Anatomical description of the human head

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WFW reportnumber: 94.003

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Contents

Chapter 1

Introduction

This paper contains a description of the anatomy of the human head. In chapter 2 only the anatomy will be described. In chapter 3 a description will be given from a mechanical point of view. This report ends with a short summary of the most important topics, that are relevant in the mathematical modeling of head-impact. The figures mentioned in the text can be found in the appendix at the end of the report. The majority of the text is based on the literature (Bastiaanssen and Jochems, 1991; Guyton, 1986; Jacob and Francone, 1976; Martin, 1989; Melvin and Weber, 1985; Sauren, 1992).

Chapter 2

Anatomy of the head

2.1 The skull

The skull consists of two parts (see Fig.A.1), the cranial vault and the facial bone. The facial anatomy is defined as; the area from the forehead to the lower jaw and includes fourteen bones. The cranial vault *((neuro)cranium)* can be subdivided in the brain case and the base of the brain case. The brain case *(calvarium)* can be seen as a shell. It is composed of eight bones that are connected by sutures. During infancy and early childhood, the articulations (joints, sutures) are composed of cartilage, which gradually disappear as the bones grow together, or ossify. The joints between the cranial bones do not allow any movement in the full-grown state. The eight bones are called (see Fig.A.1): *ethmoid, sphenoid, frontal, two temporal, two parietal, and occipital bone.* The occipital bone forms together with the *(external) occipital protuberance* a joint with the first cervical vertebra, the atlas. The thickness of the skull varies between 4 and 7 mm. The sandwich structure of the skull consists of a compact internal and external layer (*lamina interna* and *externa*) with in-between a porous layer (*diploe* - cancellous bone containing red marrow in its interstices), which is the thickest of the three layers. The brain case is covered on the outside by a 5 to 7 mm thick tissue layer, that can be subdivided into 5 separate layers; from outside to inside: hair-and-skin layer, a subcutaneous connective tissue layer, a muscle and fascial layer, a loose connective tissue layer and the fibrous tissue that covers the bone (*periosteum*). The thickness, firmness and mobility of the three outer layers serve as a protection for the head. The base of the brain case is a thick irregular plate of bone containing depressions and ridges as well as small holes for arteries, veins and nerves. The largest opening (*foramen magnum*) forms the transition area between the spinal cord and the brain.

2.2 The brain

The head of an adult human being has a mass of about 4.5 kg of which the brain contributes about 1.5 kg. The central nervous system (CNS = Brain & Spinal cord) is built up of various structures (see Fig.2.1 and Fig.A.2) :*cerebrum, cerebellum, midbrain, pons, medulla oblongata, etc.* The brain constitutes 98 percent of the weight of the central nervous system and it represents about 2 percent of the weight of the human body.

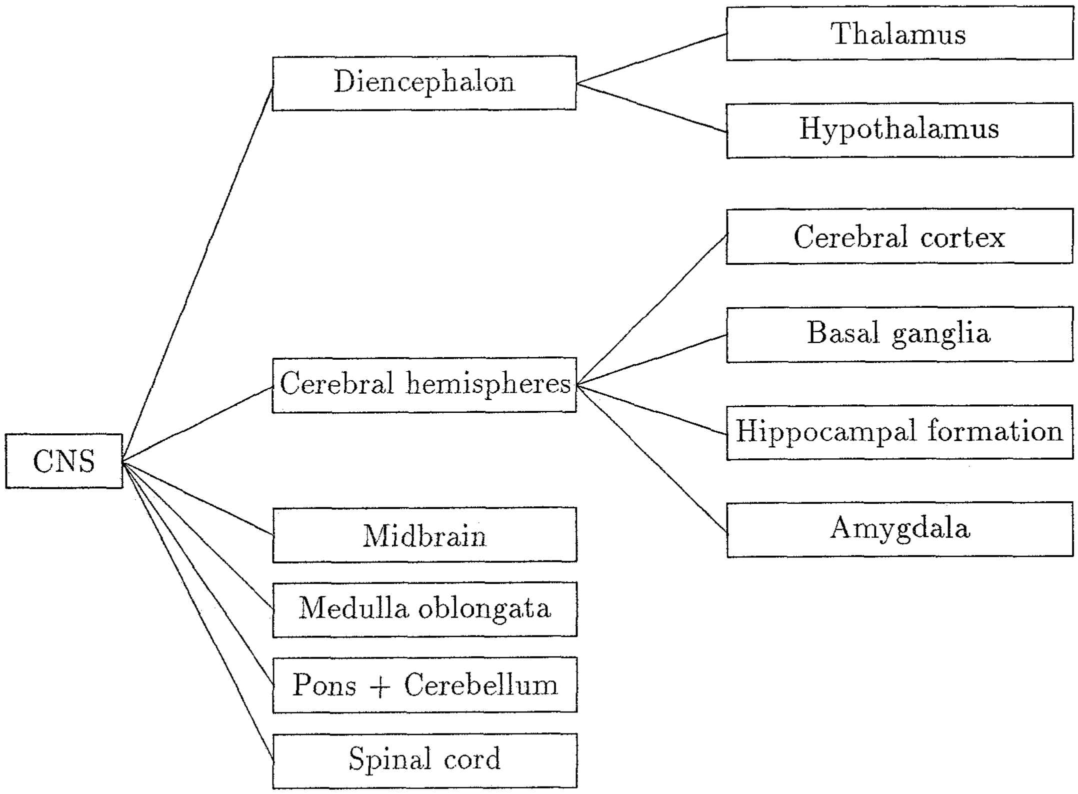

Figure 2.1: Structure of the central nervous system (CNS)

The diencephalon and cerebral hemispheres are the most highly developed portions of the human central nervous system. The *diencephalon* (Fig.A.2) consists of two major components. The *thalamus* is a key structure for transmitting information to the cerebral hemispheres. The second component, the *hypothalamus* integrates the functions of the autonomic nervous system and the endocrine hormone release from the pituitary gland.

The *cerebrum* is built up out of two hemispheres, the *cerebral hemispheres*, which represent the largest structures of the total brain. In the hemispheres various major components can be distinguished; the *cerebral cortex*, that consists of gray matter, and the white matter or the nerve fibres. The gray matter forms a 1.5 to 4.5 mm thick layer, built up of nerve-cells and support-cells (*glia*). The glia or neuroglia cells provide structural and metabolical support for neurons during development as well as in the mature brain. The cerebral cortex is arranged into a number of folds (*gyri*) (see Fig.A.3), which are separated by fissures. Due to these fissures each hemisphere can be subdivided into four lobes, named by their association to the nearest cranial bone. The four lobes are: *frontal, parietal, temporal and occipital* (see Fig. A.2 and Fig.A.3). The fibres in the white matter are arranged in tracts and serve to connect one part of a cerebral hemisphere with another, to connect the cerebral hemispheres to each other, and to connect the cerebral hemispheres to the other parts of the central nervous system. In addition, within these interior areas of white matter are a number of areas of gray matter. The fibres are wrapped by a grease-like substance, that forms the so called *myelin sheath.* DiMasi *et al.* (1991a, 1991b) postulate the possibility of anisotropic constitutive properties of the white matter due to certain preferred directions of the fibres. Beneath the longitudinal fissure the two hemispheres are connected by the *corpus callosum.* In each of the cerebral hemispheres there exists a fluid-filled space, called the lateral ventricle (see also 2.4 The cerebrospinal fluid system). Another major part of the cerebral hemispheres is the *basal ganglia,* which are deeply located collections of neurons. A major part of the basal ganglia is taken in by the *striatum.* The basal ganglia is believed to play a large role in higher brain functions, like for instance the control of movement and other aspects of behaviour, like emotion. The third and fourth major components of the cerebral hemispheres are the *hippocampal formation* and the *amygdala.* The hippocampus is believed to participate in memory, whereas the amygdala may coordinate the actions of the autonomic nervous system and hormone release as well as participate in emotions.

The *midbrain* (see Fig.A.2) forms a fibrous connection with the cerebral hemispheres above and pons below. Within the midbrain there is a canal *(cerebral aqueduct Sylvius)* that forms the connection between the third and fourth ventricle.

The *medulla oblongata* appears to be continuous with the pons above and the spinal cord below and forms the connection between the brain mass and the spinal cord. In the lower part of the medulla oblongata motor fibres cross from left to right and vice versa so that fibres from the right cerebral cortex pass to the left side of the body and vice versa. Some sensory fibres passing upward toward the cerebral cortex also cross from one side to the other in the medulla oblongata. The medulla oblongata also contains areas of gray matter within its white matter. These are nuclei for cranial nerves and relay stations for sensory fibres passing upward from the spinal cord.

The *pons* lies below the midbrain, in front of the cerebellum, and above the medulla oblongata. It is composed of white matter fibres that form the connection between the two cerebellar hemispheres. Lying deep within the white matter are areas of gray matter that are nuclei for some of the cranial nerves.

The *cerebellum* lies behind the pons and the medulla oblongata. Its two hemispheres are joined at the midline by a narrow strip-like structure called the vermis. The outer cortex of the two cerebellar hemispheres is gray matter. The outer surface of the cerebellum forms into narrow folds separated by deep fissures.

The *spinal cord* comprises two percent by weight of the central nervous system and averages 45 cm in length. Thirty-one pairs of nerves originate at the spinal cord. The spinal cord is protected by the bony spinal column, the meninges and pressurized CSF. The four structures cerebellum, spinal cord, pons and medulla oblongata are together called the *brain stem.*

2.3 The meninges

The brain and spinal cord are covered by three membranes (Fig.A.4) *(meninges)*, which have important protective and circulatory functions. *Dura mater:* Thickest and outer most of the three membranes. The dura overlying the cerebral hemispheres and brain stem actually contains two layers; outer *periosteal layer* and inner *meningeal layer*. The periosteal layer is attached to the inner surface of the skull. Within the dura there are large low-pressure blood vessels, which are part of the return path for cerebral venous blood, termed the dural sinuses. The meningeal layer forms three partitions; the *falx cerebri* between the two cerebral hemispheres, the *falx cerebelli* between the cerebellar hemispheres and the *tentorium cerebelli* between the cerebral hemispheres and the cerebellum. The dura mater that covers the spinal cord is continuous with both the meningeal layer of the cranial dura and the epineurium of the cranial peripheral nerves. The *arachnoid mater* adjoins but is not tightly bound to the dura mater, thus allowing a potential space to exist between them. This potential space, called the *subdural space*, is important clinically. Because the dura mater contains blood vessels, breakage of one of its vessels can lead to subdural bleeding and to the formation of a blood clot *(subdural haematoma)*. In this condition the blood clot pushes the arachnoid away from the dura mater, fills the subdural space and compresses the underlying neural tissue. Within the subdural space, a thin film of watery fluid, known as cerebrospinal fluid, encloses and bathes the brain. In the sagittal sinus and transverse sinuses, the arachnoid mater forms structures called arachnoid granulations, which reabsorb cerebrospinal fluid into the blood. Because the arachnoid mater bridges small and large fissures in the brain there are a number of cavities *(cistern)* below the membrane filled with cerebrospinal fluid.

The *subarachnoid space*, separates the arachnoid mater from the innermost layer, the *pia mater*. Filaments of arachnoid mater pass through the subarachnoid space and connect to the pia mater, giving the space the appearance of a spider's web (arachnoid from greek arachne; meaning 'spider'). The subarachnoid space is filled with cerebrospinal fluid and also contains the veins and arteries that overlie the surface of the central nervous system. The pia mater is a very delicate thin membrane of fine connective tissue invested with numerous small blood vessels that adhere to the surface of the brain, dipping well into its fissures, and the spinal cord.

2.4 The cerebrospinal fluid system

The entire cavity enclosing the brain and spinal cord has a volume of 1650 ml, about 150 ml of this volume is taken in by *cerebrospinal fluid (CSF)*. This cerebrospinal fluid as can be seen in figure A.5 is found in the ventricles of the brain, the cisterns around the brain, and in the subarachnoid space around both the brain and the spinal cord. The fluid spaces are all interconnected with each other and the pressure is regulated at a constant level. The CSF provides some nutrients for the brain and protects the brain from mechanical shock. The mass density of CSF is about $1.0018 * 10^3 \frac{Kg}{m^3}$ in the adult, which is approximately the same as that of blood plasma. The brain and CSF have approximately the same mass density, so that the brain simply floats in the fluid. The 150 ml of CSF constantly circulate through and around the brain.

The fluid is formed at a rate of approximately 500 ml each day. Probably two thirds or more of this fluid originates as a secretion from the *choroid plexus*, an intraventricular structure, in each of the four ventricles, mainly in the two lateral ventricles. The mechanism by which the choroid plexus secretes CSF is not well understood. It was once thought to be an ultrafiltrate of the blood, but because the ionic constituents of CSF differ from those of blood it is now believed to involve active secretory and ion reuptake mechanisms. Additional amounts of fluid are secreted by all the ependymal[2] surfaces of the ventricles, and a small amount comes from the brain itself through the perivascular spaces that surround the blood vessels entering the brain. Figure A.5 illustrates the main channel of fluid flow from the choroid plexus and then through the CSF system. The two lateral ventricles are located within the two halves of the cerebral hemisphere, and each lateral ventricle is further subdivided (Fig.A.6). The third ventricle is unpaired; it lies along the midline between the two halves of the diencephalon. The fourth ventricle is located in the brain stem. The central canal is the portion of the ventricular system that extends into the spinal cord. The interventricular *foramina of Monro* connects the lateral ventricles with the third ventricle and the *cerebral aqueduct of Sylvius* connects the third and fourth ventricles. CSF passes out of the fourth ventricle through three small apertures [3] in the roof of the fourth ventricle: the two laterally placed *foramina of Luschka* and the midline *foramen of Magendie*, entering the *cisterna magna*, a large fluid-filled space that lies behind the medulla oblongata and beneath the cerebellum. The cisterna magna is continuous with the subarachnoid space and is one of the five *cisterns* located on the midline. The other four cisterns are (see also Fig.A.5): the *interpeduncular* and *quadrageminal cisterns* are both located at the level of the midbrain, the *pontine cistern* is located ventral to the pons and the *lumbar cistern* is located in the caudal vertebral canal in the spinal cord. The cisterns are actually dilatations of the subarachnoid space. From the subarachnoid space the fluid flows into the *arachnoidal villi* that project into the large sagittal venous sinus and to a lesser extent into other venous sinuses. The fluid is finally returned into the venous blood system through the surfaces of these villi. The arachnoid villi can be seen as small unidirectional valves. Numerous clusters of arachnoid villi are especially prominent over the dorsal (superior) convexity of the cerebral hemispheres in the superior sagittal sinus, where they form a macroscopic structure called the *arachnoid granulations*.

[2]ependymal: in vertebrates, the layer of columnar ciliated epithelium backed by neuroglia, which lines the central canal of the spinal cord and the ventricles of the brain.
epithelium: compact layer of cells often secretory, lining a cavity or covering a surface

[3]apertures: openings

2.5 The vasculature

The normal blood flow through the brain tissue of an adult averages 50 to 55 ml per 100 gr of brain tissue per minute. For the entire brain of an average adult this is approximately 750 ml per minute, or 15% of the total resting cardiac output.

The vasculature through the brain and the various other substructures is illustrated in Fig.A.7. The arterial supply of the spinal cord is provided by the *vertebral arteries* and the *radicular arteries.* The brain is supplied by the *internal carotid arteries (anterior circulation)* and the vertebral arteries *(posterior circulation)*, which join at the medulla oblongata and pons to form the *basilar artery*, an unpaired artery that lies along the midline. The brain stem is supplied by the posterior system. The medulla receives blood directly from small branches of the vertebral arteries as well as from the *spinal arteries* and the *posterior inferior cerebellar artery.* The pons is supplied by *paramedian* and *short circumferential branches* of the basilar artery. Two major long circumferential branches are the *anterior inferior cerebellar artery* and the *superior cerebellar artery.* The midbrain receives its arterial supply from the *posterior cerebral artery* as well as from the basilar artery. The cerebral hemispheres and diencephalon are supplied by both the *anterior* and *posterior circulations.* The cerebral cortex receives its blood supply from the three cerebral arteries: the *anterior* and *middle cerebral arteries*, which are part of the anterior circulation, and the *posterior cerebral artery*, which is part of the posterior circulation. The diencephalon, basal ganglia, and internal capsule receive blood from branches of the internal carotid artery, the three cerebral arteries, and the posterior communicating artery.

The anterior and posterior circulation are not independent; they are interconnected by two networks of arteries (1) *the circle of Willis*, which is formed by the three cerebral arteries, the posterior communicating artery and the anterior communicating artery, and (2) terminal branches of the cerebral arteries, which anastomose [4] on the superior convexity of the cerebral cortex. The interconnection between the two arterial systems is important in compensation for the reduced arterial perfusion when one system becomes nonfunctional. In general deep structures of the brain, for example the diencephalon receive blood directly from branches of the internal carotid artery and the proximal portions of the cerebral arteries. In contrast the gray matter of the cerebral cortex and the underlying white matter are supplied by branches of more distal portions of the cerebral arteries.

The venous drainage of the spinal cord is direct to the systemic circulation. By contrast, veins draining the cerebral hemispheres and brain stem drain into the dural sinuses (see Fig.A.8). The dural sinuses are a collection of large channels located between layers of dura. The dural sinuses function as low-pressure channels for the flow of venous blood back to the systemic circulation. Venous drainage of the cerebral hemispheres is provided by *superficial* and *deep cerebral veins.* The superficial cerebral veins arise from the cerebral cortex and underlying white matter. The veins anastomose in the pia mater and drain into the sagittal and straight sinuses. The superficial veins are quite variable in their course. The deep cerebral veins drain the deeper portions of the white matter, the basal ganglia,

[4] communicate with one another like veins and arteries

and parts of the diencephalon. The *great cerebral vein (of Galen)* collects venous blood from many deep cerebral veins and, in turn, drains into the straight sinus. The venous drainage of the brain stem, like that of the cerebral hemispheres, is into the dural sinuses. Veins of the caudal brain stem drain into the *sigmoid* or *petrosal sinuses* (see Fig.A.8). The cerebellar veins drain into the great cerebral vein, which in turn drains into the straight sinus, or they drain directly into the straight sinus and the transverse sinus. The venous drainage of the midbrain takes place via the great cerebral vein or the deep cerebral veins, and then to the straight sinus.

Chapter 3

Description and brief discussion of the anatomy of the human head from a mechanical point of view

3.1 The geometry

The skull is built up of the calvarium and the facial bone. The outside of the skull is covered by the scalp, a 5 mm to 7 mm thick soft tissue layer, that cushions and protects the head. The calvarium can be further subdivided in the brain case and the base of the brain case. The brain case with a thickness between 4 mm and 7 mm is composed of various bones, which are separated by joints. In adults, these joints are grown together so they do not form a weakness in the skull (Shugar (1977)). The joints have an irregular form. Jaslow (1990) concluded from measurements on samples of goat bone with and without sutures, that the irregular form of the joints had the same bending-stiffness as bone in quasi-statical loading conditions. In impact loading conditions that lead to fracture the joints had the ability to take up 16% to 100% more strain energy than bone.

The sandwich structure of the skull has two compact outside layers and a porous layer inbetween. The base of the brain case is an irregular plate with various small openings for arteries and veins and a large hole, the foramen magnum, that forms the passway from the brain to the spinal cord.

Because in most studies of head impact the load is applied either to the frontal bone or the temporal or parietal bone in the study of side-impact, the facial bone does not have to be explicitly modeled. Only the mass and inertia effects of the facial bone have to be taken into account.

From an engineering point of view, the skull can be seen as a shell in which the brain neatly fits. In this shell there are various openings for the connections of the brain to structures outside the brain case. This viewpoint of the human head is often encountered in the literature of modelling head impact (Akka, 1975; Engin, 1969; Engin and Wang, 1970; Engin and Liu, 1970; Kenner and Goldsmith, 1973; Merchant and Crispino, 1974;

Khalil and Hubbard, 1977), especially in literature from the early seventies, the period where the finite element modelling of head impact started. The head was represented as a closed spherical shell composed of one or more layers to represent the sandwich structure. The contents of this shell was either a fluid or an (almost) incompressible solid, that represented the brain.

The brain with it's various substructures (see Fig.2.1 and Fig.A.2) forms together with the spinal cord a continuum, which is covered by the three meninges and the CSF. From a mechanical point of view this continuum of brain and spinal cord can be seen as a continuum of 2 phase multiphasic material that is suspended in the skull by the meninges and the CSF. The cerebral hemispheres are arranged in a number of folds, which are separated by fissures. These fissures separate each of the hemispheres into four lobes. The cerebrum forms the largest structure of the brain. It consists of a core of white matter surrounded by a 1.5 mm to 4.5 mm thick layer of gray matter. In the white matter there is the corpus callosum, a fibrous structure that connects the two hemispheres. The cerebellum has roughly the same structure as the cerebrum, only on a much smaller scale. The cerebellar hemispheres are also arranged in a number of folds, which are separated by fissures. The core of the cerebellum merely consists of white matter, covered by a layer of gray matter. The two cerebellar hemispheres are connected by a fibrous strip-like structure, called the vermis. Fibrous structures can also be found in the meninges and in the separations, which are actually also part of the meninges, between the cerebral hemispheres, the falx cerebri, between the cerebrum and the cerebellum, the tentorium cerebelli and between the two cerebellar hemispheres, the falx cerebelli.

3.2 The constitutive relations

The skull or actually the calvarium, because due to the load conditions the facial bone does not have to be modeled, has a sandwich structure. This bony structure can at first be modeled as being homogeneous, isotropic and linear elastic. The largest influence of the skull on the response of an impact load is probably due to the varying thickness of the skull. In literature the linear elastic modelling of the skull has been widely accepted.

For the other structures of the head, like the central nervous system, scalp and meninges, the question arises 'how to model biological structures: as viscoelastic or multiphasic materials ?'. In principle one could say that every biological material is a mixture, because the cells that constitute the structure are composed of a combination of fluid and solid material (see also (Fung, 1990, pages 300–305)). But in the head there are more fluids present namely blood and CSF. The modelling approach of these structures can either be viscoelastic or multiphasic. Thereby one could think of modelling the total contents of the head as a continuum, whereby the different substructures like cerebellum, dura mater, CSF, etc. are modeled by using different parameters in the viscoelastic case or a different ratio of solid/fluid fractions in the multiphasic case. The modelling approach is also partly dependent on the time scale of the dynamic loads and the effects, for instance wave propagation, one wishes to study and capture in the calculations.

Certain structures inside the head are expected to have anisotropic properties, due to their fibrous structure. Examples of where these structures can be found are the meninges and in separations, the falx cerebri, the falx cerebelli, the tentorium cerebelli and inside the cerebral hemispheres in the corpus callosum and the vermis.

3.3 The boundary and interface conditions

For the mathematical modelling of the head the boundary conditions are relevant for the outcome of the response. The two main boundary conditions are the modelling of the head-neck junction and the modelling of the load case whether that be an acceleration, a force or a real contact with an object. The head-neck junction moves in a complex manner when subdued to a load on the head. In most of the mathematical studies of head impact either the influence of the neck is said to be irrelevant and the model of the head is allowed to move freely in space or some kind of 'hinged' condition is prescribed at the location of the neck. This goes for the study of impact to the frontal bone of the head. In the case of side-impact also models with double-hinged conditions are used.

The prescribed load conditions in literature are often loads to the frontal bone of the brain case or a prescribed rotational acceleration around a certain point in space. As input often measured force/time or acceleration/time histories are used to make the loading conditions as realistic as possible. The use of contact conditions with another object, for instance a modeled part of a car, like numerically and experimentally done by DiMasi *et al.* (1991a, 1991b), one does not encounter very often. The use of contact conditions probably approaches the load conditions found in reality in the best possible way.

The interface conditions are especially important in the modelling of relative motion between brain and skull and between other structures. Although the brain is said to 'neatly' fit inside the skull, various researchers (DiMasi, Eppinger, Gabler III and Marcus, 1991a; DiMasi, Marcus and Eppinger, 1991b; Margulies, 1987; Galbraith and Tong, 1988; Ruan, Khalil and King, 1991; Ruan, Khalil and King, 1992; Willinger, Kopp and Cesari, 1992; Trosseille, Tarriére, Lavaste, Guillon and Domont, 1992) are of the opinion that there is the possibility of relative motion between brain and skull in extreme loading conditions. These authors modelled the skull-brain interface in two different manners, either the skull-brain interface was modelled by a compliant layer with a low shear modulus or the interface was modelled by applying various amounts of friction between the two structures to allow relative motion of the brain.

Chapter 4

Concluding remarks

Important for the mechanical modelling of the human head seems to be the fact that the brain, spinal cord and the surrounding meninges form a continuum. The spaces between the various structures are filled with the same fluid, cerebrospinal fluid. The part of the continuum that contains the brain is locked up by a container, the cranial vault. The possibility of motion of the brain relative to the container wall is stipulated by connections between, in succession, brain and meninges, between the various meninges and between the meninges and the skull.

From descriptions in literature (Khalil and Viano, 1982; Shugar, 1977; Shatsky, Alter III, Evans, Armbrustmacher, Earle and Clark, 1974) one can conclude that relative motion between brain and skull is possible in both numerical and experimental setups. Shatsky et al. (1974) showed that there is substantial experimental evidence of relative motion between brain and skull and various other brain organs. Khalil and Viano (1982) numerically showed the importance of relative motion, using a simple plane-strain model, consisting of an outer shell and an interior inviscid fluid. The results showed that the pressure distribution differed by about a factor of 8, the higher pressure occurring in the model where relative motion was not permitted. Only at the location of the foramen magnum are the meninges connected to the cranial bone, so relative motion appears to be a phenomenon that should be incorporated in future models. In general the cerebrospinal fluid is described as being a watery fluid. The only indications for this based on experiments was found in publications by McElhaney, Melvin, Roberts and Portnoy (1972) and Ommaya (1968).

The literature study (Sauren and Claessens, 1993), that was performed to get an overview of the finite element models of the human head that have been published over the last decade, showed that the anatomy of the head was often not modeled in great detail. All the authors modeled the skull and the brain, but due to various reasons the other substructures were often not modeled at all. The main reasons are; the fact that it is unknown to what extent the substructures and the detailing of the substructures influence the transient response of the head. Another reason is the fact that great detailing or taking a number of substructures into account creates a complicated mesh with a great number of nodes and elements, which leads to large computational costs. Furthermore due to the fact that the constitutive properties of most of the tissues of the head are unknown and that the experimental data are dated, meant that the modelling of the substructures could only be done by approximating the material properties. In most cases these materials were approximated by linear elastic behaviour and in a few exceptions a linear viscoelastic model was used. The last reason is the problem of creating the geometrical description of the substructures. Doing this by hand is an almost impossible task and the techniques for using MRI-data to create a mesh of the human head are still under development (Finnigan, Hathaway and Lorensen, 1990).

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Appendix A

Figures

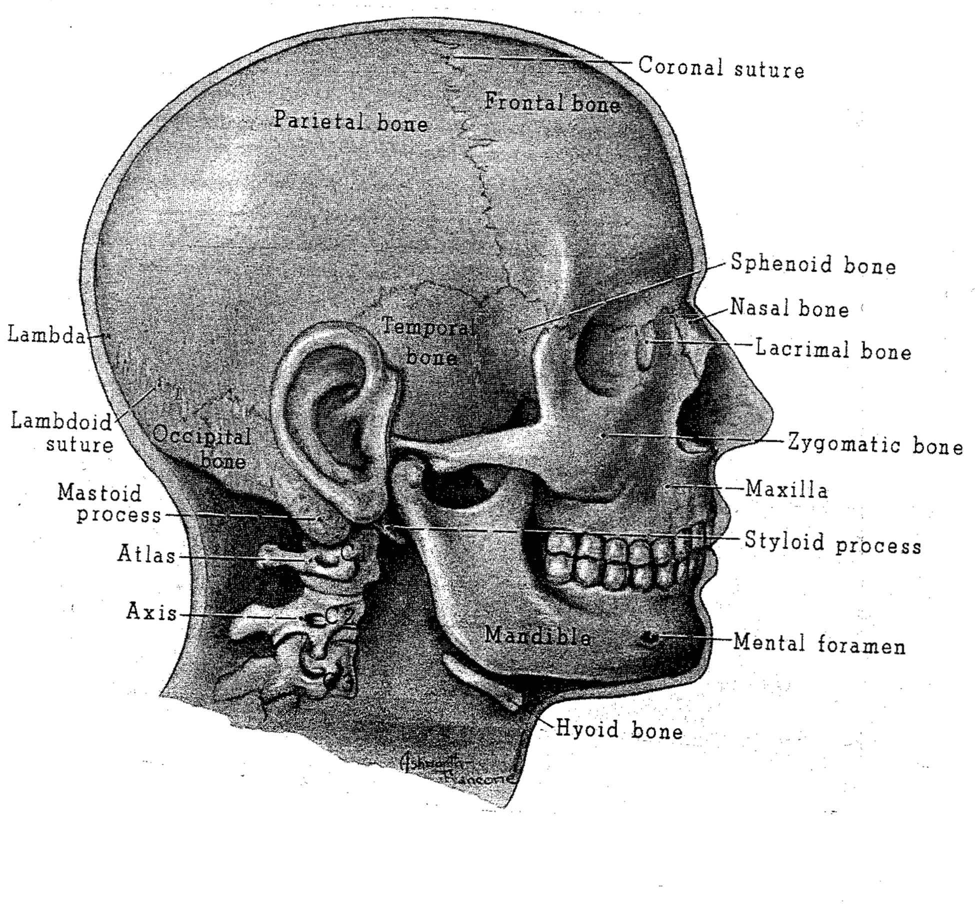


Figure A.1: The various bones of the cranial vault and the facial bone.
Source: S.W. Jacob and C.A. Francone, *Elements of anatomy and physiology*, 1976.

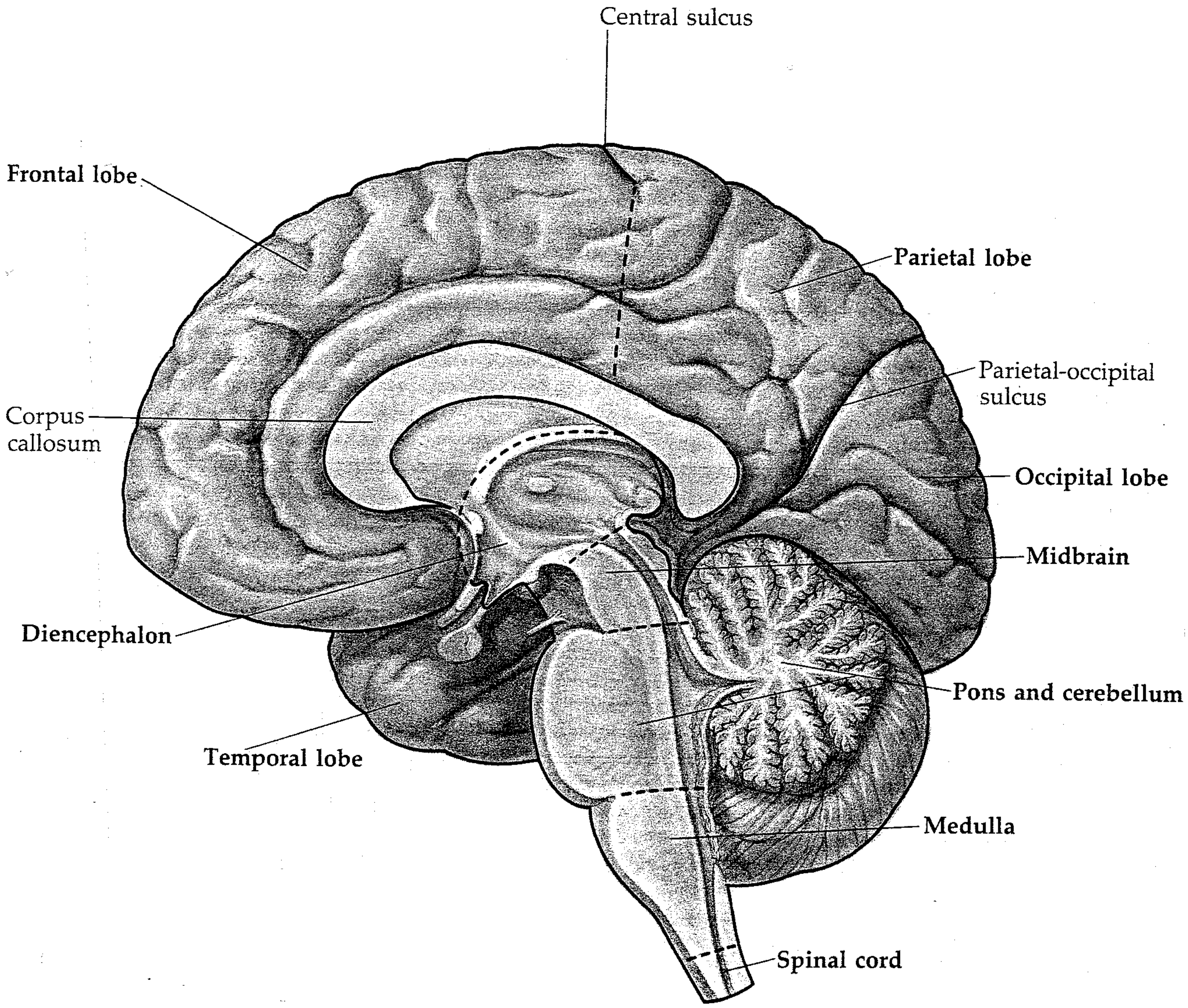


Figure A.2: Sagittal (1) view of the brain with it's various substructures. Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.

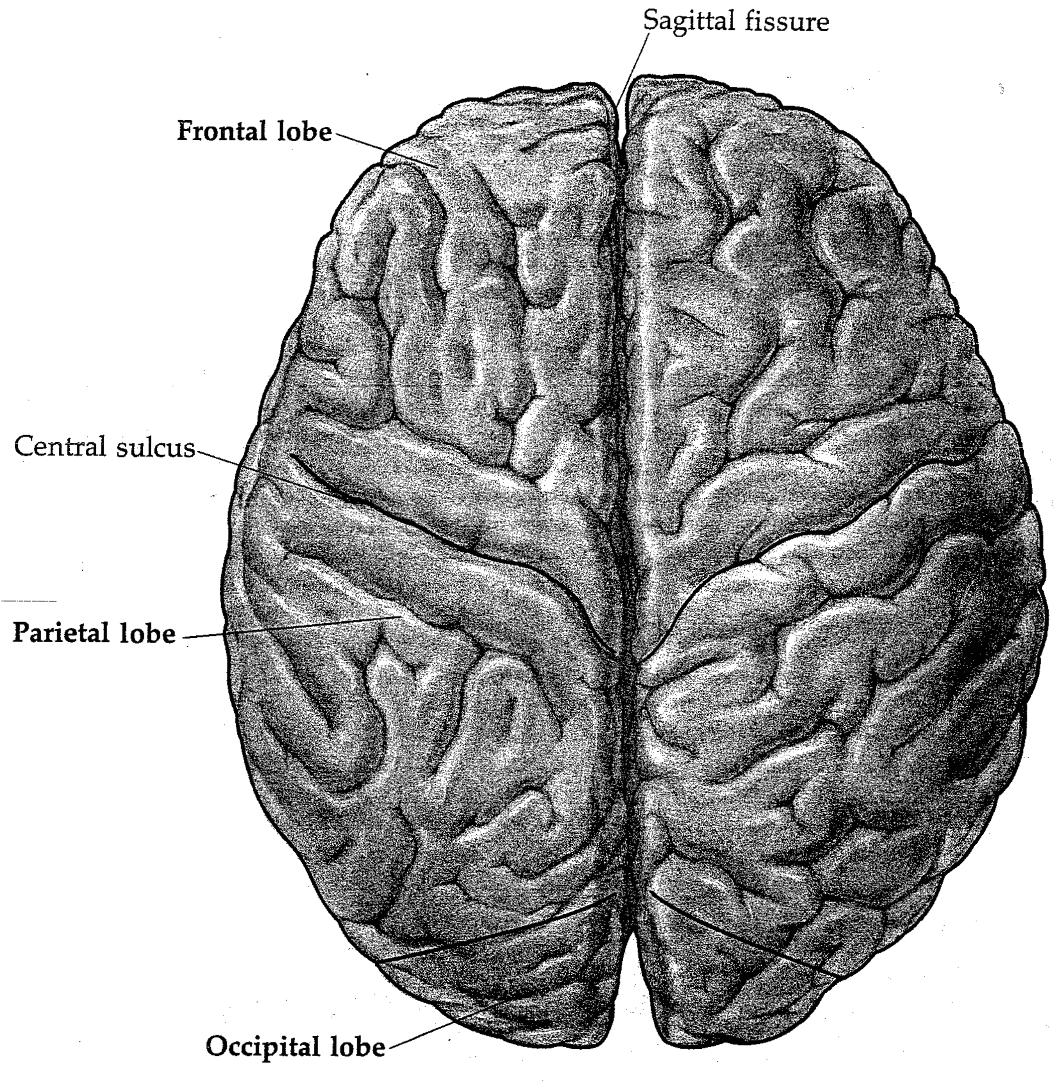
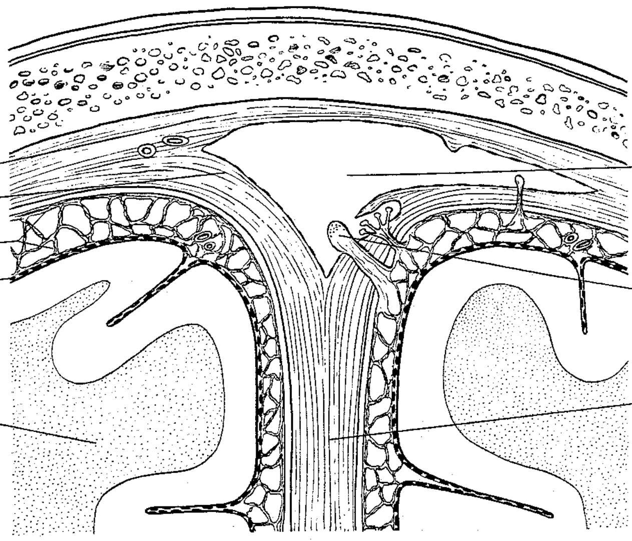


Figure A.3: The cerebral cortex (dorsal surface) with its arrangement in folds or gyri and the subdivision of the hemispheres in lobes.
Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.



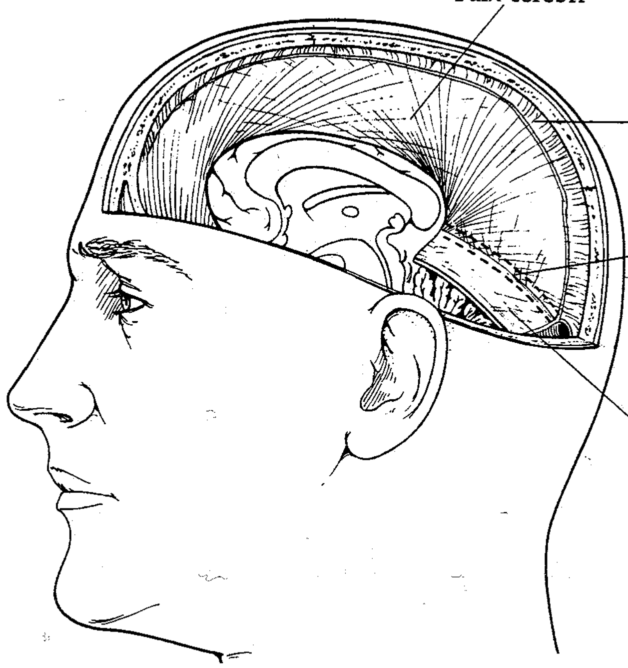


Figure A.4: A midsagittal view of the meninges, falx cerebri and the dural sinus. Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.

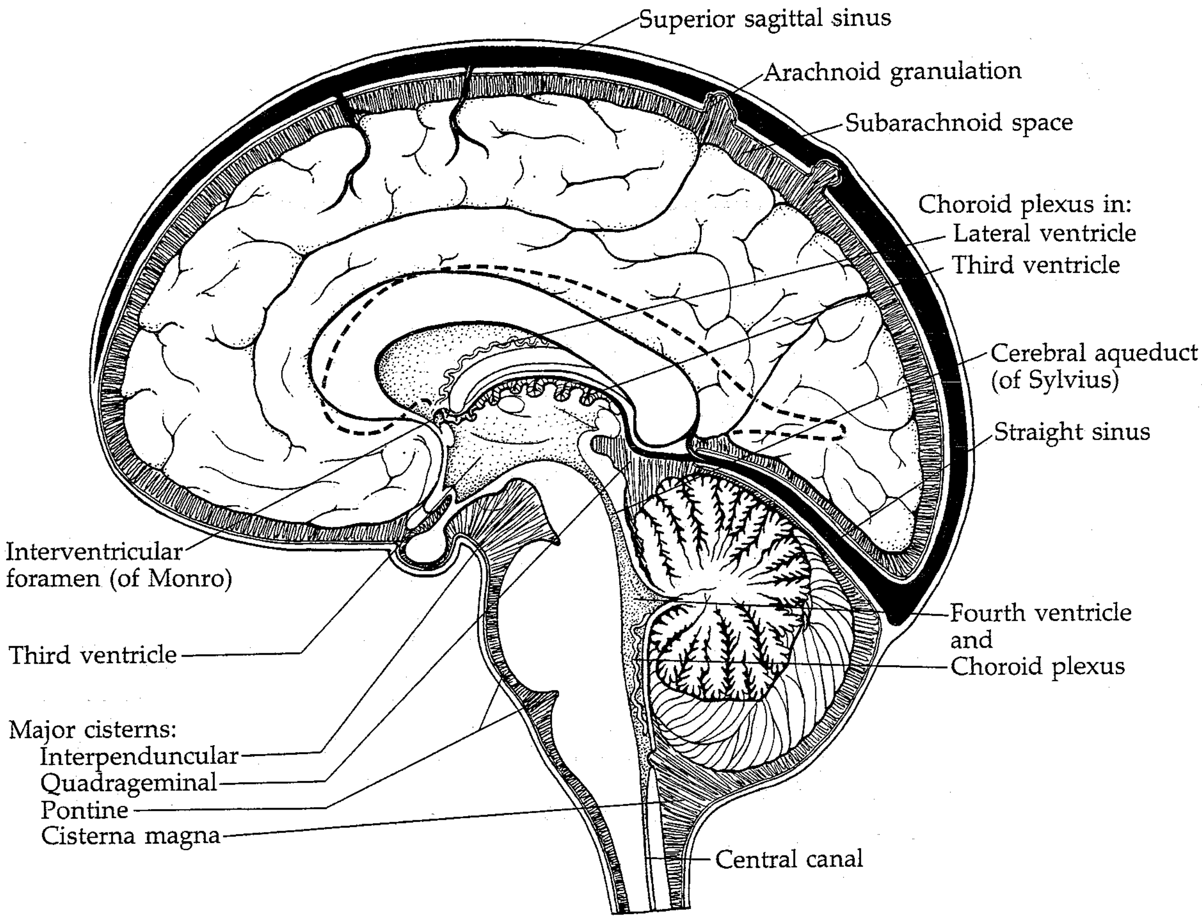


Figure A.5: Pathway of CSF from the choroid plexus in the lateral ventricles to the arachnoid granulations protruding into the dural sinuses.
Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.

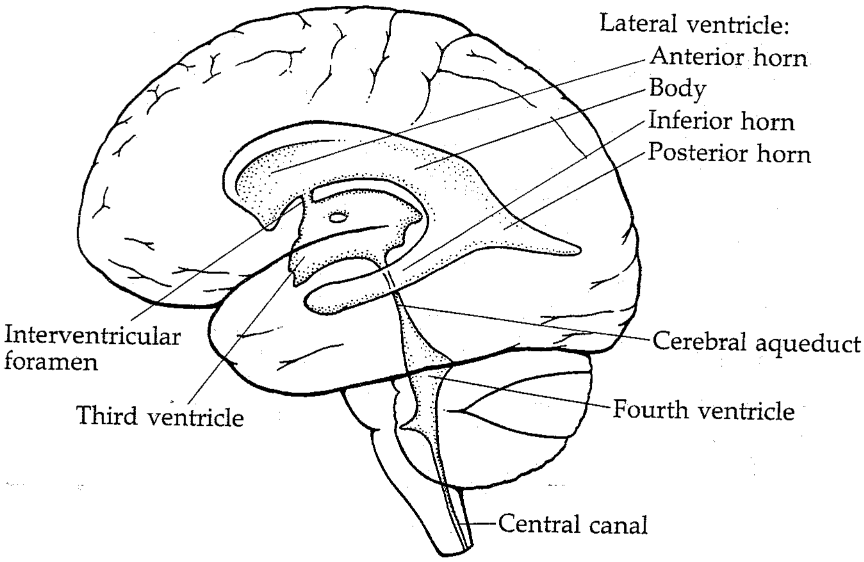


Figure A.6: The ventricular system. The lateral ventricle is divided into four main components.
Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.

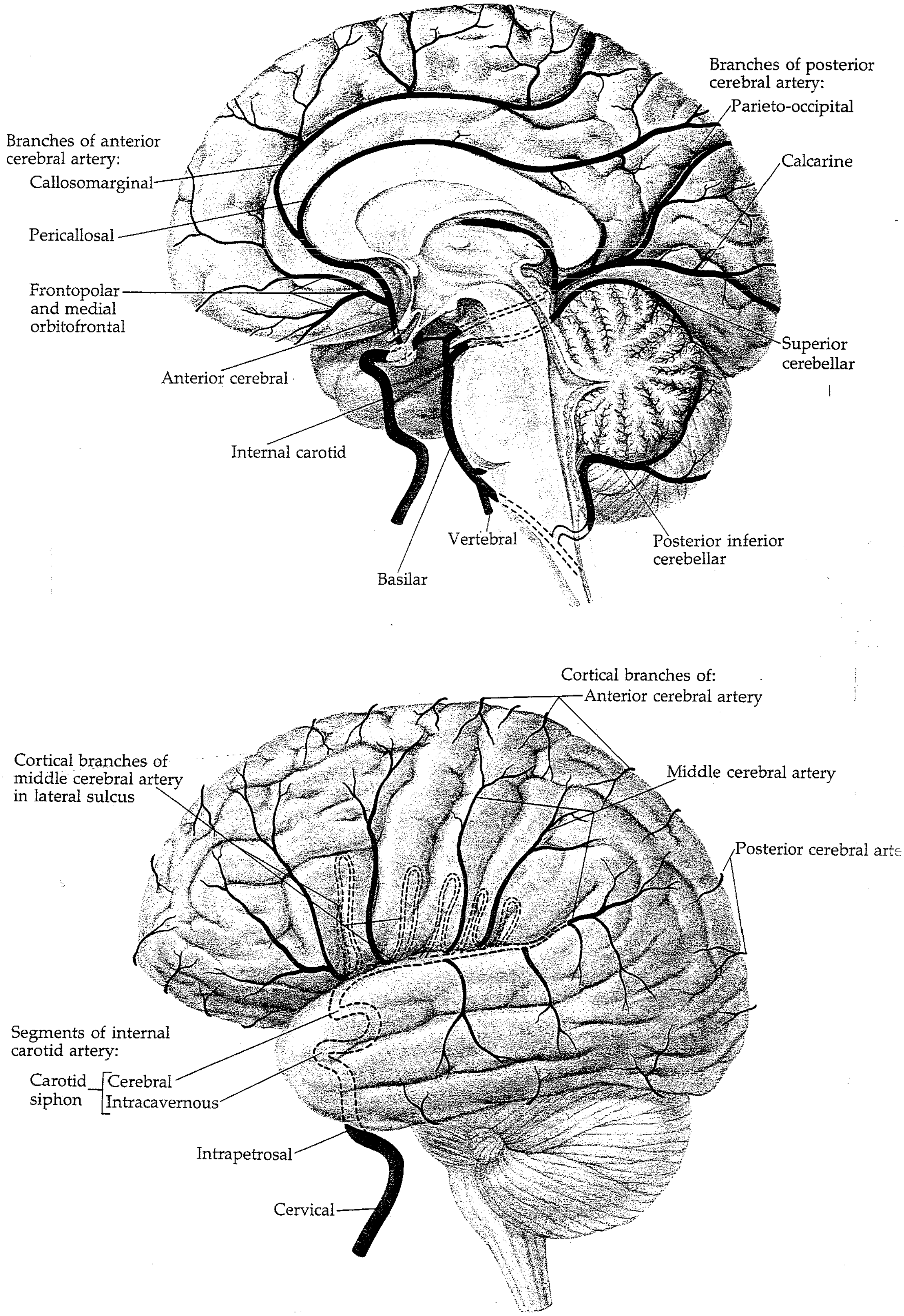


Figure A.7: Vasculature of the human head.
Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.

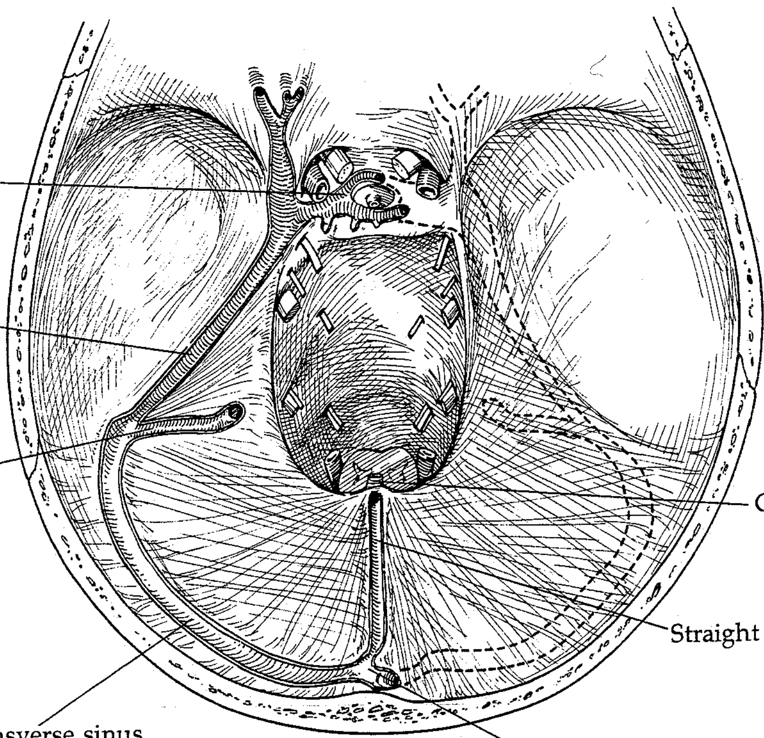


Figure A.8: Blood drainage of the human head through the various sinuses. Source: J.H. Martin, *Neuroanatomy text and atlas*, 1989.