1 Calvaria

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◆ Introduction

The cranium (skull) is divided into the neurocranium, which forms the skeleton around the brain, and the viscerocranium, which forms the skeleton of the face. The neurocranium is subdivided into the cartilaginous skull base (chondrocranium) and the membranous part cranial vault (calvaria or calvarium).

Therefore, the calvaria is the part of the cranium above the skull base. The contributing bones are the four paired frontal, parietal, sphenoid (greater wing), temporal (squamous portion), and occipital (squamous portion) bones. These flat bones are formed by intramembranous ossification. The calvaria protects the brain, and the meninges separate and cushion it from the skull.

The cranium is a mineralized structure made up of collagenous matrix, cells, vessels, and crystals of calcium compounds (hydroxyapatite). In contrast to cartilage, bone is highly vascular with the capability of repair and remodeling. Each calvarial bone is surrounded by a shell of compacted bone called the cortex. The outer cortex is called the external table, and the inner cortex is called the internal table (▶ Fig. 1.1, ▶ Fig. 1.2). The external table is covered by the periosteum. Between the two tables lies the diploe, a honeycomb-like meshwork of trabecular bone (cancellous bone) filled with bone marrow and hematopoietic cells. At birth, the bones of the cranial vault are unilaminar tables and the diploe appears later around the fourth year[1] (▶ Fig. 1.3).

At computed tomography (CT), the inner and outer tables are well defined and have very high attenuation, whereas the diploic space has slightly lower attenuation. At magnetic resonance (MR) imaging, the inner and outer tables have very low signal intensity, regardless of the pulse sequence. The appearance of the diploe depends on the age of the patient: It has low signal intensity on T1-weighted images in the first two decades of life as it is filled with red marrow, but later in life the diploic marrow becomes bright due to fatty conversion[6] (▶ Fig. 1.3).

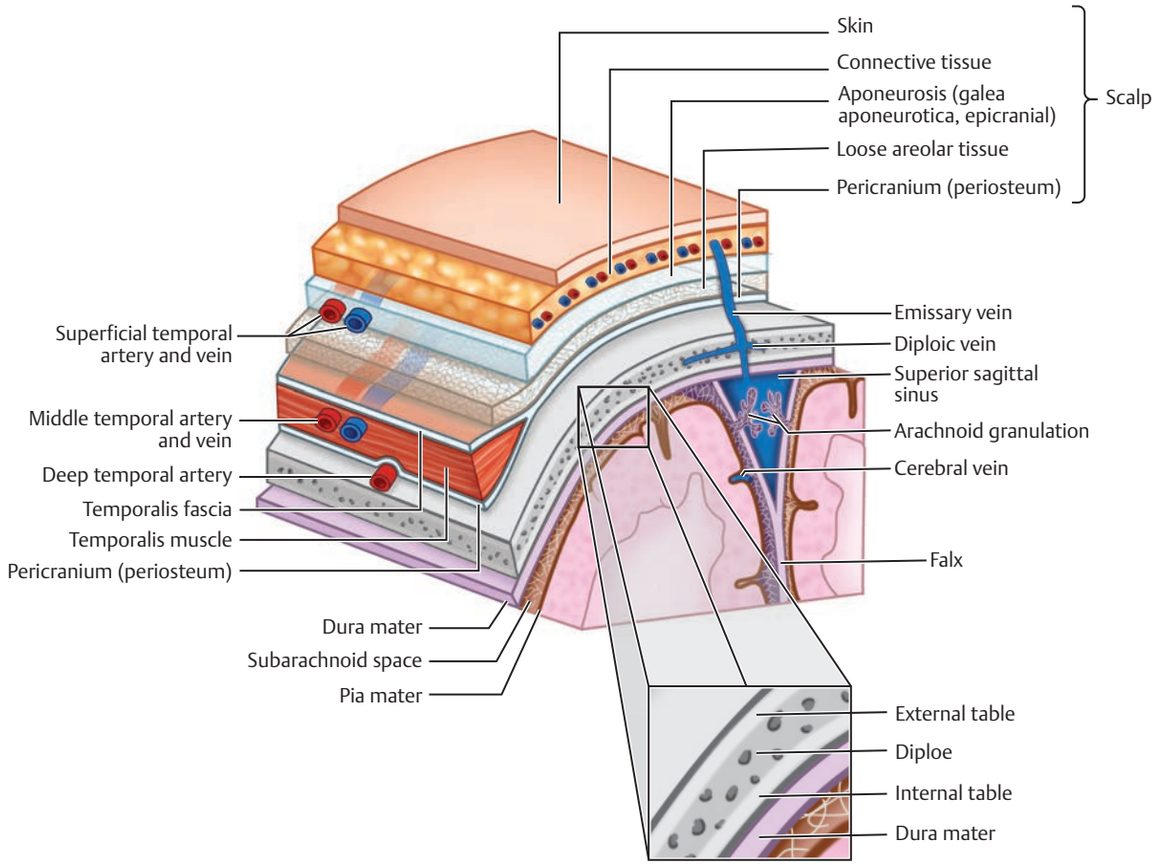


Fig. 1.1 Skull and overlying scalp. The pericranium, which is the periosteum of the skull, ends laterally with the origin of the temporalis fascia along the superior temporal line and provides nutrient supply to the bone. The scalp is composed of five layers, and the first three layers are bound together into a single unit.

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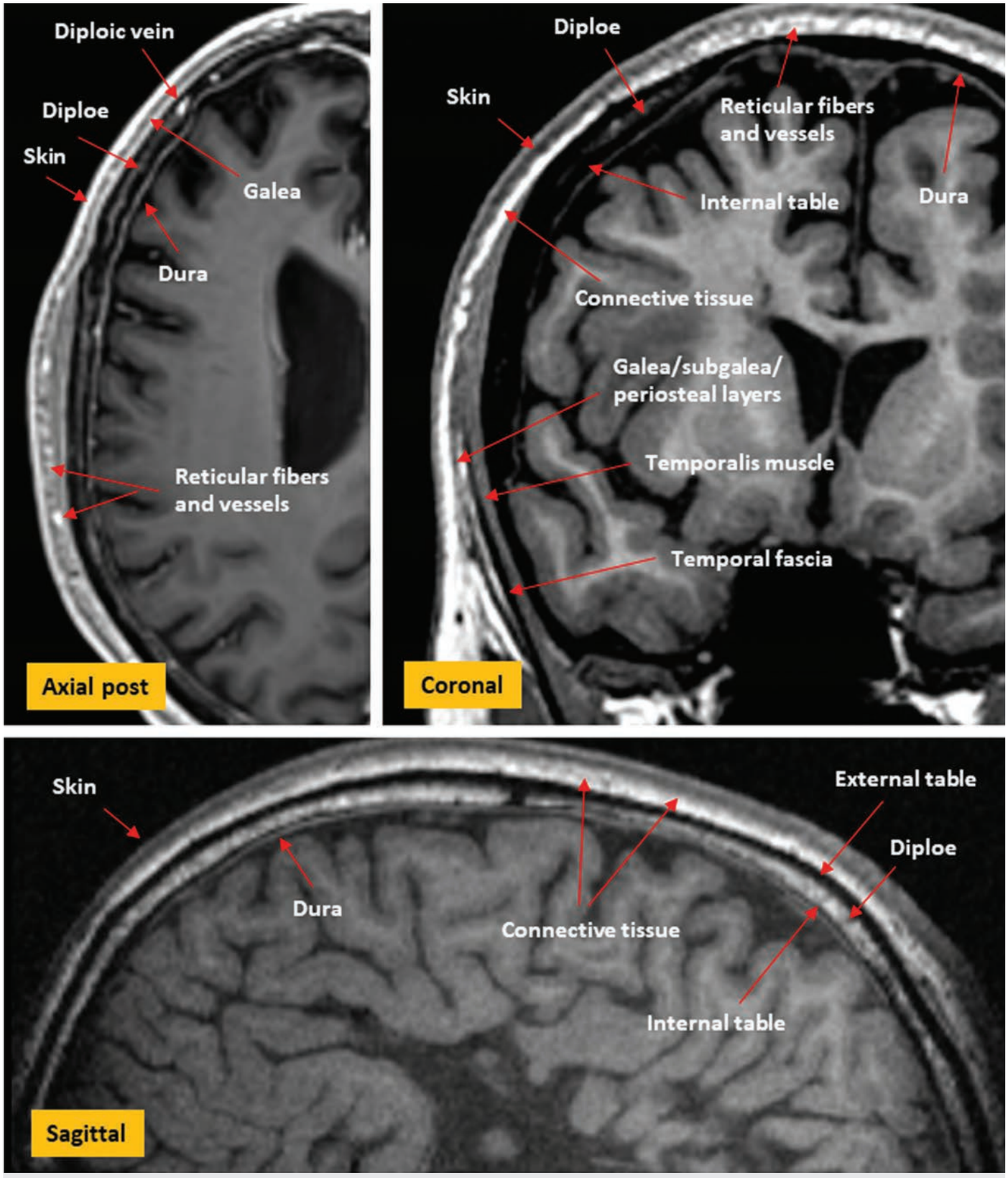


Fig. 1.2 T1-weighted magnetic resonance (MR) images in different cases showing the calvaria and the overlying scalp. Each calvarial bone is surrounded by a shell of compacted bone called the cortex. The outer cortex is called the external table and the inner cortex is called the internal table (▶ Fig. 1.1). The external table is covered by the periosteum. Between the two tables lies the diploe, a honeycomb-like meshwork of trabecular bone (cancellous bone) filled with bone marrow and hematopoietic cells. The fatty marrow of the diploe between the inner and outer tables of the skull is clearly seen. The skin and subcutaneous layers of the scalp are clearly seen. On contrast-enhanced MR scans (axial image), the signal from the dermal layer increases because there is a rich network of vessels derived from the underlying subcutaneous layer. Reticular fibers and vessels in the subcutaneous layer are also seen. However, the galea/subgalea/periosteal layers blend with the outer table of the skull. The underlying subgaleal fat is seen over the temporalis muscle on the coronal view.

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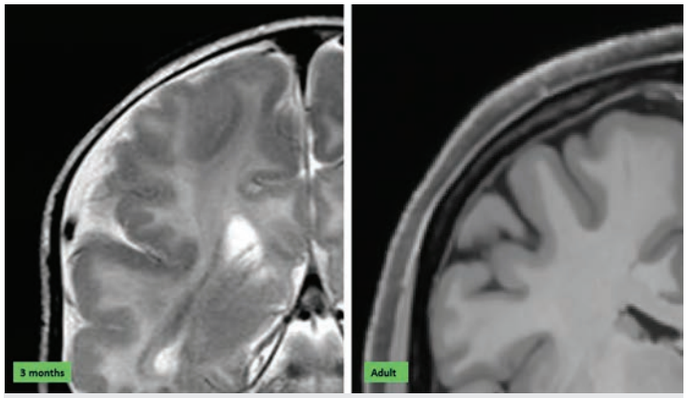


Fig. 1.3 Magnetic resonance imaging (MRI) showing the cranial vault at 3 months and in an adult. At birth, the bones of the cranial vault are unilaminar tables, and the diploe appears later around the fourth year. The appearance of the diploe depends on the age of the patient. It has low signal intensity on T1-weighted images in the first two decades of life as it is filled with red marrow, but later in life, the diploic marrow becomes bright due to fatty conversion.

◆ Development and Ossification

The cartilage, bone, and skeletal muscles are primarily formed by the mesenchyme originating from the paraxial mesoderm with variable contributions of neural crest cells of the ectoderm.[1] The neurocranium mesenchyme is derived from both the mesoderm and the neural crest, whereas the craniofacial bones and cartilage (viscerocranium) develop from the cranial neural crest only.

By the end of the third week, the paraxial mesoderm differentiates to form cranial somitomeres and somites, which differentiate to become sclerotomes. The basal occipital part is formed by the first four somites. Rostral to the first somite, the paraxial mesoderm differentiates to form seven cranial somitomeres. The somites and somitomeres of the paraxial mesoderm play a direct role in the development of the parietal, petrous temporal, and occipital bones. The neural crest participates in the formation of the frontal, sphenoid, and squamous temporal bones. The intervening sutures and underlying dura mater are derived from cranial neural crest cells.[2]

The development of the cranial bones continues with the condensation of mesenchymal cells, starting with the concentration of the occipital sclerotomal mesenchyme around the notochord and extending cranially. During the fifth week of gestation, the mesenchymal tissue that gives rise to a membranous neurocranium, called the "primary meninx," forms around the developing brain. The primary meninx consists of two layers: the endomeninx, which forms the leptomeninges (pia and arachnoid), and the ectomeninx. The ectomeninx forms an inner dura mater and an outer periosteal (endosteal) layer with osteogenic and chondrogenic capabilities.[1] Bone formation (ossification) of the ectomeninx in the cranial vault is intramembranous and that of the ectomeninx in the skull base is endochondral.

Ossification in the outer layer of the ectomeninx of the cranial vault by direct differentiation of the osteoblasts from the preexisting mesenchymal cells is called intramembranous ossification. This process occurs in a centrifugal pattern with the bone spicules radiating outward in both directions from the center of the bone. Ossification centers first appear in the future cranial bone eminences of the frontal and parietal bones as early as 8 weeks of gestation. Later, the cranial sutures are formed and contribute to intramembranous bone growth. Chondrification of the mesenchyme of the skull base begins in the spheno-occipital region during the seventh week of gestation, followed by endochondral ossification by 12 weeks of gestation (see Chapter 2: Skull Base).

Ossification of the sphenoid, temporal, and occipital bones is both membranous and cartilaginous. The membranous centers include the frontal, parietal, squamous occipital (interparietal), and squamous temporal. The lateral part of the greater wing of the sphenoid bone and the lateral pterygoid plate are derived from intramembranous ossification, whereas the rest of the sphenoid bone, including the medial pterygoids, originates from cartilage.

The process of ossification varies in fetuses and may appear early and progress rapidly. The immature embryonic bone is called woven bone, marked by random orientation of collagen fibers, which will be replaced by the more mature lamellar bone at the time of birth. In early life, only a single cortical table exists, but by the sixth year, development of a middle diploic layer between two tables is completed.[2] Compared to the outer table, the inner table of the calvaria is thinner and prone to fracture in head trauma (▶ Fig. 1.3).

Most of the bone structure is formed by a mineralized matrix. In the mineralized matrix, hydroxyapatite is the most abundant mineral. The organic matrix is composed of 85 to 90% collagenous proteins, with type I collagen being the most common. Production of the organic matrix and regulation of matrix mineralization are performed by osteoblasts.

In skeletal dysplasias, the bone mineralization may be affected. Skull bone dysplasia may manifest as a generalized decrease in calvarial density, as in hypophosphatasia, achondrogenesis, and osteogenesis imperfecta, or as a generalized increase in calvarial density, as in osteopetrosis.

Lacunar skull is a dysplasia of the membranous bone causing well-defined lucent areas in the calvaria due to nonossified fibrous bone. It is associated with neural tube defects, especially myelomeningocele and Chiari II malformation. The lacunar pattern usually resolves by the age of 6 months.

◆ Calvaria

Imaging of the calvarial bones is usually performed using plain radiographs or CT scan (▶ Fig. 1.4). CT is the modality of choice for assessment of trauma and fractures. MRI is used in certain cases for the evaluation of bone pathologies. The contributing bones of the calvaria are four paired frontal, parietal, sphenoid (greater wing), temporal (squamous portion), and occipital (squamous portion) bones (▶ Fig. 1.5, ▶ Fig. 1.6, ▶ Fig. 1.7, ▶ Fig. 1.8).

Frontal Bone

Each frontal bone originates from a single primary ossification center at the frontal eminence around the eighth week. At

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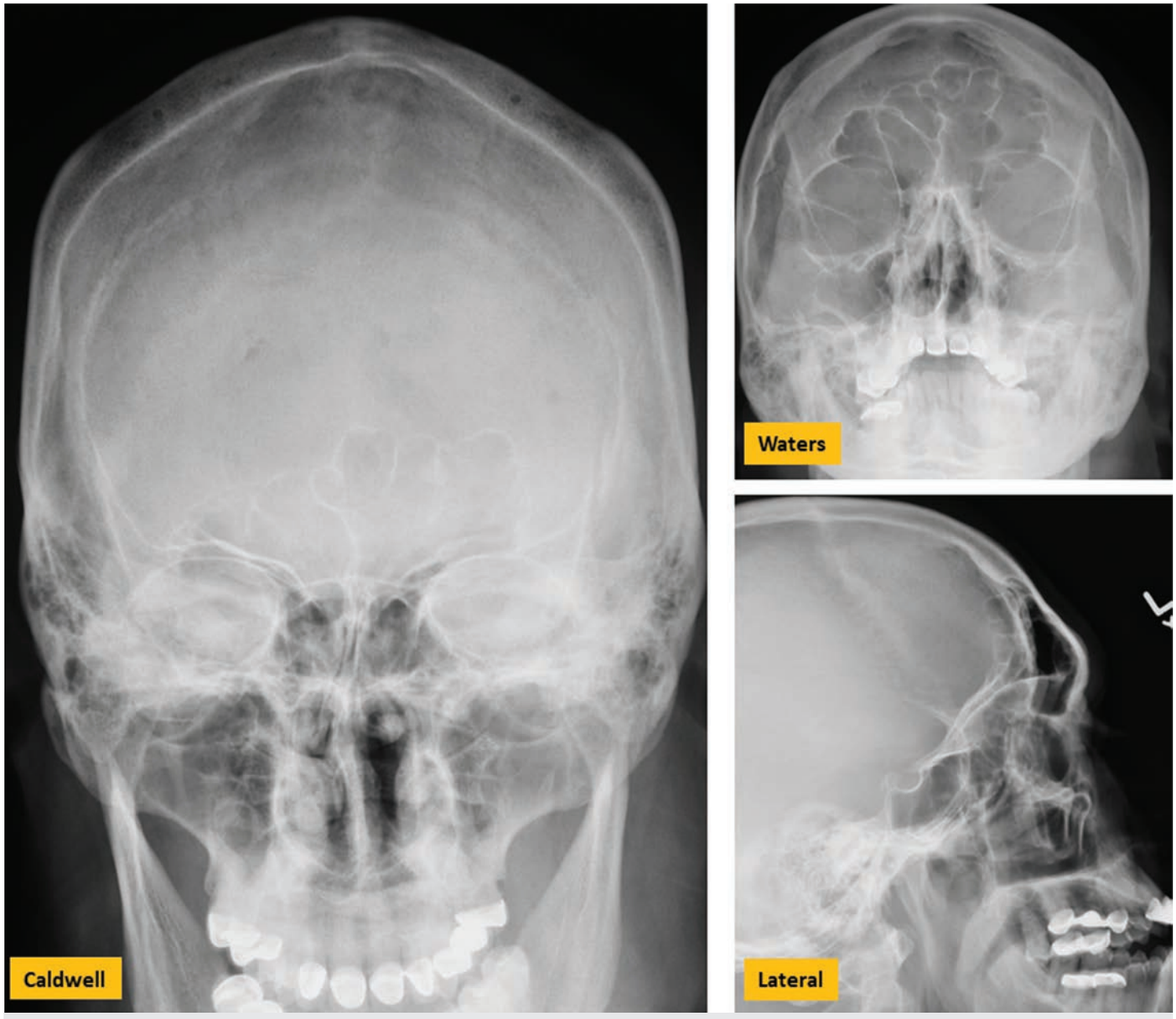


Fig. 1.4 Standard skull radiographs are Caldwell/frontal, lateral, and Waters views.

18 weeks, progressive ossification narrows the space between the medial margins of the centers and continues at a steady rate.

Three secondary centers appear later in the zygomatic process, nasal process, and trochlear fossa and fuse to the main body by 6 to 7 months.[1] Frontal sinuses develop after the first postnatal year.

Synostosis of the metopic (frontal) suture between the frontal bones occurs during the second postnatal year and becomes ossified by 7 years of age. It may persist throughout life (▶ Fig. 1.9).

A mature frontal bone can be divided into two parts: a flat vertical squamous part and a horizontal orbital plate. The orbital plate forms a major part of the orbital roof in the anterior skull base, showing an undulated surface. The midpart of the orbital plate is the thinnest, but its anterior rim (superior rim of orbit) is strong and rarely breaks. The supraorbital notch (foramen in some cases), where the supraorbital neurovascular bundle passes, is in the medial side of the superior orbital rim (▶ Fig. 1.10). The orbital plate fuses with the lesser wing of the sphenoid posteriorly.

The nasal processes are the anterior extension of the orbital plates, which fuse in the midline and form the nasal stem of the frontal bone (▶ Fig. 1.10). The nasal process fuses with the nasal bone at the nasal notch inferiorly and with the lacrimal and frontal process of the maxilla laterally. More posteriorly, the medial wall of the orbital plate fuses with the ethmoid (▶ Fig. 1.10).

Two bony depressions are seen in the anterior orbital roof: the lacrimal gland fossa anterolaterally and the trochlea anteromedially (▶ Fig. 1.10), where the tendon of the superior oblique muscle passes (see Chapter 5: Orbit).

The zygomatic process of the frontal bone extends laterally to fuse with the zygomatic bone (▶ Fig. 1.10).

With continuous bone remodeling, the shape of the frontal bones and the size of the frontal sinuses vary in young individuals and differ between genders.[3] The forehead convexity and the supraorbital ridge vary between genders and with age. The superficial anatomical landmarks in the midline are the glabella and the trichion (at the hairline; ▶ Fig. 1.8).

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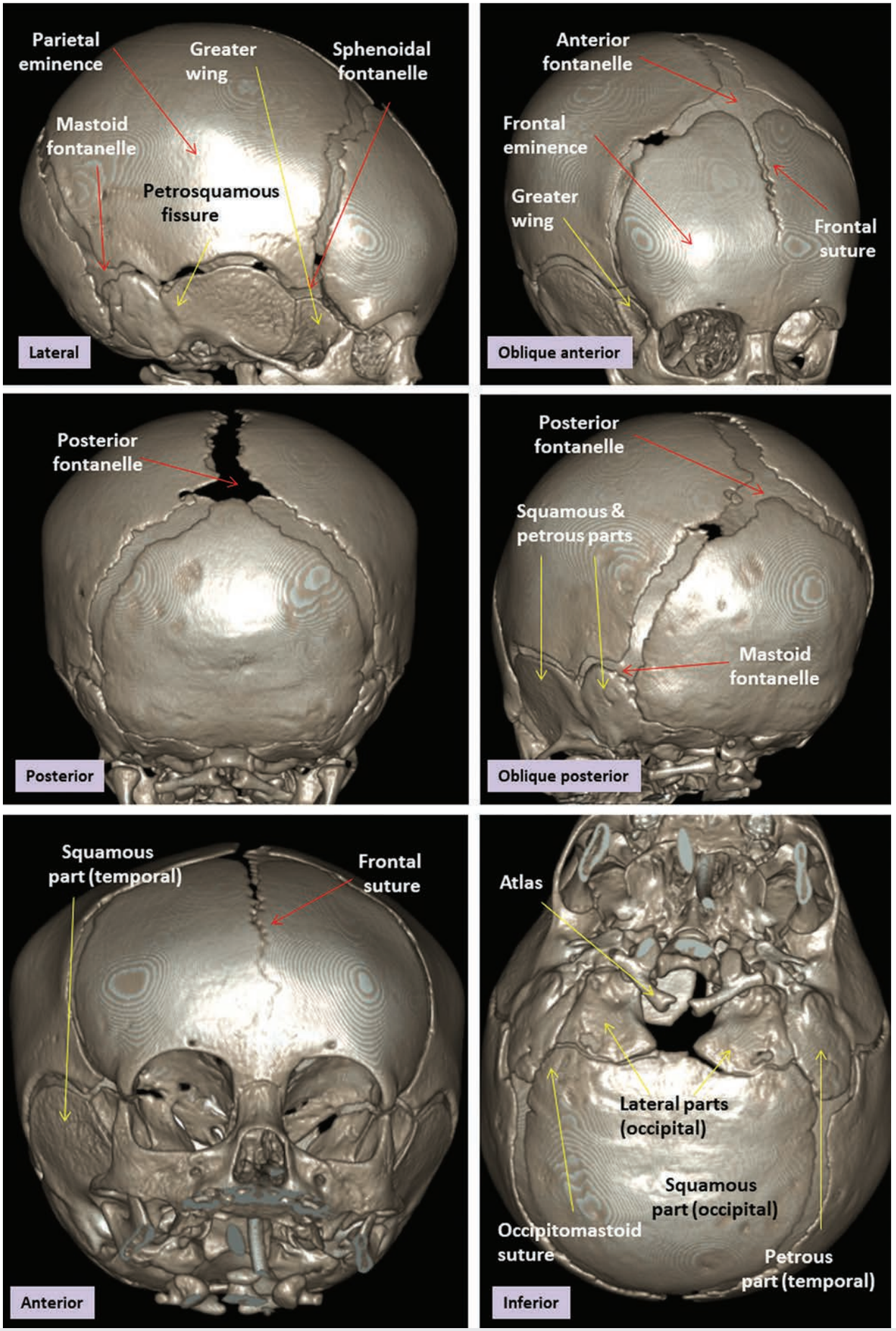


Fig. 1.5 Cranial vault sutures and bones in a 3-month-old infant. All sutures are wide open. The mendosal suture is fused.

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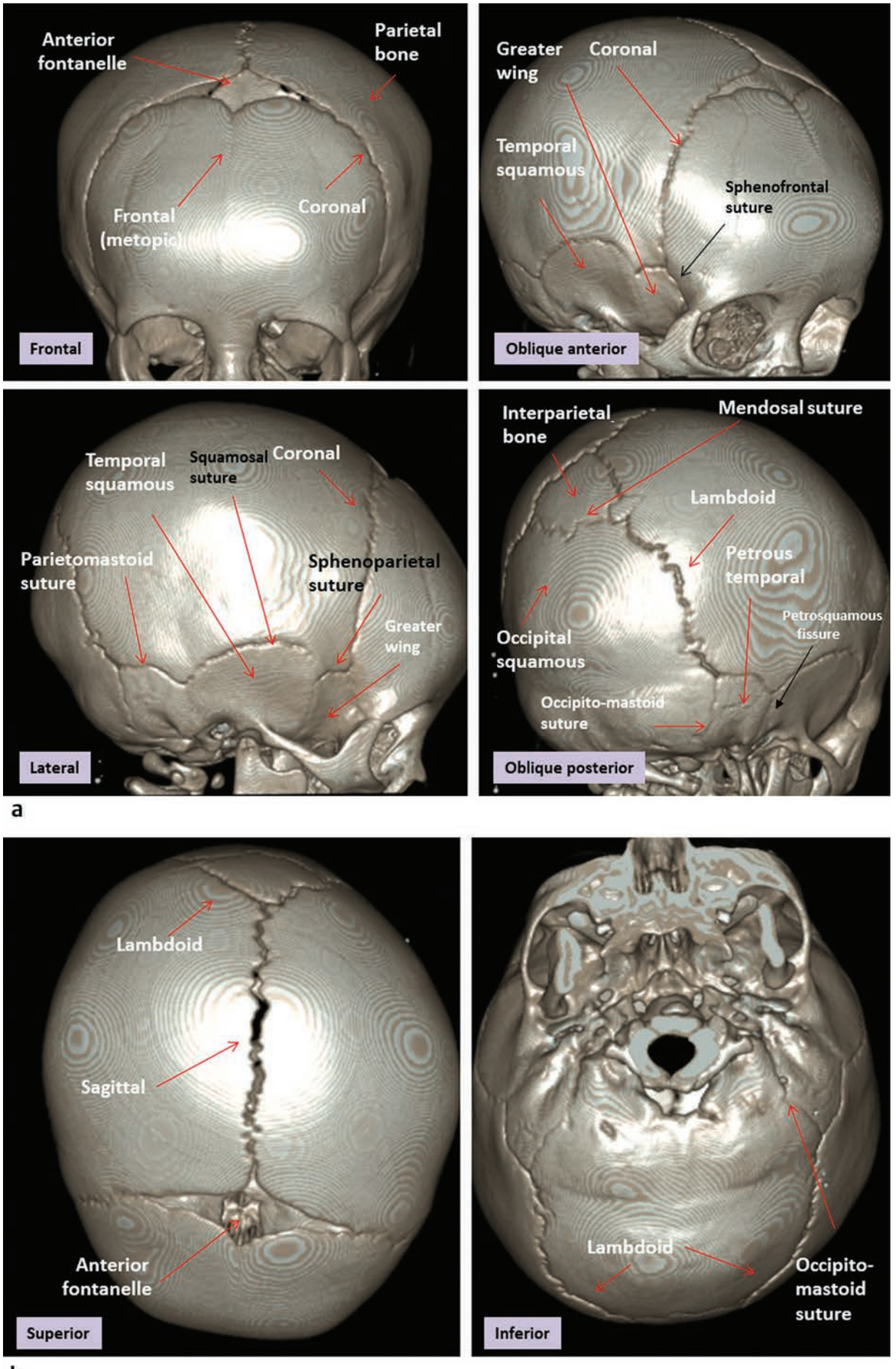


Fig. 1.6 (a, b) Cranial vault bones and sutures in a 7-month-old infant. The anterior fontanelle is not ossified. The interparietal wormian bone is separated from the squamous part of the occipital bone by the mendosal suture.

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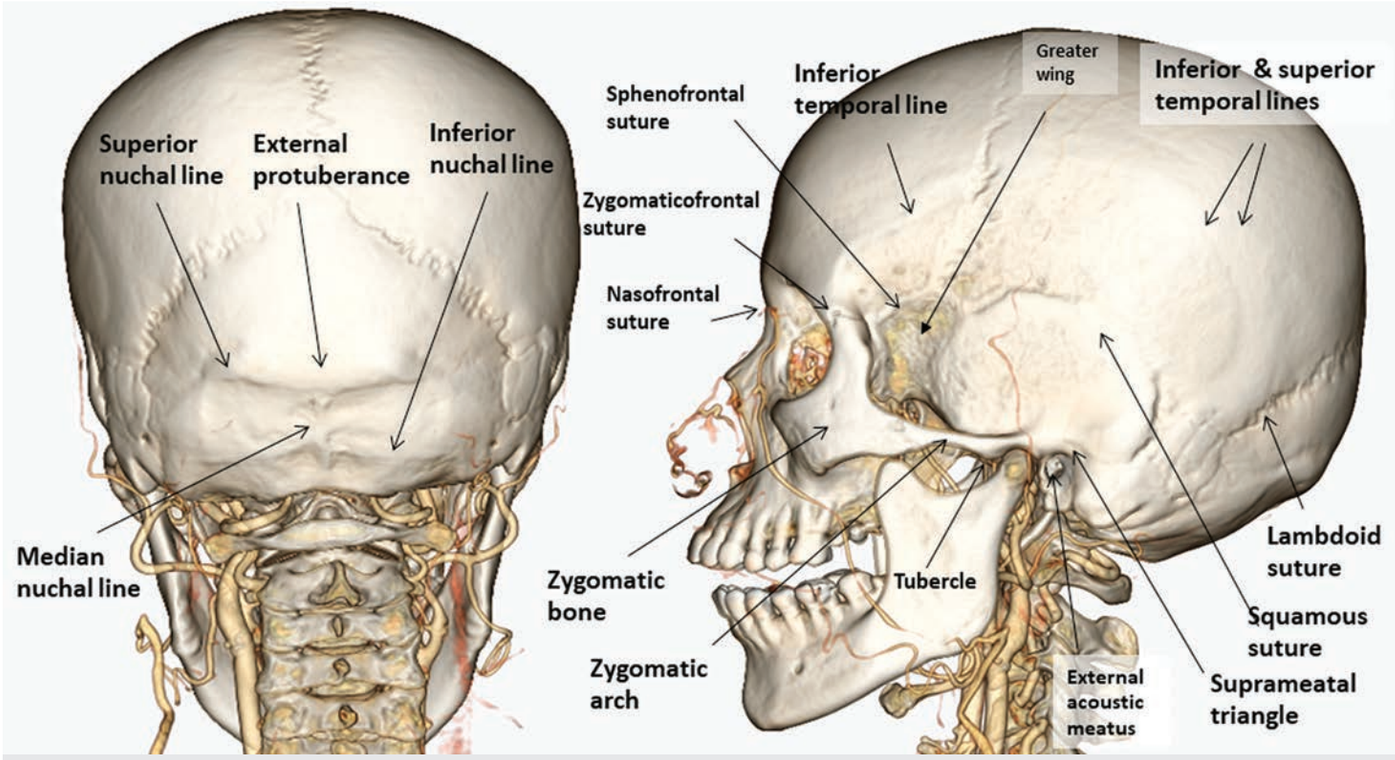


Fig. 1.7 Cranial sutures and bony landmarks in an adult. The superior and inferior temporal lines are two curved lines extending over the frontal and parietal bones. These lines are the sites of attachment of the galea, temporal fascia, and the origin of the temporal muscle. The nuchal lines are four curved lines on the external surface of the occipital bone. The highest nuchal line (not visible in this image) is where the galea aponeurotica is attached. The superior nuchal line is located at the level of the external occipital protuberance and is the site of attachment for the occipitalis, splenius capitis, trapezius, and sternocleidomastoid muscles. The ligamentum nuchae attaches to the external occipital protuberance and the median nuchal line. The inferior nuchal line crosses the median nuchal line at its halfway.

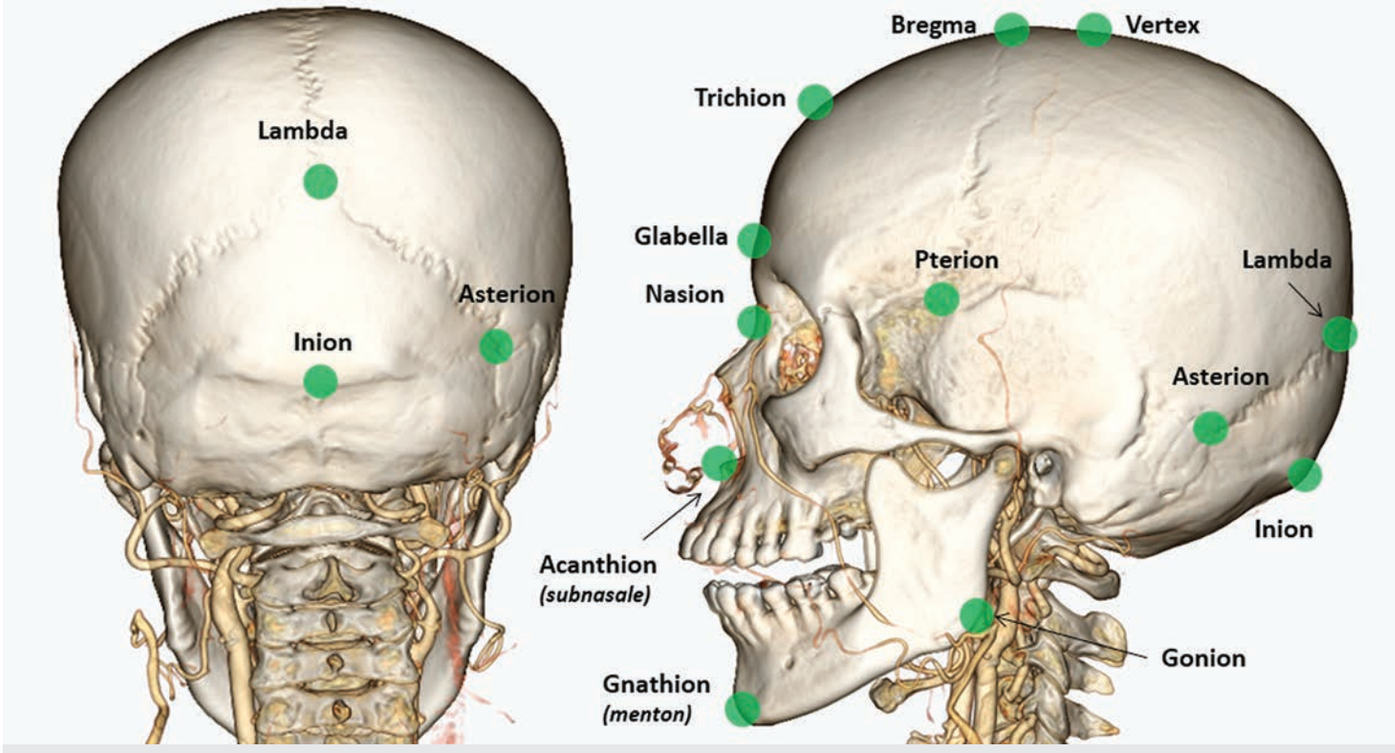


Fig. 1.8 Bony landmarks of the skull. The inion approximately corresponds to the external occipital protuberance, which is the most prominent protrusion of the occipital bone. It is the site of insertion of the ligamentum nuchae and the trapezius muscle.

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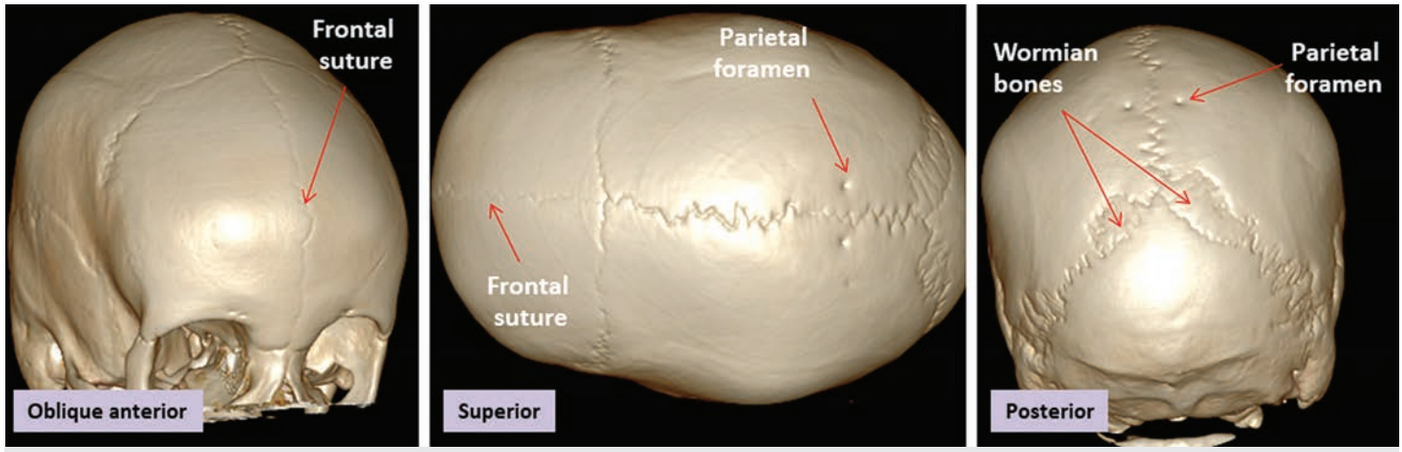


Fig. 1.9 Metopic (frontal) suture and wormian bones in a 57-year-old man.

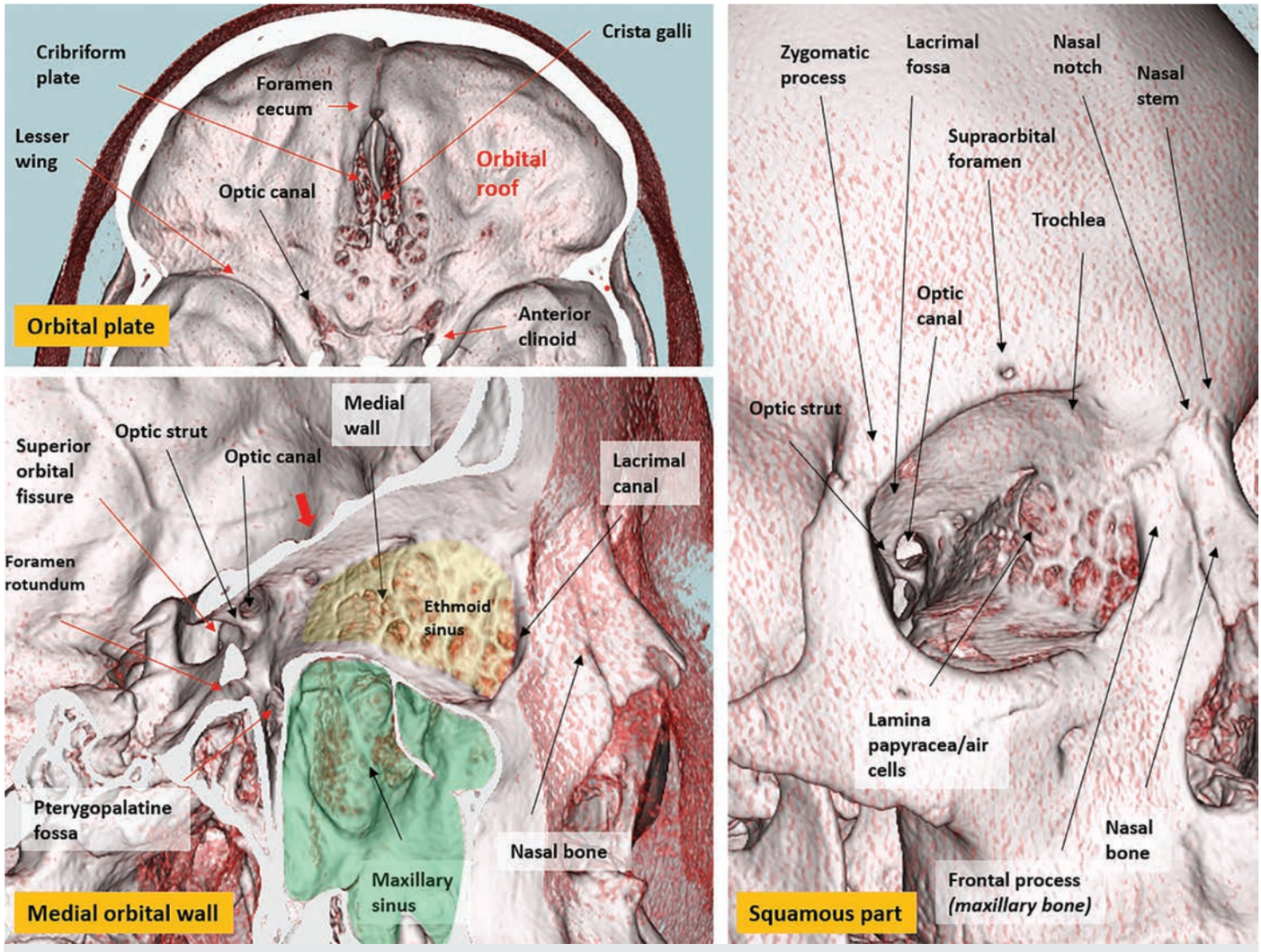


Fig. 1.10 Computed tomography (CT) images showing parts of the frontal bone. A mature frontal bone can be divided into two parts: a flat vertical squamous part and a horizontal orbital plate. The orbital plate forms a major part of the orbital roof in the anterior skull base with an undulated surface. It fuses with the lesser wing of the sphenoid posteriorly. More posteriorly, the medial wall of the orbital plate fuses with the ethmoid. The midpart of the orbital plate is the thinnest (*red arrow*), but its anterior rim (superior rim of the orbit) is strong and rarely breaks.

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Internal frontal hyperostosis is a relatively common (10%) age-related finding presenting with multiple bony projections on the inner lamina of the frontal bone on CT or radiography images (▶ Fig. 1.11). In severe cases, it extends into the dura and falx cerebri. It is more common among females after 60 years of age and is believed to be related to prolonged estrogen stimulation. Changes in African American females appear earlier in life.[4]

Parietal Bone

Each parietal bone arises from a single primary ossification center at the parietal eminence that will be fused in the fourth month. Rarely, the parietal bone ossifies from two centers. The fontanelles are seen around the parietal bone. The anterior fontanelle (fonticulus) is large, but the posterior and lateral (mastoid) fontanelles are small (▶ Fig. 1.5, ▶ Fig. 1.6). A sagittal fontanelle is rarely seen[2] (▶ Fig. 1.12). The parietal bone sutures with the frontal, the squama and mastoid portion of the temporal, the great wing of the sphenoid, and the occipital bones (▶ Fig. 1.5, ▶ Fig. 1.6). The inner surface is undulated by the cerebral convolutions and the arachnoid granulations. On the smooth outer surface, the superior and inferior temporal lines, where the temporal fascia and temporal muscle attach, may be seen on CT images (▶ Fig. 1.7).

Parietal thinning is an uncommon condition in less than 1% of skulls. It is more common in postmenopausal women with senile osteoporosis.[5] Imaging features include symmetrical thinning of the posterior parietal bones involving the outer table and diploe (▶ Fig. 1.13). The inner table is usually spared.[6]

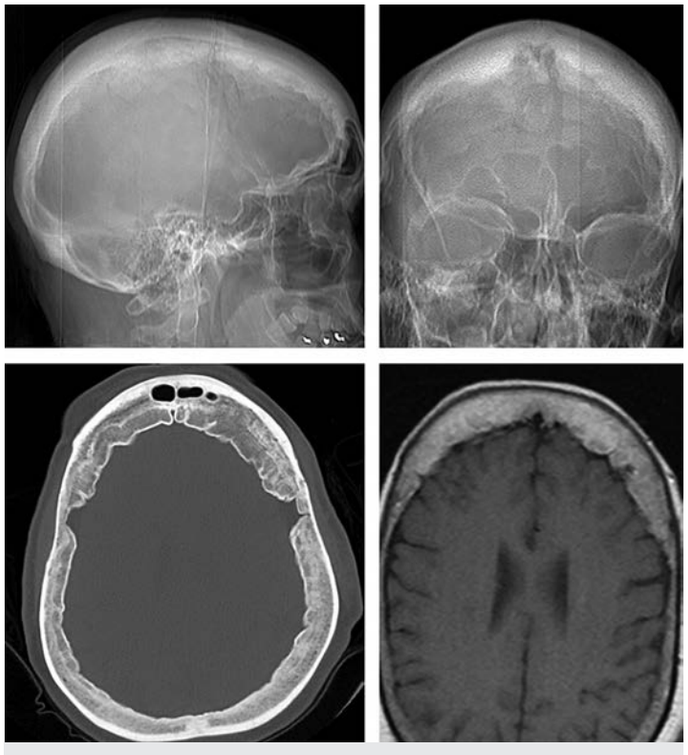


Fig. 1.11 Internal frontal hyperostosis shown by plain radiographs, and axial computed tomography (CT) and magnetic resonance imaging (MRI). This process mainly involves the inner table of the calvaria.

Parietal foramina are isolated autosomal dominant defects due to delayed or incomplete ossification of the parietal bone.[7] The calvarial defects may be large and extend to the midline. Normally, the parietal foramen, which transmits an emissary vein, is about 1 to 2 mm in diameter, located in the posterior part of the bone near the sagittal suture, and is usually present in 60 to 70% of adults (▶ Fig. 1.9).

Occipital Bone

The occipital bone consists of a squamous part (occipital squama) and a basal (basilar) part (▶ Fig. 1.5, ▶ Fig. 1.6). The occipital bone articulates with the parietal bones at the lambdoid suture superolaterally and with the mastoid part of the temporal bone at the occipitomastoid suture inferolaterally (▶ Fig. 1.5, ▶ Fig. 1.6). The outer surface of the occipital bone is marked by the nuchal lines, where muscles and ligaments attach, and the external occipital protuberance (inion) in the middle (▶ Fig. 1.7). The internal surface is marked by the grooves for the transverse and superior sagittal sinuses, which converge at the torcular Herophili, near the location of the internal occipital protuberance (▶ Fig. 1.14).

The interparietal part of the occipital squama, which ossifies intramembranously, appears in the eighth week. The rest of the occipital bone ossifies endochondrally. The basiocciput derives from the first two occipital somites.[8,9] The third occipital somite forms part of the exoccipital bone. The coalition of the caudal part of the fourth occipital somite and the cranial half of the first cervical somite produces the proatlas, which transforms into the

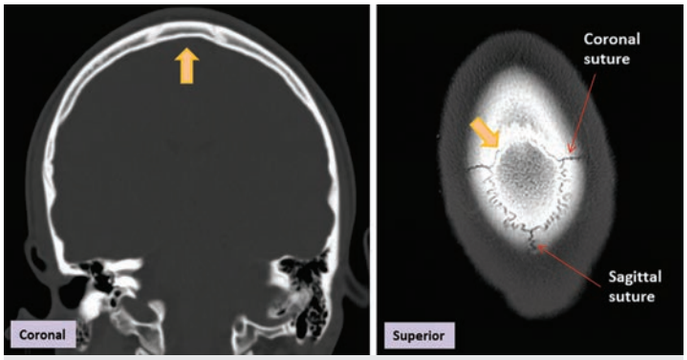


Fig. 1.12 Anterior fontanelle wormian bone (*arrow*).

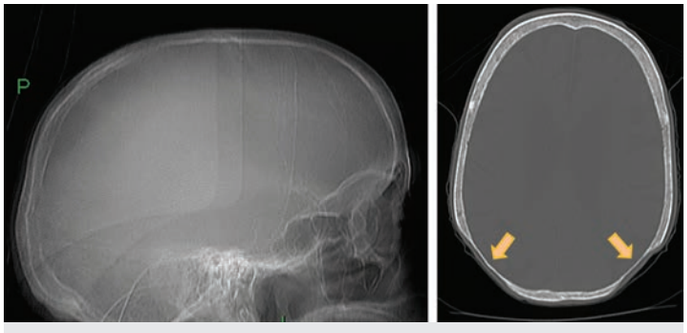


Fig. 1.13 Parietal thinning. Lateral X-ray and axial computed tomography (CT) showing symmetrical thinning of posterior parietal bones involving the outer table and diploe (*arrows*). The inner table is spared.

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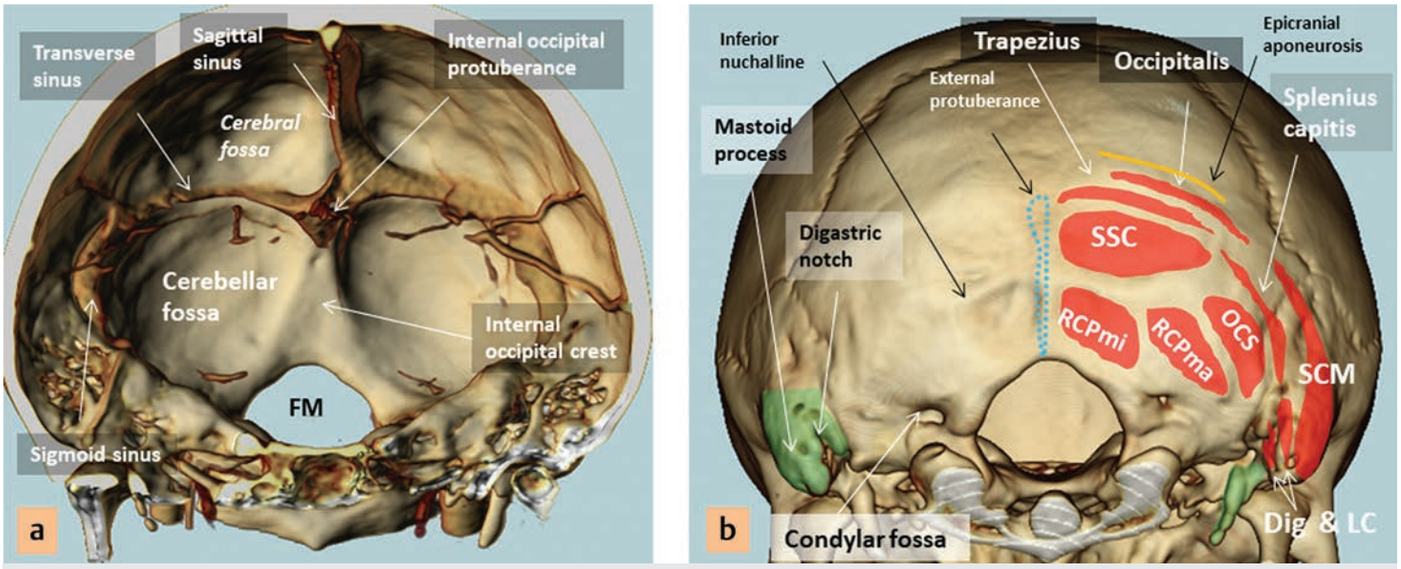


Fig. 1.14 Occipital bone. **(a)** Inner view showing the internal grooves, forming the so-called cruciform eminence. An internal occipital protuberance is located approximately at the torcular Herophili, the confluence of the transverse and superior sagittal sinuses. **(b)** Outer view. The insertion sites of the muscles to the occipital bone are shown. The epicranial aponeurosis attaches to the highest nuchal line. The trapezius, occipitalis, and splenius capitis muscles attach to the superior nuchal line and the semispinalis capitis (SSC) muscle in the depression below it. The ligamentum nuchae attaches to the external occipital protuberance and the median nuchal line. The rectus capitis posterior minor (RCPmi), rectus capitis posterior major (RCPma), and obliquus capitis superior (OCS) muscles attach to and inferior to the inferior nuchal line. Dig, digastric; FM, foramen magnum; LC, longissimus capitis; SCM, sternocleidomastoid.

basion of the basioccipital, occipital condyles, and the apical segment of the dens (see Chapter 2: Skull Base).

The basal part of the occipital bone is formed from the union of four primary cartilaginous centers around the foramen magnum including the basioccipital (clival) part anterior to the foramen magnum, two exoccipitals (condylar) at each side of the foramen, and the inferior part of the supraoccipital, which corresponds to the occipital squama below the superior nuchal line and the external protuberance (▶ Fig. 1.3).

The occipital squama consists of the supraoccipital and interparietal parts (▶ Fig. 1.6, ▶ Fig. 1.15, ▶ Fig. 1.16). The supraoccipital bone develops from both cartilage and membrane, whereas the interparietal is purely membranous. The superior part of the supraoccipital bone between the superior and highest nuchal lines, also known as the torus occipitalis transversus, is ossified in membrane from two centers that fuse in the midline by 3 months of gestation. The interparietal part of the occipital squama lying above the highest nuchal line is directly ossified from up to four membranous centers, two medial plates, and two lateral plates that coalesce to form a single interparietal bone.[8,14] Failure of fusion of these centers gives rise to various anatomical variants such as persistent mendosal suture, interparietal bone, or sutural bones[6,9,15] (▶ Fig. 1.6, ▶ Fig. 1.9, ▶ Fig. 1.16). The interparietal part connects laterally with the parietal bone at the lambdoidal suture and inferiorly with the supraoccipital part at the mendosal suture. Failure of fusion of the medial plates forms a persistent median fissure (▶ Fig. 1.17). Lateral fusion of the interparietal and supraoccipital parts starts at 34 weeks of gestation. Failure of fusion results in the formation of mendosal sutures.[8] By 14 weeks, progressive union of the supraoccipital and interparietal segments has reduced the mendosal sutures to narrow slits[9] (▶ Fig. 1.15). At birth, only the lateral part of the mendosal sutures is visible, which usually disappears by the second year.

Abnormal development of the occipital bone results in several abnormalities. Abnormal development of the cartilaginous part of the occipital squamous in Chiari I malformation results in a small lower posterior cranial fossa. Variable degrees of underdevelopment and hypoplasia of the basal occiput are seen in Chiari I malformation and several dysplastic bone syndromes that can be associated with platybasia and basilar invagination.

Temporal Bone

The temporal bone is composed of five parts: the squamous, mastoid, petrous, styloid, and tympanic parts. The squamous part forms the lateral part of the cranial vault (temple). The mastoid part is an extension of the squamous and petrous parts of the temporal bone (▶ Fig. 1.6, ▶ Fig. 1.15). All parts of the temporal bone contribute to the formation of the ear structures (see Chapter 4: Temporal Bone: Petrous Pyramid, Stylomastoid Region, and Inner Ear).

The squamous part and the tympanic ring of the temporal bone ossify intramembranously at the eighth week and the third month, respectively. The two membranous parts fuse at birth. The petrous portion of the temporal bone ossifies endochondrally.

The temporal squama ossifies from a single center that appears in its lower part and advances superiorly and anteriorly. The inferior part grows to form the zygomatic process and the postauditory process (▶ Fig. 1.7). The postauditory process fuses with the tympanic ring (▶ Fig. 1.14). This process is the border between the tympanic segment and the petromastoid segment.

The cartilaginous petrous segment begins to ossify at 16 to 17 weeks of fetal life. Ossification develops from four principal centers and advances rapidly. The ossification of the otic capsule is complete by the 23rd week.[2]

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