The Sutures of the Skull

Anatomy, Embryology, Imaging, and Surgery

Mehmet Turgut
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Chapter 1
Introduction

Mehmet Turgut, R. Shane Tubbs, Ahmet T. Turgut, and Aaron S. Dumont

1.1 Introduction

One type of fibrous joint of the body is known as a suture (Figs. 1.1 and 1.2). These irregular and quite variable articulations are limited to the skull. Early anatomists and physicians have always been fascinated with these unusual bony features, especially those of the calvaria (Figs. 1.3, 1.4, and 1.5). The sutures are separated only by the so-called sutural ligament or membrane. These unique structures of the skull have been classified based on their appearance. Serrate sutures, such as the sagittal suture, have a sawtooth pattern (Figs. 1.6 and 1.7) and typically, are not deeply placed. Deeply placed sutures, such as most lambdoid sutures, are made of many tooth-like projections with free ends that generally become wider and are referred to as denticulate sutures. Williams and Warwick [1] have pointed out that these sutures provide a more effective interlocking between the adjacent bones as compared to serrate sutures. When a bone of the skull overlaps with adjacent bone in a bevel it is called a squamous suture (Fig. 1.8). These beveled edges can be ridged or serrated and in such cases, are referred to as a limbous suture. Lastly, if contiguous

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Fig. 1.1 Beauchenne preparation of the human skull noting the articulations between many of the bones of the skull

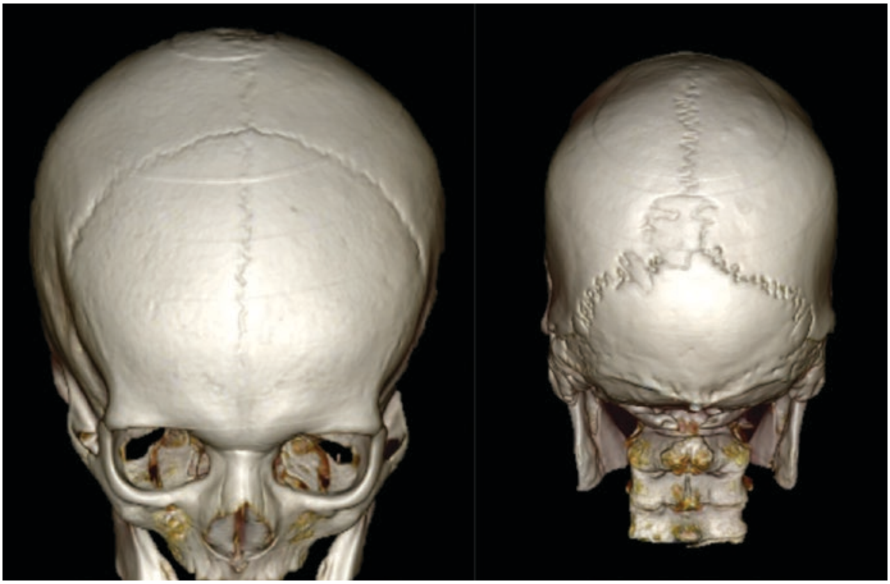

Fig. 1.2 3D reconstructed CT of the skull anterior and posterior views. The anterior view (left) illustrates the sagittal, coronal and metopic sutures. The posterior view (right) notes the sagittal suture and associated sutural bone and lambdoid sutures

surfaces have a simple apposition, they are called plane sutures and usually have an irregular or roughened edge such as the articulation between the palatine and zygomatic bones [2].

To our knowledge, this is the first text devoted entirely to the sutures of the skull. Chapters in this book cover the individual sutures e.g., those of the calvaria and skull base, embryological considerations, pathology, radiology and surgery. Our goal is to provide the reader with a comprehensive resource that can be consulted with any question related to these specialized joints of the skull.

Fig. 1.3 Drawings of the human skull illustrating the sutures of the calvaria from Johann Dryander's *Anatomia capitis humani* published in 1536

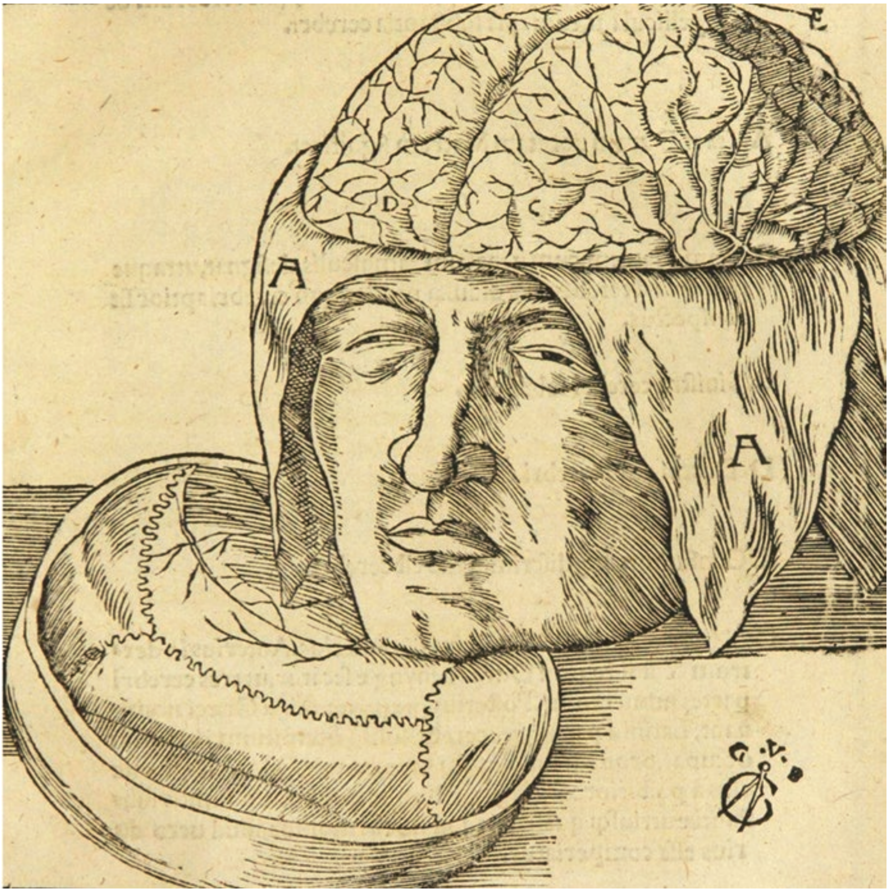

Fig. 1.4 Drawings of the human skull illustrating the sutures of the calvaria from Johann Dryander's*Anatomia capitis humani* published in 1536

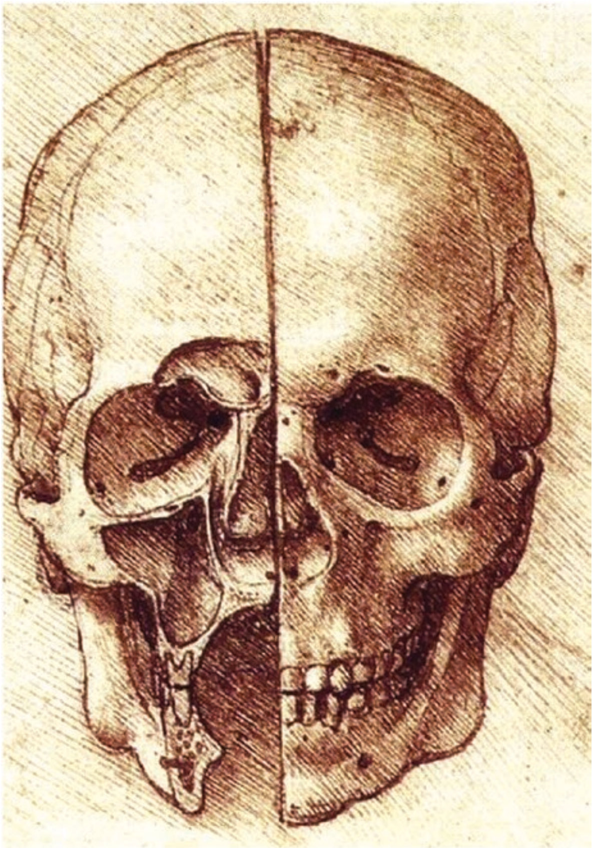

Fig.1.5 Drawing by Leonardo da Vinci (1452–1519) noting the coronal sutures

Fig. 1.6 Internal view of the right half of the sagittal suture from a disarticulated parietal bone

Fig. 1.7 External view of the right half of the sagittal suture from a disarticulated parietal bone

Fig. 1.8 External view of the right parietal part of the squamous suture from a disarticulated parietal bone

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Chapter 2
The Sutures of the Skull: A Historical Perspective

Nikolaos Ch. Syrmos, Vaitsa Giannouli, and Mehmet Turgut

2.1 Introduction

Skull sutures are essential anatomical and morphological elements of human skull structure. Moreover, they are important anthropologically for elucidating the evolution of mankind. They directly affect the growth of the human cranium and also specific brain development, but in addition they are relevant the evolution of the human central nervous system. The purpose of this study is to identify the most important historical perspectives on studies of the skull sutures [1–5].

2.2 Homer and Mythological Era

Hellenic Homer (Όμηρος) was the legendary author of the Odyssey (Οδύσσεια), the journey of Odysseus (Όδυσσέας) from Troy to his homeland Ithaca. He was also the author of another epic masterpiece, the Iliad (Ιλιάδα), the first documented civil war in human history, between two Hellenic populations (same language, same gods, same customs): Acheans (Αχαιοί) and Trojans (Τρώες). In his descriptions of war-related skull and cranial traumas in the Iliad, there is also a detailed mention of cranial sutures, providing evidence of the medical and anatomical knowledge of that time [1–7].

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2.3 Hellenic Hippocrates Era

Hellenic Hippocrates (Ιπποκράτης) of Kos (Κώς) (460–370 BCE), the first documented medical doctor and neurosurgeon in human history, together with his students, gave a detailed description of in skull and cranium anatomy in his marvelous books (Fig. 2.1) [4–9]. In particular, his work On Head Wounds (Περί των εν κεφαλή τραυμάτων), which has a total of 21 chapters, presents much information about elements of both craniology (Κρανιολογία) and cranial morphology (Μορφολογία). This book distinguishes various skull sutures types [5–11]:

- Back prominence type,
- T-type,
- H-type,
- X-type etc.

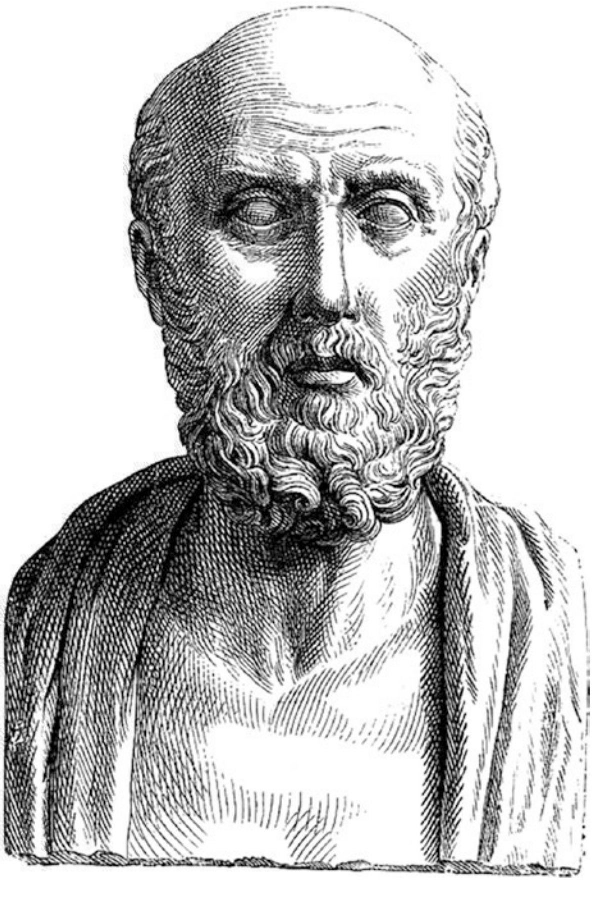

Fig. 2.1 Hippocrates (460–370 BCE)

His descriptive details of the thinner skull in the bregmatic cranial area are particularly interesting as evidence for the vulnerability of this part of the human body. All other areas of the skull are also discussed, in particularly the temporal region, the second thinnest part. He mentions its morphology; regarding its function, he notes it as the area where seizures develop. In addition he gives a detailed macroscopic view of structure and texture [6, 7, 12–15]. He also makes the first statement in history regarding skull and cranial anatomy in relation to anthropology: "*The heads of men are not all alike, nor are the cranial sutures arranged the same in all*". This statement is still valuable within the range of anthropology-related sciences [12–17].

The impact of Hippocrates on the ancient Hellenic world is reflected in many other neurosurgical operations and anatomical considerations within that world [14–19].

2.4 Other Ancient Hellenic Studies

Another important Hellenic (Asia Minor) physician, Herodotus (Ηρόδοτος) Halicarnassus (Αλλικαρνασσός), who lived between 484 and 425 BCE, managed to perform a study comparing skulls from Egypt and Persia (Fig. 2.2) [6–12]. He conducted an interesting experiment using stone impacts to verify the resistance of various cranial parts, observing the damage caused. Because the Egyptians used caps, their skulls were thicker than Persian ones on account of a physical compensatory mechanism [6–11, 13].

He wrote various books such as Histories (Ιστορίες), which dealt with the Persian Wars (Περσικοί Πόλεμοι), the attempts of the Persian Empire to conquer the separate Hellenic cities-states (Πόλεις-Κράτη). In particular, after the famous battle of Platea (Μάχη των Πλατεών) in central Greece, 479 BCE, where a Hellenic army lead by Pausanias managed to destroy the Persians under General Mardonius, he describes a skull with not a single suture, made by a unique type of bone [6–11, 14].

Aristotle (Αριστοτέλης), 384–322 BCE, was a Hellenic philosopher and polymath during the Classical period in Ancient Greece. He was born is Stagira, Macedonia. He was the teacher of Alexander the Great, 356–323 BCE, during the reign of his father, Phillip II of Macedonia. He was the first to mention the anatomical and skull differences between males and females [6–11, 15].

Galen of Pergamon (Πέργαμος) lived between 130 and 200 CE in the same geographical area as Herodotus, though later. Galen made the first attempt to categorize the clinical and pathological significance of morphological and cranial suture differences. He introduces the concept of craniosynostosis (Κρανιοσυνόστοση ή Κρανιοσυνοστέωση) for the first time by coining the term "oxicephaly" (Οξυκεφαλία). In his work De iuvamentis memborum, he clearly describes the cranial commissures (Fig. 2.3) [6–11, 16].

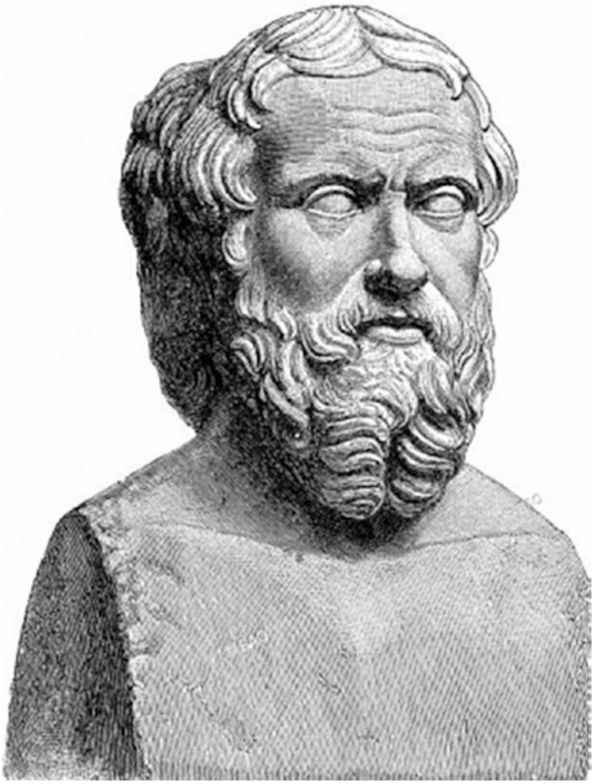

Fig. 2.2 Herodotus (484–425 BCE)

It is important to note that the Hellenic language and its spread, thanks to the conquests of Alexander the Great, gave rise to a great deal of terminology that has been used to the present day. The Latin-Italian terms that succeeded are also very descriptive and important for accuracy in anthropological and morphological studies [6–11, 17].

2.5 American-African and Mediorient Ancient Studies

Major civilizations also developed in other parts of the world: Central and Latin America, the North African and Mediterranean Area, and the Middle East (Maya, Incas, Aztecs, Zapotec, Minoans, Egyptians, Babylonians, Sumerians, Assyrians, Hittites, Persians, Jewish-Israelis, etc.) [6–12, 18]. They too developed knowledge of cranial sutures through the centuries, as revealed by various studies but mainly by paintings and other archeological findings, mainly to help them perform cranial

Fig. 2.3 Galen (130–200 CE)

neurosurgical procedures and also procedures related to religious acts, sacrifices etc. [1–5].

2.6 Arabic World

In his work Canon (Κανόνας), Avicenna, who lived between 980 and 1037 CE, describes the coronal suture for the first time, as "*An arc in whose center a perpendicular line has been set up*". He also studied the sagittal suture as "*The suture that divides the skull into two halves*". Avicenna identified the lambdoid suture as having

Fig. 2.4 Avicenna (980–1037 CE)

a form similar to the Greek letter Λ (Λάμδα) (Fig. 2.4) [6–11]. The Arabs also developed knowledge of anatomy and anthropology [1–5].

2.7 Medieval Times

During the medieval period, a great wave of knowledge spread over the whole European continent, especially in central countries such as Italy, France, Belgium, and Germany. All the sciences during this era were very active and at the same time educational for the European population. Many medical schools (such as Montpellier-France, Padova-Italy, and Bologna-Italy) were productive in the fields of human anatomy and physiology [6–11].

Medical literature, in combination with the anatomical dissections of that time, was invaluable for physicians studying the cranial sutures and achieving a better understanding of human morphology and function [6–11].

William of Saliceto (1210–1277) and his student Lanfranc of Milan (1250–1306) adopted the terms used by Avicenna to name the cranial bones and the skull sutures [6–11].

The Italian Mondino De Luizzi (1270–1326), from Bologna, Emilia Romagna, known as Mundinus, an innovative and provocative physician and anatomist, was also an innovative medical illustrator. He produced three-dimensional econographic studies of the skull (lateral, superior, posterior), pioneering work of its kind, and verified the locations of the cranial sutures exactly (Fig. 2.5) [6–11].

In France, Henri de Mondeville (1260–1320) and his student, Guy de Chauliac (1300–1368), proposed the cranial sutures as essential landmarks for performing accurate anatomical dissections. In Paris they studied thousands of skulls and they discussed the differences between males and females according to classical Aristotelian ideas and beliefs [6–11].

Leonardo da Vinci (1452–1519), the phenomenal scientist and artist, produced important and detailed descriptions of the skull sutures [6–11].

Berengario da Capri (1460–1530), another important anatomist and surgeon, noted for the first time that adhesion of the dura mater underlying the sutures of the cranium causes them not to be stronger than other areas [6–11].

Johann Dryander, a German physician, artist, scientist and anatomist from Marburg, lived between 1500 and 1560. He published an important 12-volume work, Anatomia Capitis Umani, with anatomical figures, in which he suggested that the frontal suture persists less in men than women [6–11].

Fig. 2.5 Mondino De Luizzi (1270–1326)

In Central Europe, Andreas Vessalius (1514–1564), a Flemish anatomist and physician, decided to follow Galen theory and attempt to reconcile morphology with function. He wrote the detailed masterpiece of his era, De humani corporis fabrica, to explain human body morphology thoroughly and show how it underpinned physiological functions (Fig. 2.6) [6–11, 18]. He attempted, not always with absolute success, to establish the most probable combinations among missing structures and relate them to cranial deformations. His most important contributions were his various graphical representations such as [6–11, 18]:

- Normal skull, normal sutures,
- Absence of coronal suture without causing bracycephaly (Βραχυκεφαλία),
- Absence of lambdoid suture without causing plagiocephaly (Πλαγιοκεφαλία),
- Replacement of both lambdoid and coronal sutures by a latero-lateral suture in turricephaly (Πυργοκεφαλία) cases,
- Sagittal suture missing, but no scaphocephalic (Σκαφοκεφαλία) shape.

He used his studies to relate such anatomical variations to normal or pathological function [6–11, 18].

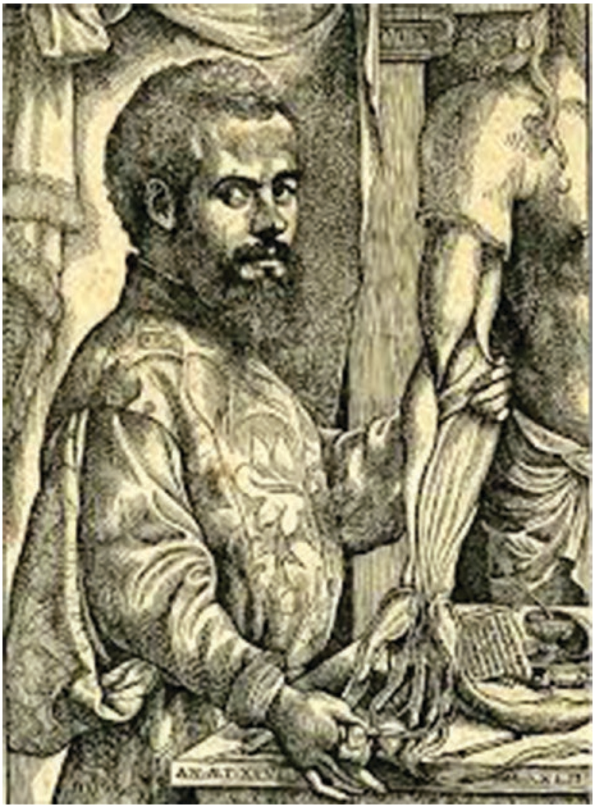

Fig. 2.6 Andreas Vesalius (1514–1564)

2.8 Nineteenth Century

Rudolph Virhow (1821–1902) was an outstanding scientist of his era. He was simultaneously physician, anatomist, pathologist and biologist despite having other duties such as politician, editor, writer and historian. He and the anatomist Adolph Otto (1786–1845) indicated the sutures as the main cause of craniosynostosis (Fig. 2.7) [10–13].

Odilon Marc Lanellongue, a French surgeon from Castera Verduzan, who lived between 1840 and 1911, was the first to describe performing a linear craniotomy for an operation mainly to preserve normal human brain growth [6–11]. Many surgeons of that time believed strongly in craniectomy as the appropriate treatment for craniosynostosis and other malformations related to the skull sutures. They had poor results and there were many early and late complications. Later, they changed their treatments to achieve better results and to optimize patient quality of life [6–11].

The medical illustrations together with the anatomical cadaveric procedures of this time greatly helped physicians to study the cranial sutures [6–11].

Fig. 2.7 Rudolph Virchow (1821–1902)

2.9 Modern Era

At the beginning of the twentieth century, neurosurgery became an autonomous medical and surgical discipline mainly thanks to the pioneering efforts of Harvey Cushing (1869–1939), the first modern neurosurgeon, and Walter Dandy (1886–1946), the first modern pediatric neurosurgeon, but also of other neurosurgeons all over the world [1–4, 6–11]. This first generation of pure neurosurgeons spent a lot of time studying the cranial sutures to improve surgeries for their patients. The introduction first of X-rays, and later of neuroimaging (CT and MRI), and nowadays of three dimensional (3D) imaging, were very important steps in improving the study of cranial sutures [13–17].

The development of other medical disciplines related to neurosurgery, such as neurology, pediatic neurology, neuroradiology, radiology, etc. were also a great help in improving understanding of the functions of the human cranial sutures. The development of pediatric neurosurgery by Antony J. Raimondi (1928–2000) during the 1970s as a subspecialism of adult neurosurgery was also a very important step [13–17].

The establishment of the European Society of Pediatric Neurosurgery (ESPN) and the International Society of Pediatric Neurosurgery (ISPN), together with the European Association of Neurosurgical Societies (EANS) and the World Federation of Neurosurgical Societies (WFNS), facilitates dialogue and knowledge growth among young neurosurgeons through courses and congresses. Neurosurgeons and pediatric neurosurgeons all over the world, such as Concezio Di Rocco (July 16, 1944) (Fig. 2.8), James T. Goodrich (1946–2020) and others,

Fig. 2.8 Concezio Di Rocco (July 16, 1944)

perform both classical and innovative techniques (endoscopic and others) to manage and treat craniosynostosis appropriately and effectively [13–17].

Nowadays, we also have 3D computer technology for performing accurate anatomical studies and also genetic insights into the development of the sutures, invlauable for predicting malformations from prenatal evidence and perhaps correcting them.

2.10 Conclusion

Through this historical study we infer the importance over the centuries of studies of cranial-skull sutures for improving understanding of the development and the anthropological and functional evolution of humankind. Furthermore, the same types of anatomical and morphological studies have helped greatly in establishing neurosurgery as a distinct medical discipline with useful approaches from related medical specialties and with the appropriate medical technology and upcoming new facilities.

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Chapter 3
Embryological and Histological Features of the Cranial Sutures

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3.1 Introduction

3.1.1 An overview of the Embryonic Development of the Skeletal System and Skull

The skeletal system develops in the embryo, originating from the neural crest and paraxial and lateral plaque parts of the mesoderm. From the paraxial mesoderm, tissue clusters develop as segments around the neural tube, known as somitomers in the head region and somites in the occipital region. The ventromedial parts of the somites form sclerotome and the dorsolateral parts form the dermomyotome. The sclerotome consists of mesenchyme, a loosely arranged tissue containing cells of different types. Mesenchymal cells can transform into fibroblasts, chondroblasts, or osteoblasts, with their various migration and differentiation capabilities. The parietal layer of the lateral plaque mesoderm also can form bone, not just sclerotome cells. In the lateral plate mesoderm, the bone parts of the extremities, the sternum, pelvis and shoulder arise in this layer, while cranial neural crest cells (CNC) turn

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into mesenchyme, forming the bones of the face and skull. Somitomeres and occipital somites are also involved in forming the base of the skull. While most body bones are formed from cartilage originating from mesenchymal tissue (endochondral ossification), most of the skull bones are formed by direct differentiation of mesenchymal tissue (intramembranous ossification).

The skeletal structures of the skull develop from the embryonic mesoderm and the CNC, which originate from the neuroepithelium of the neural folds. CNC cells undergo epithelial-mesenchymal transition and migrate from their area of origin to the craniofacial regions [1]. CNC and mesodermal cells are highly plastic. Osteoblasts developed from CNC or mesoderm are functionally indistinguishable from each other. The functions of these cells can be shaped by inductive signals from the niche. Therefore, the niche including osteoblasts is more important than the niche of the CNC and mesenchymal cells. However, when the formation, migration, or proliferation of CNC cells is abnormal, the origin of the cells becomes important [2].

3.1.2 An Overview of Ossification in the Skull Bones

There are two types of bone formation in the head: endochondral and intramembranous ossification. Endochondral bone is formed from a hyaline cartilage precursor while intramembranous bone is formed by direct differentiation of mesenchymal cells to osteoblasts. Most of the skull bones are formed by intramembranous ossification. The subset of skull bones that supports the nasal sinuses, oral cavity, and pharynx and forms the face is called the '*viscerocranium*', and the part surrounding the brain is called the '*neurocranium*'. The neurocranium also consists of two parts; the base of the skull and the calvaria (skull vault). The bones of the skull base are formed by endochondral ossification and the cartilaginous joints between them are called synchondroses. The calvaria and facial bones are formed by intramembranous ossification [1, 3].

The bones of the skull consists of two parts: viscerocranial and neurocranial. The viscerocranial bones are of neural crest origin and are called facial bones. They originate from the first and second pharyngeal arches. The dorsal parts of the first arc-originated structures are responsible for forming part of the maxilla, zygomatic bone and temporal bone. The ventral parts contain Meckel's cartilage and ossify with the mesenchyme around it to form the mandible. The ear bones, malleus, incus and stapes, also originate from the dorsal end of the mandibular protrusion and the second pharyngeal arch, which ossifies during the fourth month, making them the first bones to ossify completely. The neurocranium can be examined in two parts: the membranous part forming the bones surrounding the brain, and the cartilaginous part forming the skull base.

The membranous part originating from the CNC and paraxial mesoderm ossifies and surrounds the brain. The needle-like bone spicules that it contains spread from the ossification centers to the surroundings. During this process, which continues after birth, new layers are formed in the outer parts. These flat bones in the skull are separated from each other by limited connections consisting of connective tissue, called sutures. The origins of these connections differ; whereas the sagittal suture is of neural crest origin, the coronal suture is of paraxial mesoderm origin. Also, if the junction parts belong to more than two bones, they are found more broadly and are called fontanelles. The cartilaginous part of the skull ossifies endochondrally [4–6].

3.2 Development of Sutures

An adult has eight bones in her skull: one frontal, two parietal, two temporal, one ethmoid, one sphenoid, and one occipital. The numbers of these bones vary because of the ossification processes during development. Their borders make contact with each other by surfaces of fibrous tissue known as skull sutures, which differentiate from embryonic mesenchyme [7].

Intramembranous ossification begins from a center within vascularized mesenchyme or embryonic connective tissue and spreads to form the bone (Fig. 3.1). Thus, intramembranous ossification areas are formed. As ossification progresses, the bone areas come closer to each other, then sutures develop between them [6].

The sutures are not only joints between bones. They are also osteogenesis regions where osteoprogenitors proliferate, differentiate, and function on the bone margins. During the formation of a cranial suture, the osteogenic edges of the two bones involved, the mesenchymal tissue of the suture, the inner surface in contact with dura mater and the outer side in contact with pericranium, work together (Fig. 3.2b) [8]. These tissues of the suture complex interact to ensure proper formation of the suture or aperture throughout development. The cells in the middle of the mesenchymal tissue of the suture do not differentiate during bone formation, but those at the two osteogenic bone edges initiate intramembranous ossification and differentiate to osteoblasts. In order for the brain to continue growing in the skull cavity, the middle of this center must remain unossified, and the sutures forming between apposed bone edges must allow osteogenesis to continue with osteoblast formation.

Skull sutures are formed either by the direct joining or the overlapping of adjacent bones [7]. The sutures are usually of intramembranous ossification origin. However, the frontoethmoidal suture is formed by a combination of intramembranous and endochondral ossification [1].

The sutures and fontanelles have some degree of flexibility, as evidenced by the compression of the skull during birth. For structural and protective reasons, the sutures lose this limited mobility and become more rigid. This is accomplished by interlocking of the apposed bone margins and fusion along the suture.

In the human skull, the sutures are named metopic (between the frontal bones), sagittal (between the parietal bones), coronal (between the frontal and parietal bones), lambdoid (between the supraoccipital and parietal bones), and squamosal (between the parietal, temporal, and sphenoid bones) (Figs. 3.2, 3.3, and 3.4). Suture formation begins as these calvarial bones approach each other.

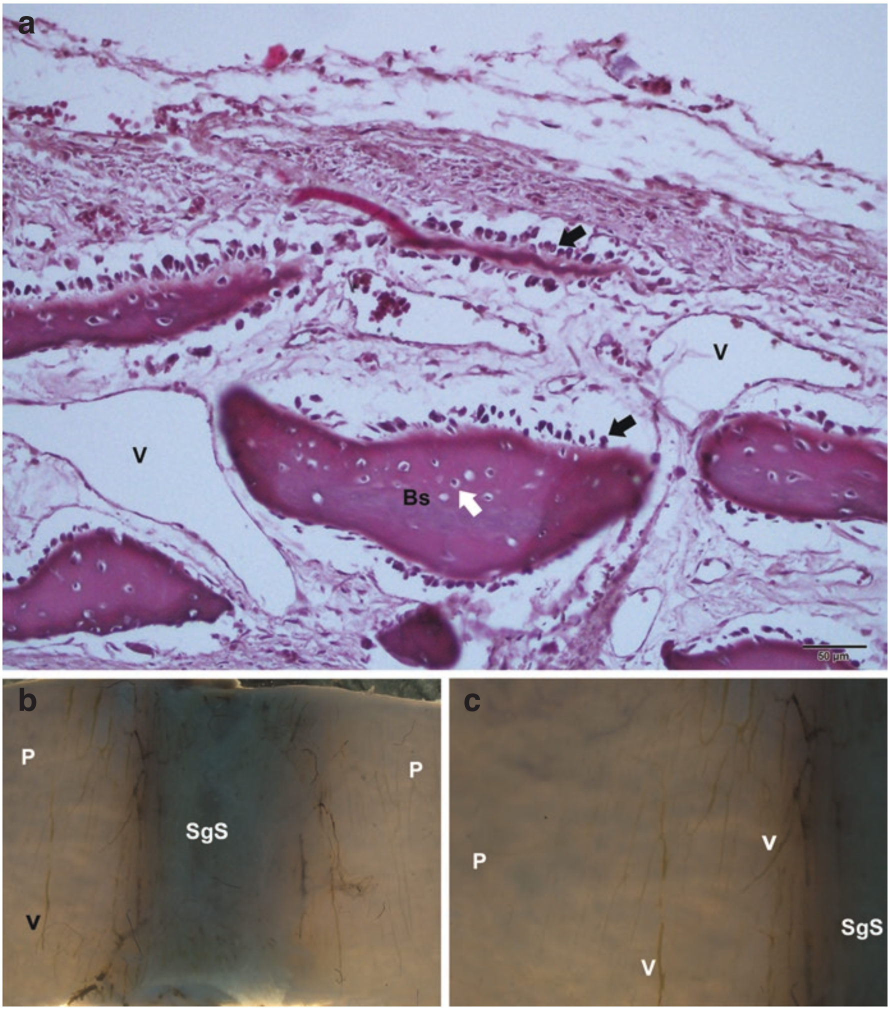

Fig. 3.1 Ossification of parietal bone in a 3.5-month fetus. (**a**) Histological view and (**b** and **c**) translumination stereomicroscopic view (Olympus SZ61, Olympus SC50, Japan) before histological sampling. Vessels in the bone tissue are seen extending radially from the ossification centers. (With permission of Ege University Faculty of Medicine Department of Anatomy). Abbreviations: Black arrow: Osteoblasts, Bs: Bone spicules, P: Parietal bone, SgS: Superior sagittal sinus, V: Vessel, White arrow: Osteocytes

During fetal life, the flat bones of the calvaria are separated by dense connective tissue membranes that form fibrous joints, calvaria sutures, and six large fibrous areas (fontanelles) where several sutures come together. The softness of the bones and the loose connections formed by the sutures allow the calvaria to change shape during childbirth. In areas where three or more bones come together in the calvaria, the sutures expand and become fontanelles. Fontanelles are larger than sutures

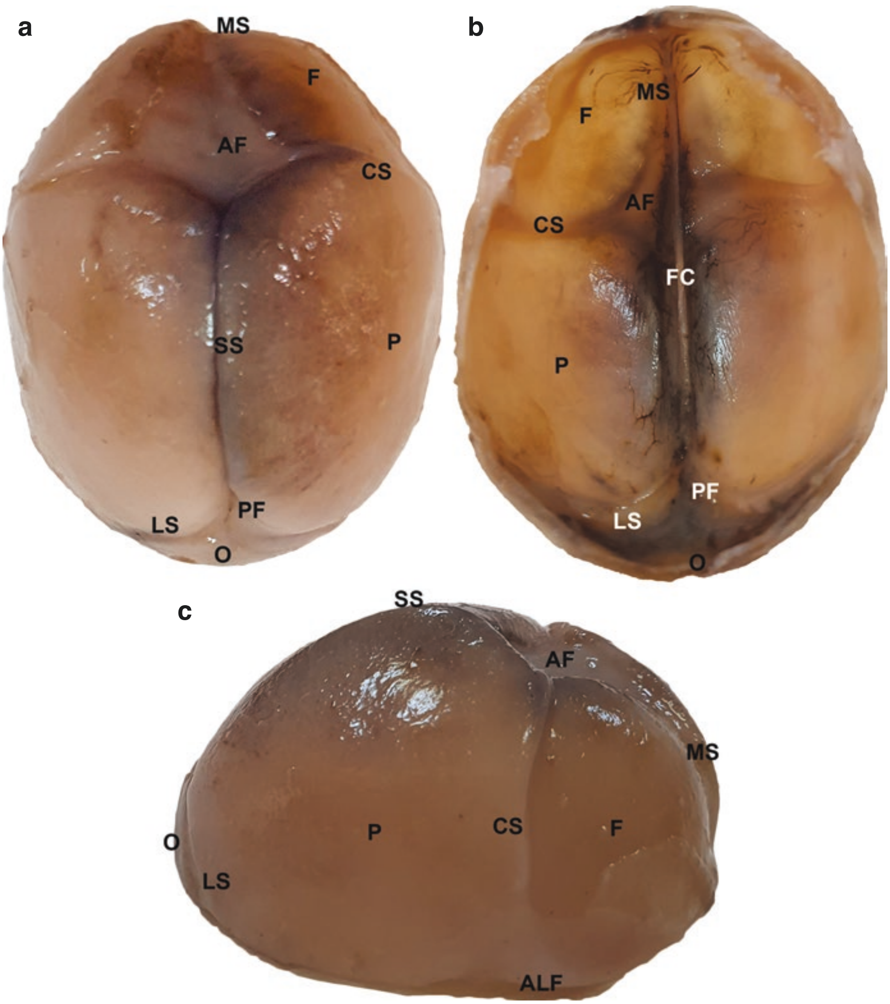

Fig. 3.2 The calvaria of a 3.5-month fetus. (**a**) Superior view of the calvaria after the scalp is removed. (**b**) Inferior view of the calvaria covered with cranial dura mater. (**c**) Lateral view of the calvaria. (With permission of Ege University Faculty of Medicine Department of Anatomy). Abbreviations: AF: Anterior fontanelle, ALF: Anterolateral fontanelle, CS: Coronal suture, F: Frontal bone, FC: Falx cerebri of cranial dura mater, LS: Lambdoid suture, MS: Metopic suture, O: Occipital bone, intraparietal part, P: Parietal bone, PF: Posterior fontanelle, SS: Sagittal suture

during birth, but the calvarial bones continue to grow postnatally and the fontanelles quickly shrink. Sutures and fontanelles are robust structures. They are flexible during birth to allow the calvaria to be temporarily compressed [1]. The fontanelles in a developing fetus are anterior, posterior, anterolateral and posterolateral.

Anterior fontanelle: The anterior fontanelle is also called the fonticulus major. It measures approximately 4 cm in the anteroposterior and 2.5 cm in the transverse

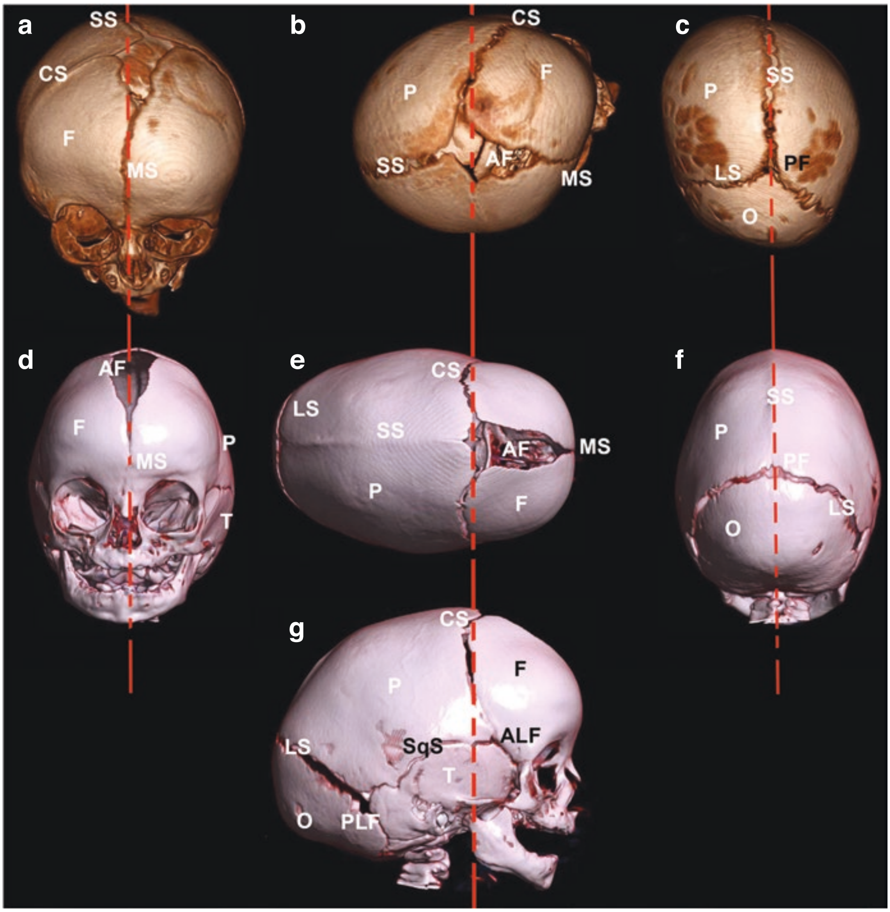

Fig. 3.3 CT 3D reconstructions of newborns with cranial suture and ossification anomalies. (**a**–**c**) Premature closure of right part of the coronal suture in 6-month-old child. (**d**–**g**) Premature closure sagittal suture in 4-month-old child. (Courtesy of Dr. Saim Kazan). Abbreviations: AF: Anterior fontanelle, ALF: Anterolateral fontanelle, CS: Coronal suture, F: Frontal bone, FC: Falx cerebri of cranial dura mater, LS: Lambdoid suture, MS: Metopic suture, O: Occipital bone, P: Parietal bone, PF: Posterior fontanelle, PLF: Posterolateral fontanelle, Red lines: Orientation lines for sutures, SqS: Squamous suture, SS: Sagittal suture, T: Temporal bone

dimension. This diamond-shaped, membrane-filled space is located between the anterior end of the sagittal suture and the frontal bone in the developing fetus. Its location is also the intersection of the metopic, coronal, and sagittal sutures. The anterior fontanelle, which initially has a membranous structure, usually fuses by the age of 18 months. Examination of it, where two parietal and two frontal bones come together, provides useful information about whether ossification is proceeding normally [1]. After the anterior fontanel closes, the sagittal and coronal sutures join at the same point. This junction point is called the bregma (Figs. 3.2, 3.3, and 3.4).