screens, and audiovestibular tests. Even with these limited resources, reasonable estimates as to the general location of lesions and their pathological diagnoses could be determined by our predecessors. It was felt that a diagnosis could be reached 90% of the time following a detailed history and thorough physical examination. A further workup was felt not to significantly increase the yield (Osler). These fundamental clinical skills still remain important today.

From the neuroclinical point of view, tumors within the CNS may present with one or a constellation of signs and symptoms, indicating either local tumor effects or a generalized change in intracranial pressure. These findings may suggest focal pathology or they may indicate a false localization. On the other hand, tumors may be discovered accidentally. It remains fascinating, but as yet unclear, how even very large lesions with a significant intracranial compression can be completely silent and leave the patient asymptomatic.

Advances in morphological diagnosis using noninvasive instantaneous modalities such as CT scanning and MRI, have clearly revolutionized the neuroscientist's ability to precisely define CNS pathology. At the same time it is strongly advised that neuroclinical findings continue to direct and guide the "spotlight" which has been provided by advanced neuroimaging techniques and, thus, avoid the "shotgun approach" to diagnosis, namely that of over-utilization of the newest and most expensive technology.

In assessing patients clinically and studying the results of a variety of investigations, we frequently come to almost instantaneous conclusions regarding the "treatability–operability" of their lesions. These critically important decisions are based on a variety of factors (see Table **3**), but principally upon the topographical accessibility and the assumed nature (malignant propensity) of the tumor. It is decided whether there is great hope, an uncertain future, or little chance of survival with any meaningful quality of life. Using learned paradigms, the informed physician reaches a conclusion as to what seems to be in the best interests of the patient. A physician's assessment of an individual patient's prognosis at the time of the initial decision-making process is influenced most by the individual physician's own past experiences. When a patient's final outcome is assessed and confirms the predicted outcome, the physician's opinion regarding the correctness of his or her original treatment decisions are often reinforced (even though other treatment strategies may have resulted in a better outcome). In other words, if we avoid analyzing and looking closely at our failures, we may find ourselves judging them as successes.

Despite advances in almost every sphere of neuroscientific investigation and treatment, a major deficiency still exists in the understanding of fundamental CNS tumor biology. The structural and functional relationship between tumor and normal tissue

(both focal and global) remains ambiguous and much work toward a comprehensive understanding of what can be expected when a particular lesion is diagnosed, needs to be undertaken. Our knowledge of fundamental brain organization and its local and generalized reaction to insult is vastly incomplete. This information is critical to the neurosurgeon's decision-making process in patients harboring CNS neoplasms. The measurement of tumoral physiological activity and other tumor-related changes have provided some essential diagnostic information. More comprehensive, specific, instantaneous imaging is becoming available through still other new technological advances including PET, magnetic resonance spectroscopy, and dynamic 3D-MRI. The limits of neuroimaging technology as related to the needs of CNS tumor surgeons, however, will need to be repeatedly evaluated and modified in order to finally attain the required standard.

Noninvasive and instant neuroimaging techniques have immensely improved diagnostic capacities, but they have not clarified or helped to indicate fully convincing therapeutic options. On the contrary, increasingly controversial developments are observed concerning therapeutic modalities, for instance: tumor biopsy only, decompression, partial or complete removal of the tumor using various technical approaches with or without additional therapeutic options such as radiation techniques, chemo-, immuno-, thermo-, or phototherapies and, finally, no active treatment at all, apart from perhaps merely symptomatic pharmacotherapy attended by the attitude "wait and see."

The situation, which is irritating for the patients and their families, for their primary-care physicians, and for the colleagues in nonneuroscience fields, is not only due to the advances in neuroimaging, but mainly due to the lack of corresponding breakthroughs in biology.

As there is still no curative therapy available, each therapeutic endeavor remains, in the final analysis, a palliative action, as in the case of anaplastic glioma as well as in some cases of extrinsic tumors such as adenomas, craniopharyngiomas, meningiomas, and neurinomas.

Despite significant deficiencies in our neuropathological and neurophysiological understanding of CNS tumors, a comprehensive approach primarily utilizing current neuroanatomical and neuroradiological knowledge should be formulated. New paradigms to better determine the operability of individual patients' tumors should be constructed. Two of the great nineteenth-century neurophysiologists and neurologists, notably John Hughlings Jackson and David Ferrier, showed that the brain was not a single unified organ but contained within it complex functional localizations. This theory is all too often forgotten. The brain is a conglomerate of many organs linked by a vast and complex network of communication systems.

This complex organization within the brain allows for great paradoxes in clinical presentation of CNS tumors and in surgical outcome. In addition it leads to enormous diversity in the development of neurological *plasticity* and accommodation, and in endless variability in the outcome following pathological insults or surgery.

There is little doubt, however, that the infinite variability of tumor growth rates, aggressiveness, immunological character, cytochemistry, invasiveness, and interaction with the surrounding areas of the CNS, will leave us with problems of management for many years to come. Many of these basic problems associated with tumor surgery that plagued Cushing and Dandy still exist today, for instance, our ability to preoperatively describe a tumors' location, composition, and interface with neighboring structures.

It is of the utmost importance for us to understand not only the advances that have been achieved, but also the limitations that remain.

In the final analysis, each Surgeon should constantly reassess his or her approach to the operability of a given case, based upon up-to-date principles and the collective worldwide experience, and it is our hope that this Book will, in some measure, help in this purpose.

Table **3** The internal computer for decision-making

Stage	Question
1. Preliminary diagnosis	Nonsurgical or surgical lesion
2. Preliminary differential diagnosis	Vascular, neoplastic, infection, or autoimmune lesion
3. Special differential diagnosis	Type of tumor – Classification – Grading
4. General topographic diagnosis	Supra- or infratentorial: extrinsic or intrinsic or mixed
5. Special topographic diagnosis	
a) More precise localization b) Modes of expansion (circumscribed or diffuse)	Epidural, dural, subdural, subarachnoid, or mixed, or neopallial, transitional, central nuclei, intraventricular
6. Prognostic information	Natural history of tumors
a) Vital	Blood, CSF tests (enzyme) Possible reaction to the therapeutic modalities (surgery, radio- and chemotherapy)
b) Functional	Potential functional deficits (eloquent or noneloquent areas)
c) Possible reaction to therapeutic modalities	Radiation, chemotherapy
7. Final decision	Which treatment, alone or multimodality therapy?

1 Anatomy

Max Bill
Surface of a Spiral
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Topographic Anatomy for Microsurgical Approaches to Intrinsic Brain Tumors

Introduction

The surgical anatomy of the cerebral and cerebellar hemispheres and its relation to the surgery of tumors will be discussed in this chapter, and in particular, the new concepts developed (in an evolving patchwork fashion) by the senior author over the last 26 years in the operative treatment of over 3400 tumors of the central nervous system. Some of the special surgical anatomy in relation to the extrinsic group of tumors will be presented in Volume IV B.

The anatomy of the central nervous system (including special considerations, such as the embryological, parenchymal, vascular, functional, topographical, neuroradiological, and stereotactic aspects) with both macrosurgical and microsurgical perspectives, is extensively described in numerous textbooks and publications. Furthermore, excellently illustrated atlases, beautifully stained gross cross-sectional references with stereoscopic slides, and idealized computer models are readily available today to further aid our understanding of the fascinating morphology of the CNS (Key and Retzius 1875, Retzius 1896, von Economo and Koskinas 1925, Elze 1932, Rose 1935, Villiger and Ludwig 1946,1951, Mettler 1948, Basset 1952, Krieg 1953, Ludwig and Klingler 1956, Clara 1959, Delmas and Pertuiset 1959, Schaltenbrand and Bailey 1959, Wolf-Heidegger 1962, Elliott 1969, Kahle 1969, Ferner 1970, Rohen 1971, Lang 1973–1988, Waddington 1974, Stephan 1975, Szikla et al. 1977, Kieffer and Heitzmann 1979, Dejerine 1980, Pernkopf 1980, Angevine et al. 1961, Brodal 1981, Smith 1981, Töndury 1981, Koritké and Sick 1982, Creutzfeld 1983, Heines 1983, McGrath 1984, Benninghoff 1984, Fitzgerald 1985, Gray 1985, Clemente 1985, Watson 1985, Formann and Heym 1985, Jones and Peters 1986, Maillot 1986, Wilkinson 1986, Fix 1987, 1992, Leonhard et al. (eds.) 1987, Zenker (ed.): 1985, Barr and Kiernan 1988, de Groot and Chusid 1988, Niewenhuys et al. 1988. Ferner, Staubesand (eds.): 1973, 1975, Talairach et al. 1988, Armon de et al. 1989, Martin 1989, Williams and Warwick 1989, Lasjaunias and Berenstein 1990, Lippert and Seiderer 1990, Von Hagens et al. 1990, Carpenter 1985–1991, England and Wakely 1991). (See also Yaşargil, 1984, vol. I. pp. 5–53—subarachnoid cisterns; pp. 54–168—intracranial arteries; vol. III A, 1987, pp. 284–319—sulci and fissures; pp. 320–6—microcirculation; pp. 327–32—venous system; pp. 338–49—cortical blood vessels; pp. 350–68—calcarine sulcus; and vol. III B, p. 7, pp. 205–10, pp. 287–90.)

The work of Basset 1952), Huang (1964–1985), Stephens and Stilwell (1969), Duvernoy (1969–1988), Waddington (1974), Newton and Potts (1974), Salamon (1973), Williams and Warwick (1975), Lang (1973–1992), Seeger (1978, 1980, 1984), and Marinkovic (1985–1992) has given us, to a degree, the necessary topographical details we require. The elegant series of studies by Rhoton and his associates (1976–1992) describes the precise microsurgical details of various brain regions, with their corresponding vasculature, from the neurosurgeon's point of view.

Nevertheless certain areas of the brain have not received the same precise and neurosurgically relevant anatomical analysis. Important aspects of the brain, such as the surgical anatomy of the gyri and white matter, and associated variations in the leptomeningeal and cortical vasculature have only partially been elucidated (Salamon et al. 1972–74, Waddington 1974). Experts in stereotactic techniques have particularly contributed to the development of precise atlases of areas deep within the brain (Szikla et al. 1977). Similarly, computer technology has proved of immense help in displaying three-planar maps of these structures (Matsui and Hirano 1978, Heiss et al. 1985, William and Haughton 1985, Daniels et al. 1987, Gouaje and Salamon 1988, Talairach and Tournoux 1988, Courchesne et al. 1989, Hirsch et al. 1989, Press et al. 1989, Aichner et al. 1989, Schnitzlein and Murtag 1990, Steinmetz and Huang 1990, Toga 1990, Kretschmann and Weinreich 1991, Dietemann 1993).

Three-dimensional magnetic resonance images will undoubtedly become available in full color and in film sequences (Levin et al. 1989, Hu X et al. 1990). Positron emission tomography (PET) and magnetic electroencephalography (MEG) are providing new insights into the localization and regional integration of cerebral functions in both normal and pathological brains and demonstrate a spectrum of variation not previously imagined. The impact of the function (local and global) of similar pathological lesions (often widely disparate) can now be studied in evolution. Developments in imaging techniques have done much to advance the convergence of (sometimes conflicting) morphological and functional brain maps.

The more detailed information provided by neuroimaging techniques, the results of neurophysiological, neuropathological, and neuroimmunological investigations, and extensive surgical anatomical experience, have demonstrated that the CNS is a unique morphofunctional unit consisting of an integrated, dynamic network of several subsystems. Precise topographic and functionally defined diagnoses of brain lesions and adequate treatment decisions require from the neurosurgeon (as well as from interventional neuroradiologists, radiotherapists, and chemotherapists) more sophisticated knowledge of the anatomy and physiology of the CNS.

Following the historical sketch of brain architecture and a short description of the neuroembryogenesis and neurogenesis, the surgical anatomy of the cerebral and cerebellar hemispheres, including the borderlines, sulci, gyri, and white-matter segments, and their arterial and venous patterns will be presented.

Historical Sketch of Brain Architecture

The 160-year history of research on the structure of the brain cortex has been well described by several authors (Soury 1899, Scarff 1940, Rasmussen 1947, Lorente de Nó 1949, Brazier 1959, 1963, 1978, Riese and Hoff 1951, Haymaker and Baer 1953, Kolle 1954–1963, Penfield and Rasmussen 1957, Walker 1957, Magoun 1958, Zangwill 1963, Klingler 1967, McHenry 1969, Haymaker and Schiller 1970, Meyer 1971, Clarke and Dewhurst 1972, Stephan 1975, Creutzfeldt 1983). The history of the discovery of cerebral gyri in particular, is eloquently presented in the monograph by Clarke and Dewhurst (1972). According to Clarke and Dewhurst, "This story is of particular fascination and relevance because it not only reveals a sequence of intriguing notions, but also contributes to our understanding and appreciation of the modern view." As the anatomy of gyri is an important part of this chapter, some passages from this excellently illustrated monograph will be presented here.

"Erasistratus of Alexandria (260 B. C.) stated that the gyri were comparable to the coils of the small intestine, but interestingly he contended that in animals the gyral complexity was directly proportional to intelligence."

The earliest pictorial representation of the convolutions is in an eleventh century manuscript, the earliest known Western illustration of brain function (Fig. 1.**1a**). It is in the shape of a Celtic stone cross, sometimes found in Anglo-Saxon diagrams. Around the circle is written, "There are present four principal human members," which are, in clockwise sequence from 12 o'clock, the liver, heart, testes, and brain ("cerebrum"). The latter is, in fact, a drawing of the skull facing inwards and seen from above, with the coronal, sagittal, and lambdoid sutures represented by double lines. The mental faculties inscribed on it are "fantasia" (imagination), "intellectus" (reasoning), and "memoria" (memory) (Fig. 1.**1a**).

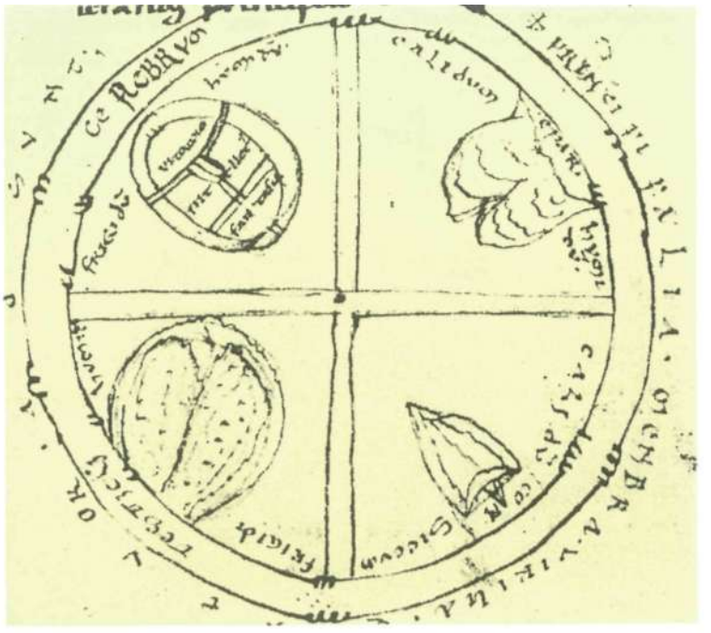
Figure 1.**1b,** showing the eyes and brain, "seems to have originated in a treatise on ophthalmology written in the second half of the thirteenth century by a Syrian, Halifa, but actually it may date back further (to at least, A. D. 1000). It is, therefore, probably the oldest figure of its kind, though the present manuscript is dated to 1560. The drawing has been reported on many occasions but is only fully described by K. Sudhoff (1914) and J. Hirschberg (1905)."

"Guido da Vigevano (ca. 1280–ca. 1349) wrote a discourse on anatomy, illustrated by a series of interesting drawings (1345). There is vague patterning on the surface of the exposed brain which may possibly be an attempt to draw the cerebral convolutions. If so, it is the earliest portrayal of them" (Fig. 1.**1c**).

"As with most other organs and systems, the best brain illustrations [of the Renaissance] appeared in the *De Fabrica* of **Vesalius** (1543). Vesalius was more concerned to identify structures other than the convolutions. He agreed, however, that they appeared like coils of small gut or like clouds drawn by schoolboys, having no standard pattern."

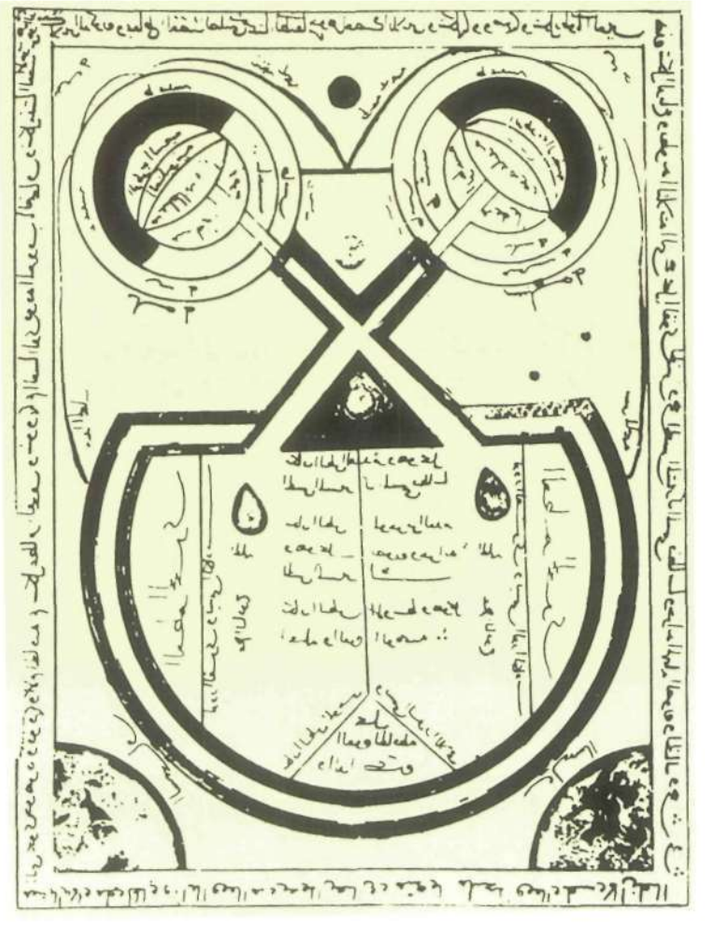
"Raymond de Vieussens of Montpellier (1644–1716), whose name is still occasionally associated with the 'centrum ovale,' published in 1685 his *Neurographia Universalis,* wherein the cerebral convolutions and cortex received some attention."

"Samuel Thomas Soemmering (1755–1830) introduced our present classification of the cranial nerves. The gyri are well depicted in a drawing, but they are not yet named."



a

Fig. 1.**1a–i** Early depictions of the brain (from Clarke and Dewhurst, *An Illustrated History of Brain Function,* Oxford 1972)
a From an eleventh-century manuscript, this is the earliest known Western illustration of brain function



b

b This schematic depiction of the eyes and brain, dating from the late thirteenth century, is probably the oldest of its kind

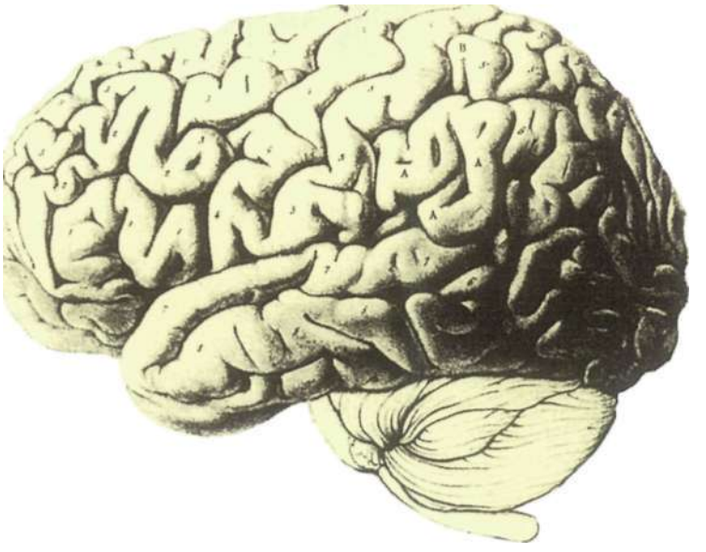


Fig. 1.**1 c–d**
c The history of the anatomy of the cerebral convolutions by Guido de Vigevano (ca. 1280–1349). There is a vague patterning on the surface of the exposed brain, which may be an attempt to show the cerebral convolutions. It so, it is the earlist portrayal of them

d Louis-Pierre Gratiolet (1815–1865) is the most renowned of the French anatomists who investigated the cerebral gyri and sulci. Gratiolet used the terms "frontal," "temporal," "parietal," and "occipital," which had been introduced by Arnold in 1838 and defined the boundaries of these areas. This picture illustrates the beginning of a new conceptual era

"Felix Vicq d'Azyr (1748–1794), whose name is still associated with the mammillothalamic tract, began to differentiate gyri by grouping them into anterior, middle, posterior, and inferior and by describing the pre- and post-central convolutions. Vicq d'Azyr also described some of the lobes' constituent convolutions: the 'convolution that follows the corpus callosum.' He introduced the name 'uncus,' which means crochet (hook).

"The fissure of Sylvius was the first sulcus to be identified and named. The island of Reil or insula, clearly depicted by **Bartholin** (1641), was described in detail by **Johann Christian Reil** (1759–1813) in 1809. They were the first two landmarks, to which was added the fissure of **L. Rolando** (1931)." Rolando, who performed the first studies of the effects of electrical current on the brain of animals, named the precentral and postcentral gyri "processi verticali di mezzo."

"Louis Pierre Gratiolet (1815–1865) by comparative studies distinguished primary from secondary gyri, in accordance with their chronological appearance in evolutionary sequence. Gratiolet used the terms 'frontal,' 'temporal,' 'parietal,' and 'occipital' lobes (introduced by **F. Arnold** in 1838), and defined their limits. He first published these in 1854, and Fig. 1.**1d** shows the high standard that pictorial representation of the gyri had reached. The legend gives the convolutions names, several of which are still used. Arnold's publication has only one picture showing the brain from a basal view; the gyri are not well delineated. Arnold himself gives credit to **Chaussier,** but does not give any references."

C. **Bell** (1774–1842) established the fact that the nerves of special senses could be traced from specific areas of the brain to their end organs (Bell's palsy).

F. Burdach (1819) gave the names to the gyrus cinguli, precuneus, and cuneus (tweak, pinch).

J. G. F. Baillarger (1840) discovered the connection between the white and gray matter. He introduced the terms lissencephalic and gyrencephalic cortex.

R. Remark (1844) was the first to recognize histologically the six cortical cell layers.

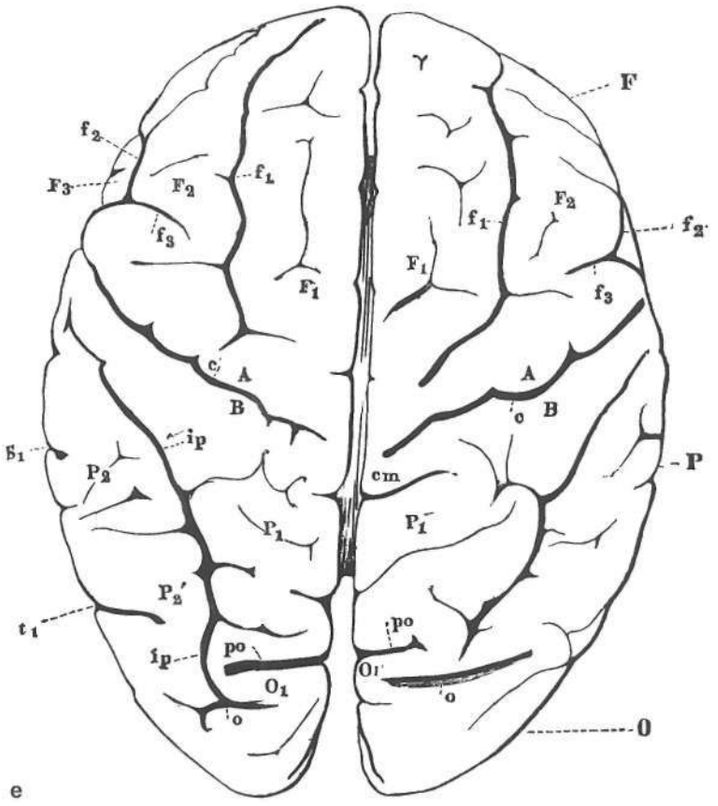
R. A. von Kölliker (1845) anticipated the neuron theory.

Thomas H. Huxley (1861) gave the name to the superior and inferior frontal sulci and calcarine fissures.

"The first lithograph photograph of the brain was published by **Emil Huschke** (1797–1858) of Jena. It appeared in 1854 and was the first step towards direct photography of the brain. Huschke contributed to gyral morphology by naming the gyrus centralis anterior and posterior and the 'fusiform' and 'lingual' convolutions."

William Turner (1832–1916) of Edinburgh redefined the limits of the cerebral lobes and established the fissure of Rolando as the posterior limit of the frontal lobe in 1866.

Alexander Ecker (Freiburg, Germany) in 1869 described in a small book (53 pages) all the sulci and gyri of the telencephalon in detail, which can be called complete and valid even 124 years later (See Fig. 1.**1e–g**). He gave their names to the orbital, precentral, parieto-occipital, interparietal, and transverse occipital sulci. He drew attention to the fact that a gyrus consists of three parts: the primary gyrus in a convoluted chain; the secondary gyri, separated by secondary sulci; and the tertiary gyri, intrasulcal extensions that cannot be seen on the surface without spreading the sulci, for example the temporal transverse gyri of Heschl. The tertiary gyri parts of which are well visualized on MR images, should be given a generally accepted anatomical name—tertiary or transverse gyri. **G. Retzius** (1896) suggested for the secondary gyri the term "gyruli," and for the tertiary gyri the term "transitivi" or "profundi."



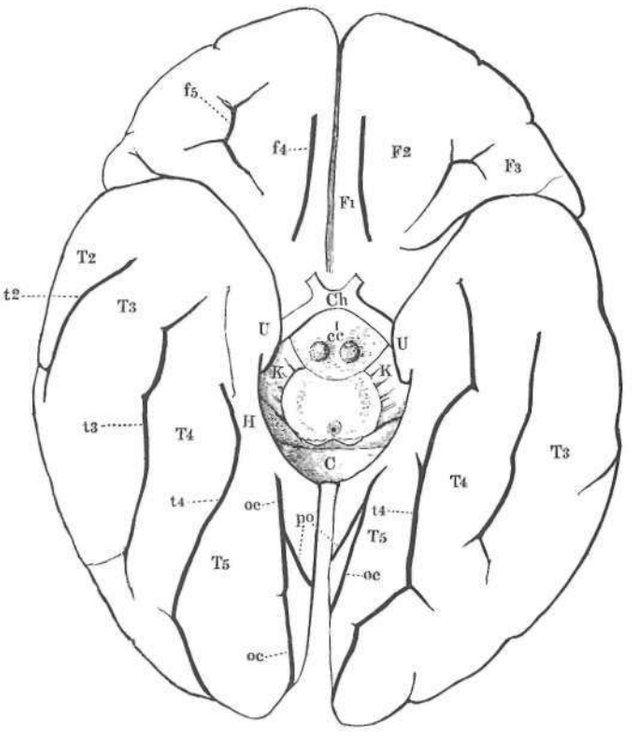
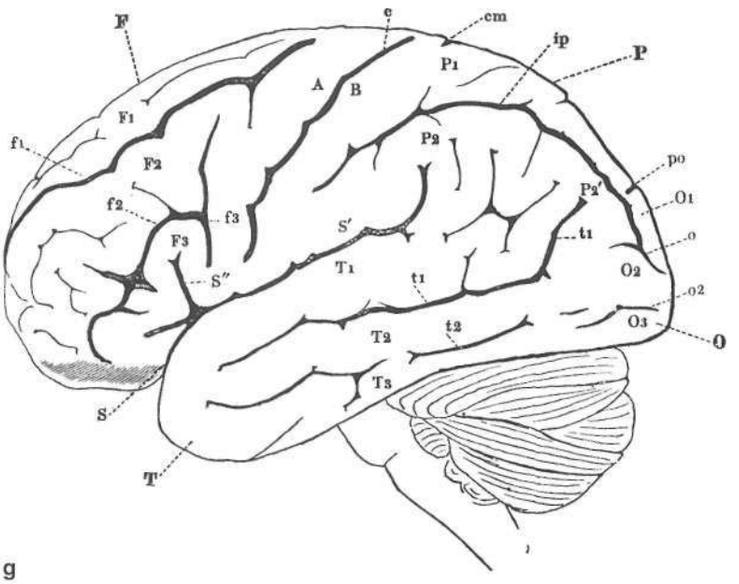


Fig. 1.**1e–g** Depictions of the brain (from Ecker, *Die Hirnwindungen des Menschen* [1869], 2nd ed. Braunschweig 1883)

e Superior view
- A Anterior central gyrus
- B Posterior central gyrus
- C Central sulcus
- cm Callosomarginal sulcus
- F Frontal lobe
- F1 Superior frontal gyrus
- f1 Superior precentral sulcus
- f2 Inferior precentral sulcus
- F2 Middle frontal gyrus
- F3 Inferior frontal gyrus
- f3 Precentral sulcus
- ip Interparietal sulcus
- O Occipital lobe
- o Transverse occipital gyrus
- O1 First occipital gyrus
- P Parietal lobe
- P1 Superior parietal lobule
- P2 Inferior parietal lobule (P2 = supramarginal gyrus, P2' = angular gyrus)
- po Parieto-occipital fissure
- t1 Superior temporal sulcus

f Basal view
- C Callosum
- CC Corpora candicantia
- f4 Olfactory sulcus
- f5 Orbital sulcus
- H Hippocampus
- K Cerebral peduncle
- oc Calcarine fissure
- po Parieto-occipital fissure
- t2 Middle temporal sulcus
- t3 Inferior temporal sulcus
- t4 Inferior occipitotemporal sulcus
- U Uncus



g Lateral view. The gyri are precisely named
- cm Callosomarginal sulcus
- f1 Superior frontal sulcus
- f2 Inferior frontal sulcus
- f3 Precentral sulcus
- ip Interparietal sulcus
- 01 Superior orbital gyrus
- 02 Middle orbital gyrus
- 03 Inferior orbital gyrus
- S Sylvian fissure
- S′ Horizontal branch
- S″ Ascending branch
- T1 Superior temporal gyrus
- t1 First temporal sulcus
- T2 Middle temporal gyrus
- t2 Second temporal sulcus
- T3 Inferior temporal gyrus

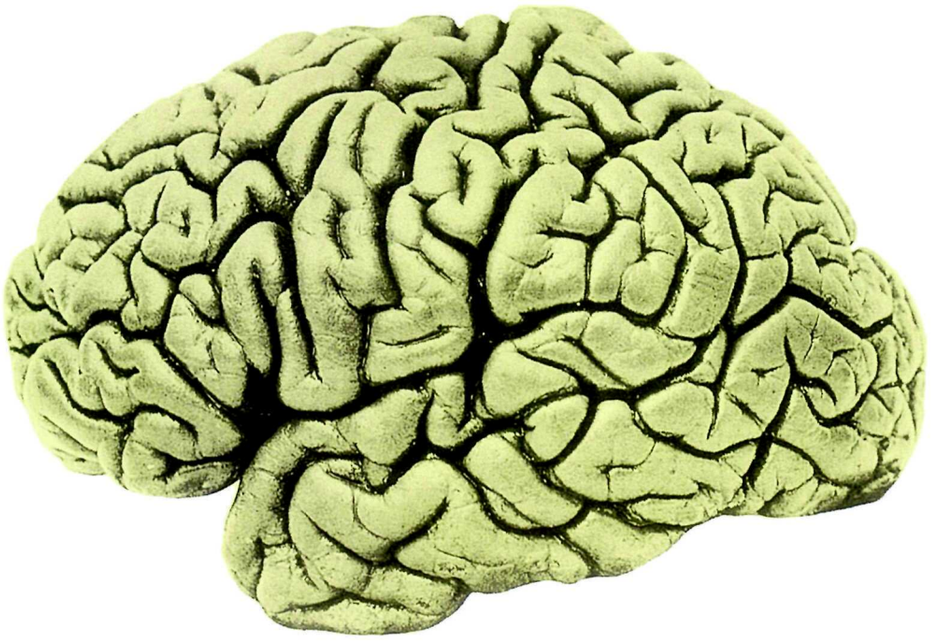


Fig. 1.**1h** The left cerebral hemisphere (from Retzius, *Das Menschenhirn;* illustration by *Sigrid Anderson,* Stockholm: Nordstedt, 1896). "An organ as important as the human brain deserves to be precisely illustrated in all its parts and variations" (Retzius, p. iv)

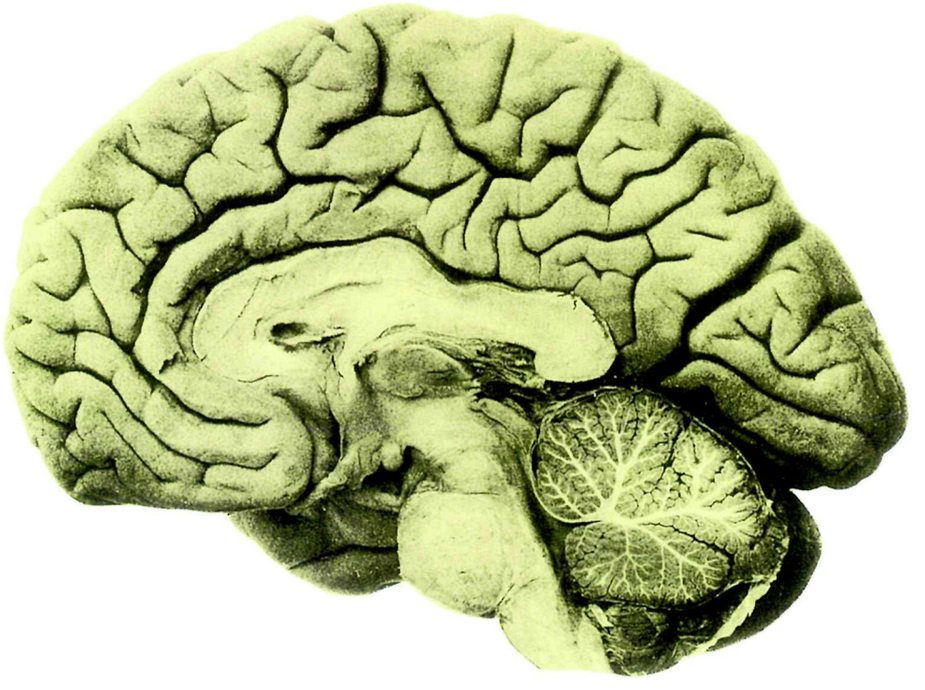


Fig. 1.**1i** Medial view of the right cerebral hemisphere (from Retzius, *Das Menschenhirn,* Stockholm: Nordstedt, 1896); illustration by *Sigrid Anderson*

The study of the macroscopic anatomy of the CNS has developed on a large scale; E. Huschke (1854), T. L. Bischoff (1868), A. Richter (1887), W. His (1889), F. Marand (1891), N. J. Cunningham (1897), F. Hochstetter (1894), and G. Retzius, who in 1896, published two volumes of brain anatomy including an unprecendented 96 plates (Fig. 1.**1h, i**).

Once the gyri and sulci had been accurately delineated and named, the stage was set during the 1860s for the emergence of new concepts of functional localization. T. Meynert (1833–1892), teacher of C. von Economo (1876–1931) introduced the terms *"association"* and "*projection"* systems, which was a great step forward in our understanding of the cortex. Meynert thus opened the field for exploring the relationship between the cortex and other structures, such as the basal ganglia, a term that had been introduced by F. J. Gall (cited by Brazier 1978). C. Golgi discovered, using the silver stain technique, previously invisible nerve structures and connections (1883). P. E. Flechsig, who invented the concept of myelogenesis and discovered auditive radiation, developed (1893) the theory of projection and association centers. W. Waldeyer introduced the term "*neuron"* in 1891, before W. His and A. Forel independently formulated (1887) the concept of the cellular functional unit, which was supported a few years later by Ramon y Cajal (1890).

W. Campbell (1905), K. Brodmann (1908, 1909), O. and C. Vogt (1919, 1926), C. von Economo and G. N. Koskinas (1925) published renowned myelo- and cytoarchitectonic maps. Donaldson (1895) pointed out that one-third of the neocortex is on the surface, while two-thirds are in deep sulcal areas (cited in Creutzfeldt 1983). Campbell pointed out the important deficiency of all such "maps," the artist's inability to show parts of the cortex concealed in the depths of sulci.

G. Elliot Smith (1919) gave meaning to the phylogenic changes in the surface topography of the brain through his studies of the subcortical and cortical factors that influence the elaboration and modification of the convolutions of the pallium (Walker 1957).

O. and C. Vogt introduced the terms isocortex and allocortex (1912). C. Sherrington (1937) introduced the term "*synapse*" instead of "*Syndesm.*"

The discovery of the alpha rhythm in the human brain by H. Berger (1924–1931), using an electroencephalograph, opened an entirely new era for the study of brain function, which then culminated in the intracellular registration of electrical activities (Adrian 1936, Adrian and Moruzzi 1939, Jung et al. 1953, Eccles 1953, Philips 1956, Jaspers 1960). Bard (1928) and Hess (1948) pioneered epoch-making research on the hypothalamus.

The intensive research work carried out during surgical exploration of human brains resulted in the creation of the term "sensory and motor homunculus" by W. Penfield, E. Boldrey and R. Rasmussen (1937–1968). G. Moruzzi (1954) and H. W. Magoun (1958) showed that the reticular formation maintains the tone of cerebral neurons.

E. W. Demsey and R. S. Morrison (1943) investigated the thalamocorticothalamic circuit.

H. Gastaut (1961) pointed out that the thalamic nuclei are responsible for maintaining the direction of attention.

The functional role of the limbic system in relation to the cortical localization was investigated by Papez (1937) and McLean (1949–1953).

Various techniques have been used to study the connectivity of functional systems of the brain, such as the retrograde changes after axonal lesions (Walker 1957), silver-staining degenerated axons and terminals (Glees, Nauta, and Kuypers (1938–1954).

Combined studies using the Golgi technique, degeneration techniques, and electron-microscopic investigations, led to a renewal of functional microanatomical concepts (Sholl 1956, Szentágothai 1970).

Hubel and Wiesel (1977) presented maps of functional anatomy, and Eccles (1969), who succeeded in 1953 in identifying the intracellular spinal motoneuron, coined the terms "excitatory" and "inhibitory" neurotransmitters.

New fields of research, on the chemoarchitecture and immune network of the CNS, are very promising (for detailed information, see Höcfeld et al. 1985, Niewenhuys 1985, Coon 1958 and Roitt, 1993). It would be beyond the scope of this book to mention all the neuroscientists who have contributed essential insights to build up our present state of knowledge of the anatomy and physiology of the CNS. Fascinating discoveries on brain architecture are incessantly continuing.

Embryology

Neuroembryogenesis

At approximately 16–17 days of age (15 mm), the ectoderm along the dorsal aspect of the midline thickens to form the neural plate (Fig. 1.**2**). A primitive streak then develops (Henson's node), forming a neural groove and neural folds on each side. The anterior portion of the neural plate enlarges to form the brain plate, which eventually becomes the brain (for figures depicting the development of the nervous system, see Hamilton et al. 1962, Kahle 1969, Starck 1955, Rakic 1972, Rager 1985, Carpenter 1983, Töndury and Kubik 1987, Töndury and Zilles 1987, Hinrichsen 1990).

After approximately one month, the brain tube further differentiates and enlarges into the three primary brain vesicles known as: the (1) prosencephalon or forebrain, the (2) mesencephalon or midbrain, and the (3) rhombencephalon or hindbrain (Table 1.**2a**). The brain continues to develop over the next several weeks at a greater rate than the overall growth rate of the neural tube. This development of the "contorted" brain involves several complex, integrated processes: 1) inward bending of the brain vesicles to form recognizable flexures, 2) differential development of several areas, 3) an "over"-growth of the cerebral hemispheres, consuming deeper parts, and finally, 4) the formation of gyri and sulci within the hemispheres.

At approximately two months' gestational age, the brain has differentiated into five recognizable parts. These are the telencephalon, diencephalon, mesencephalon, metencephalon, and myelencephalon. The telencephalon enlarges to become the cerebral hemispheres, which encircle the underlying diencephalon. The hippocampal formation occupies an intermediate zone, and enlarges with the telencephalon.

The cerebellum develops from a bilateral expansion of the metencephalic alar plate (rhombic lips), and comes to occupy most of the posterior fossa, overlying the posterior aspects of the pons and the medulla.

The telencephalon is phylogenetically the most recently developed portion of the nervous system. Its many convolutions and infoldings point to its general anatomic complexity. The overall form of the brain is recognizable at three months. It is the continual growth and differentiation of the cerebral hemispheres thereafter that leads to the various lobe, sulci, and gyral patterns (Figs. 1.**3**–1.**7**).

The accompanying figures in this section are to help formulate within our memory the embryological development of the gyral convolutions, for a better understanding of the predilection sites of CNS tumors.

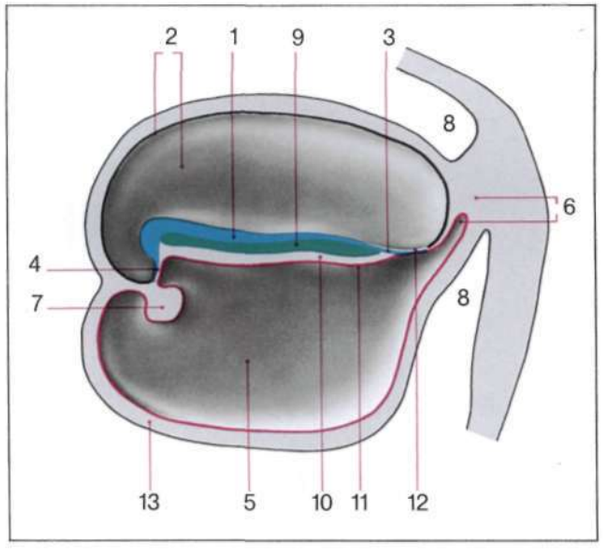


Fig. 1.**2** The human embryo (7 somite stage) (from Leonhardt, Töndury and Zilles, *Rauber/Kopsch: Anatomie des Menschen,* Stuttgart: Thieme, 1987, vol. 3, p. 12, Fiq. 2.1)

1 Ectoderm from the neuroplate
2 Amniotic cavity
3 Primitive knot
4 Oropharyngeal membrane
5 Dotter sack
6 Allantois
7 Heart and pericaval cavity
8 Extraembryonal coelom
9 Chorda dorsalis
10 Intraembryonic mesenchyme
11 Entoderm
12 Cloacal membrane
13 Extraembryonic mesenchyme

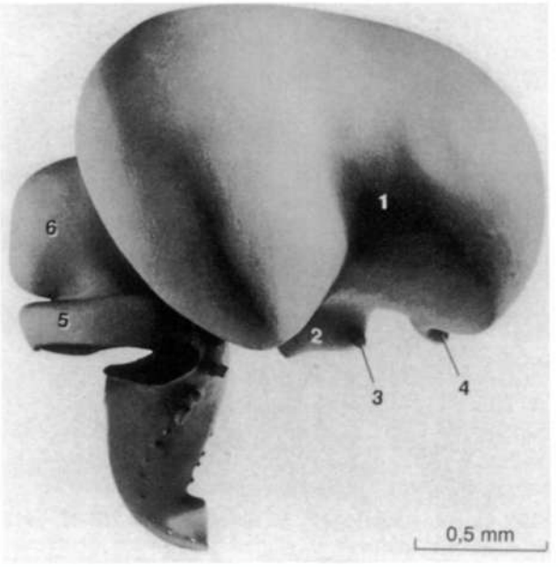


Fig. 1.**3** Fetus, 5.3 cm long (Hochstetter, Zagreb; from Hinrichsen, *Humanembryologie,* Berlin: Springer, 1990, p. 391)

1 Sylvian fissure
2 Hypothalamus
3 Stalk of eye
4 Olfactory bulb
5 Cerebellum
6 Mesencephalon

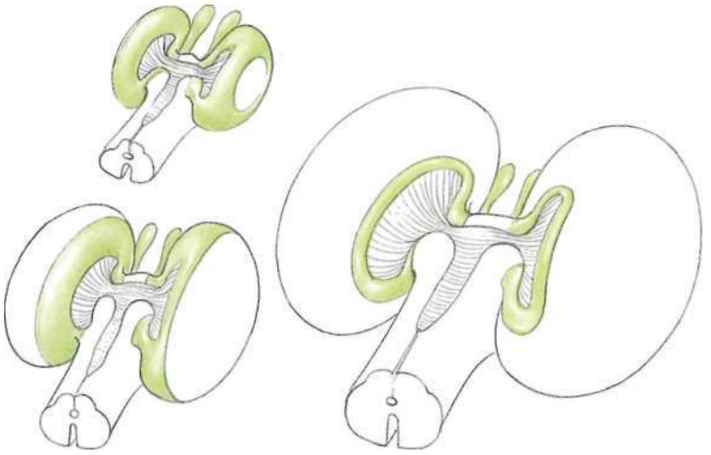


Fig. 1.**4** The development of the rhinencephalon (green) (after Elliot and Penfield, *Textbook of the Nervous System,* Philadelphia: Lippincott, 1954). Elliot and Penfield state, "Primitively the rhinencephalon (or small brain) occupies all of the hemisphere. Nonolfactory elements are depicted as a small white area on the lateral surface. With expansion of these areas, however, the rhinencephalon proper comes to occupy only a relatively small collar around the neck of the hemisphere"

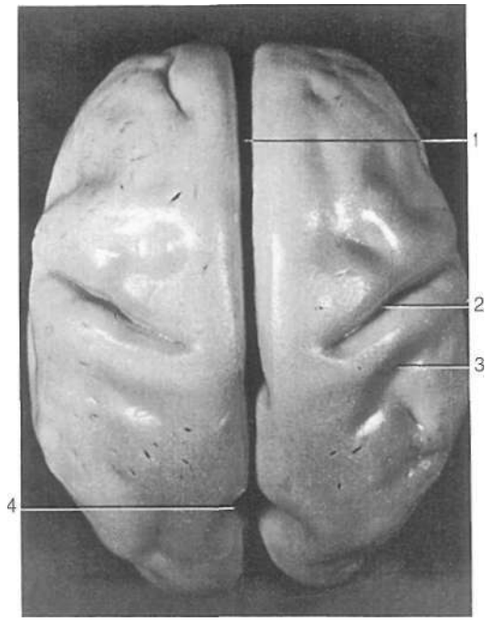


Fig. 1.**5a** The brain of a human embryo (24 cm), seen from above (from Leonhardt, Töndury and Zilles, *Rauber/Kopsch: Anatomie des Menschen,* Stuttgart: Thieme, 1987, vol. 3, p. 139, Fig. 7.23)
1 Interhemispheric sulcus
2 Central sulcus
3 Postcentral sulcus
4 Parieto-occipital sulcus

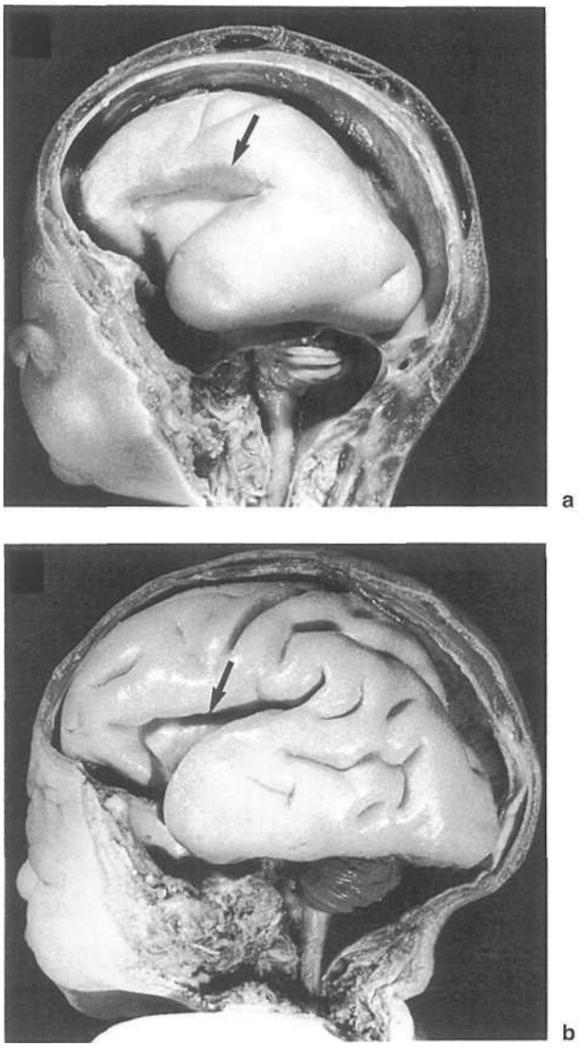


Fig. 1.**5b–c** Lateral view of the brain of a human embryo (from Ono, Kubik, and Abernathey, *Atlas of the Cerebral Sulci,* Stuttgart: Thieme, 1990, p. 7, Fig. 1.3)
b 19 cm
c 24 cm. The developing Sylvian fissure is quite conspicuous (arrow)

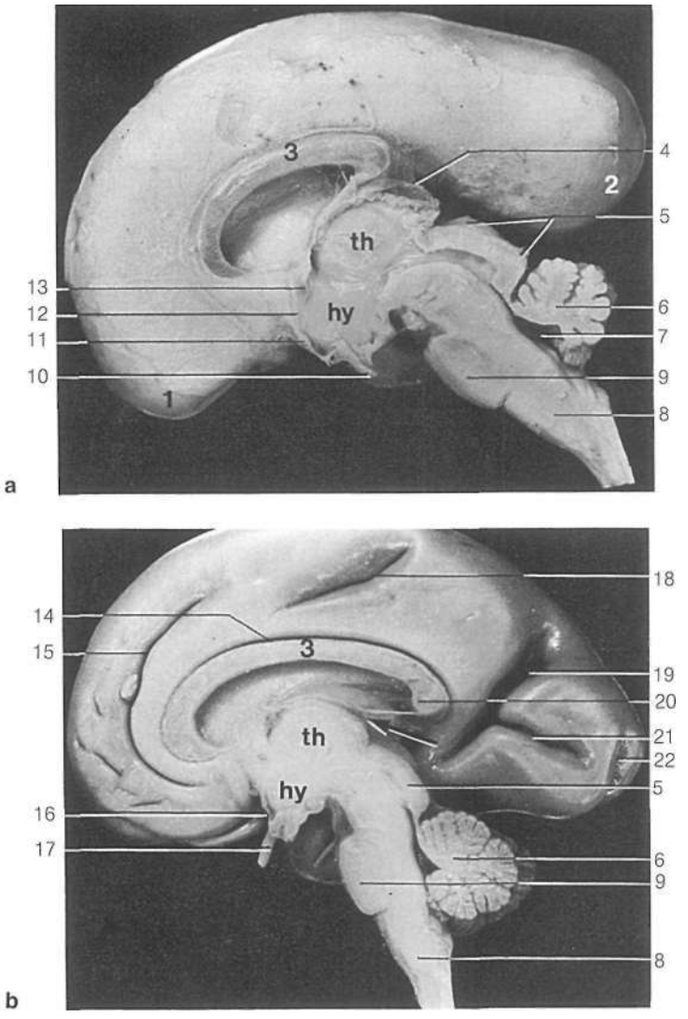


Fig. 1.**6a–b** Medial view of the brain of a human embryo (from Leonhardt, Töndury and Zilies, *Rauber/Kopsch: Anatomie des Menschen,* Stuttgart: Thieme, 1987, vol. 3, p. 139, Fig. 7.22). **a** 19 cm, **b** 24 cm

1 Frontal pole
2 Occipital pole
3 Callosal body
4 Choroidal tela of the third ventricle
5 Quadrigeminal plate
6 Cerebellar vermis
7 Fourth ventricle
8 Medulla oblongata
9 Pons
10 Infundibulum
11 Optic chiasm
12 Lamina terminalis
13 Anterior commissure
14 Callosal sulcus
15 Cingular sulcus
16 Lamina terminalis
17 Optic nerve
18 Subparietal sulcus
19 Parieto-occipital sulcus
20 Splenium
21 Calcarine sulcus
22 Lunate sulcus
th Thalamus
hy Hypothalamus

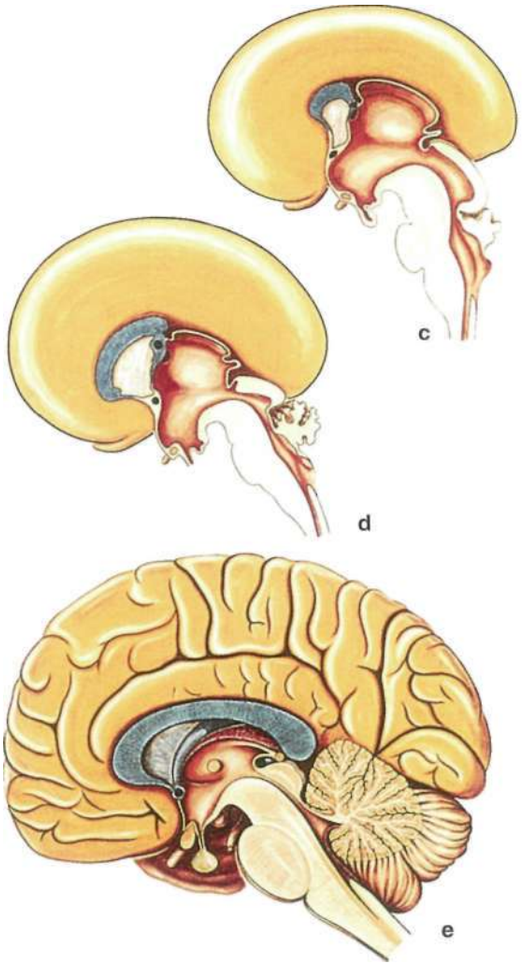


Fig. 1.**6c–e** The development of the commissural system, the fornix, and the septum pellucidum (blue) (from Hinrichsen, *Humanembryologie,* Berlin: Springer, 1990, p. 393)
c Fetus, 10.5 cm
d Fetus, 12.5 cm
e Adult

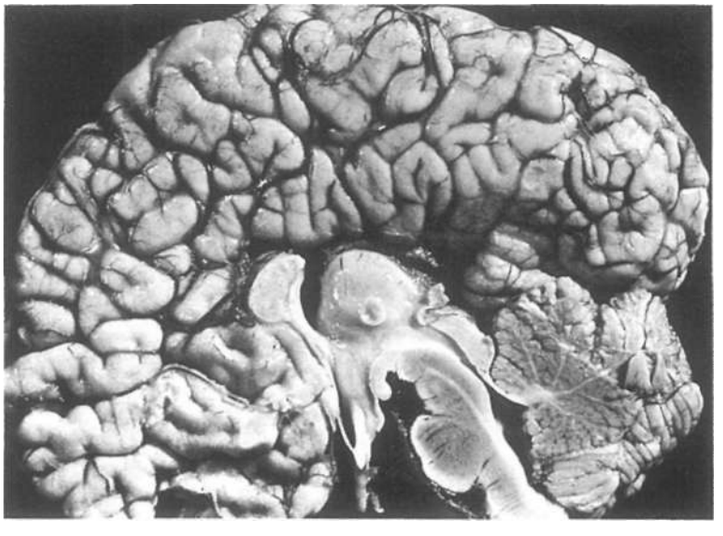


Fig. 1.**6f** A case of agenesis of Corpus Callosum, showing associated maldevelopment of the Cingulate gyrus, in the brain of a newborn.

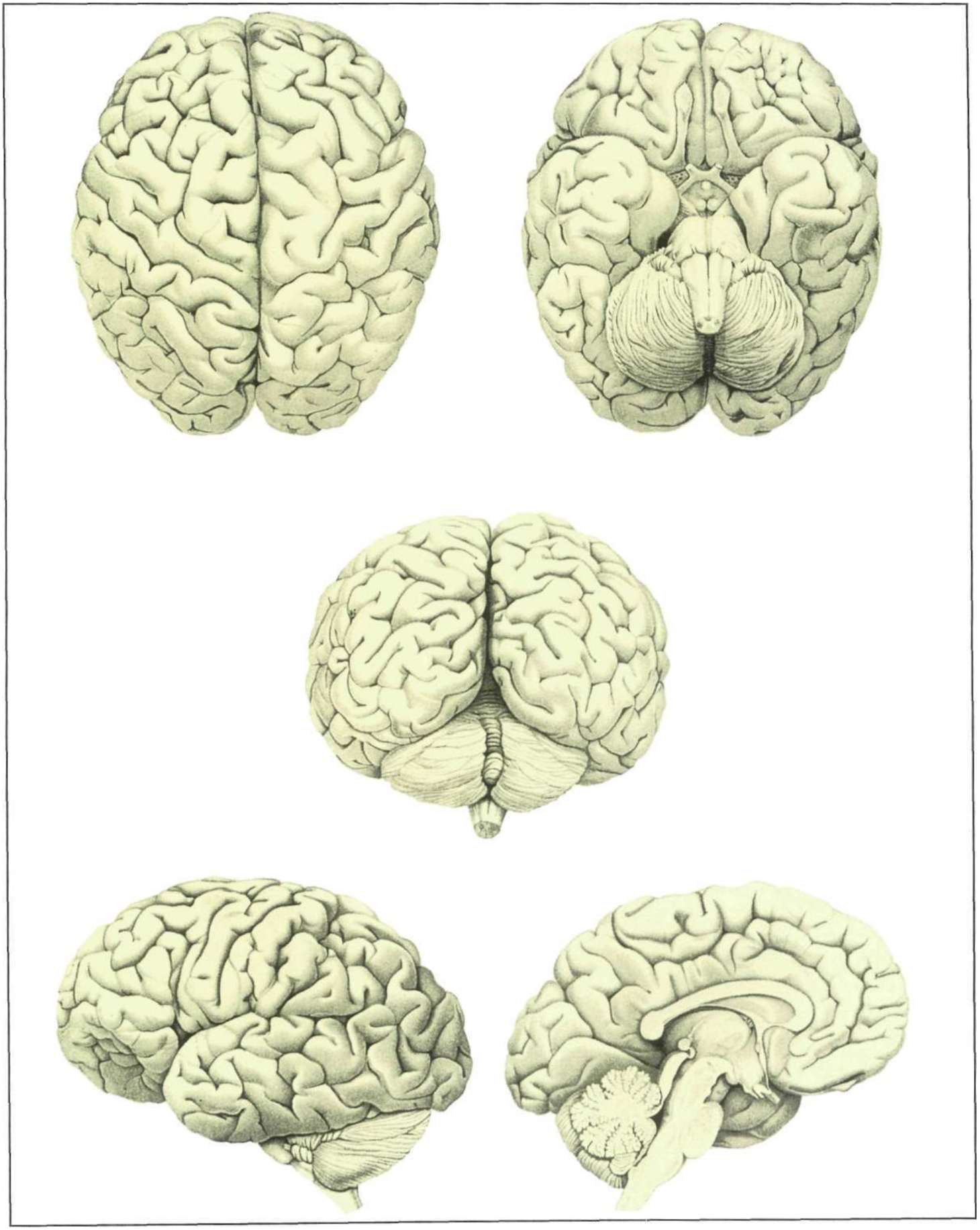


Fig. 1.7 Male fetus, 48 cm (from Retzius, *Das Menschenhirn,* Stockholm: Nordstedt, 1896; illustration by Sigrid Anderson)

Neurogenesis

Both neuronal and glial cells are generated from precursor cells (germinal cells) located in close proximity to the cerebral and cerebellar ventricles. Each distinct type of neuron and its supporting glial cells are formed during a narrow period of time (a few days to two weeks) during neurogenesis. It appears that, immediately after proliferation, each neuron undergoes topographical programming as to its eventual functional status. At this point, neuronal (and associated glial) migration occurs, with ameboid-like movement of the nerve cells along the processus of special astrocytes until the final "adult" location is reached. The most complex (neocortical-associative) neurons are produced last, as archiogenesis is repeated (Rakic 1972) (Fig. 1.**8**, Table 1.**1**). The direction of this migration (as directed by these special astrocytes) from the ventrical matrix to cortical regions may explain the growth patterns of intrinsic gliomas (from subcortical areas of origin back towards the ventricle). It may be that neurogenesis is reversed in this manner.

The arrival of a group of similar neurons at their final location (selective cell aggregation) triggers a complex series of events, during which the functional activity of the neuron is developed. Steps in this process include: 1) *Neuronal cytodifferentiation* (the development of axons and dendrites, the synthesis of ion channels, and the beginning of transmitter function). 2) *Axonal outgrowth* (the growth of functional similar axons along defined paths to reach intended target fields. 3) *Synaptogenesis* (the refinement of connections, with the dying out of perhaps 50% of the neurons and the elimination of many synapses). This process of synapse development and then elimination permits the development of definitive circuitry within the CNS, and forms the basis for developmental and neuromorphologic plasticity.

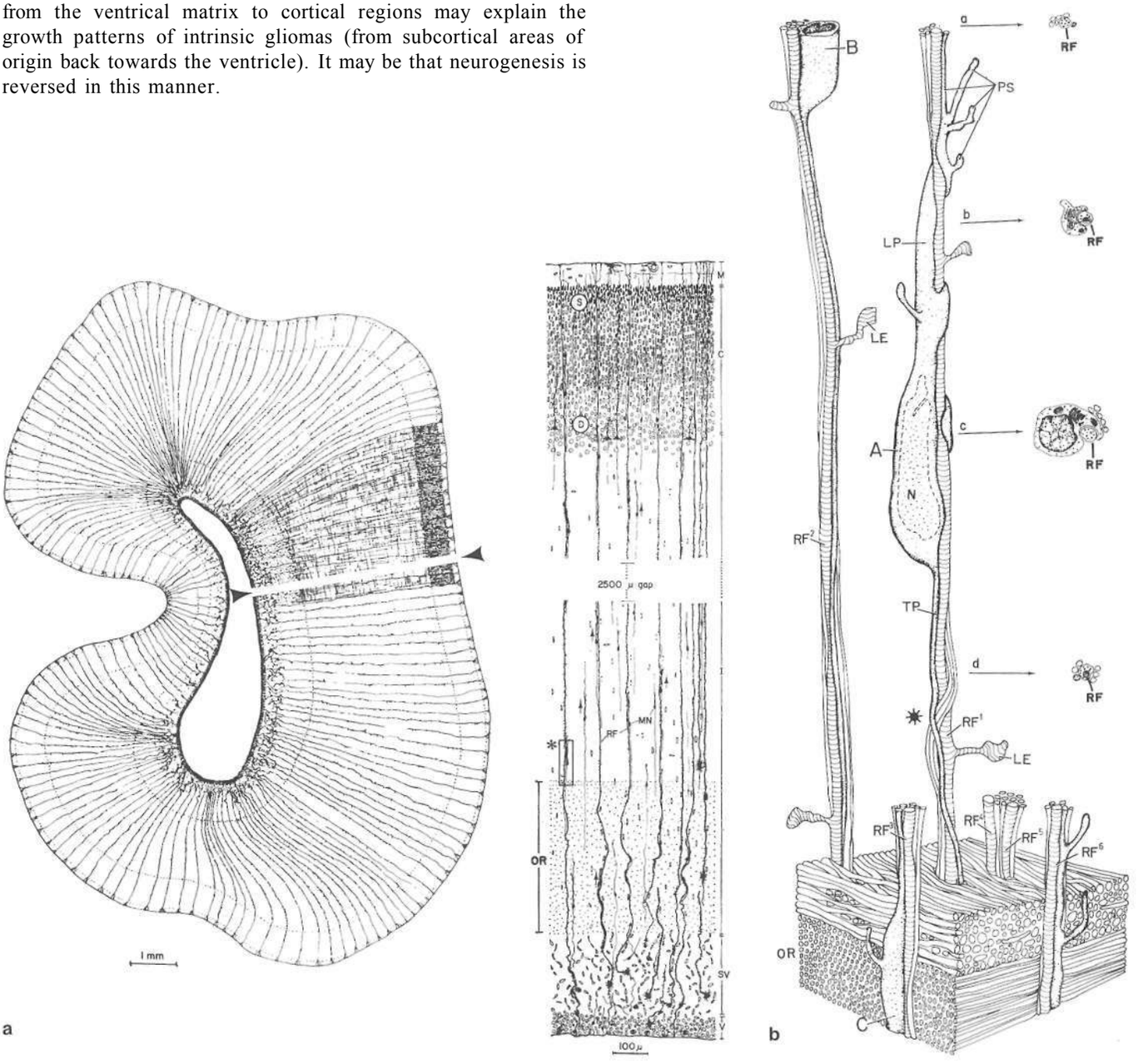


Fig. 1.**8a, b** Neurogenesis and migration. Young neurons generally migrate outward from the ventricular zone along the surfaces of a specialized class of glial cells. The illustration on the left shows the disposition of the radial glial in a section through the developing cerebral hemisphere, and the insets on the right show how they span the entire thickness of the wall of the hemisphere and provide a substrate for the migrating neurons as they move out to form the cortical plate. It is noteworthy that this migration pattern is similar to the pattern of spread for most white-matter gliomas, except that these spread in the reverse direction (Rakic 1972, Cowan 1979)