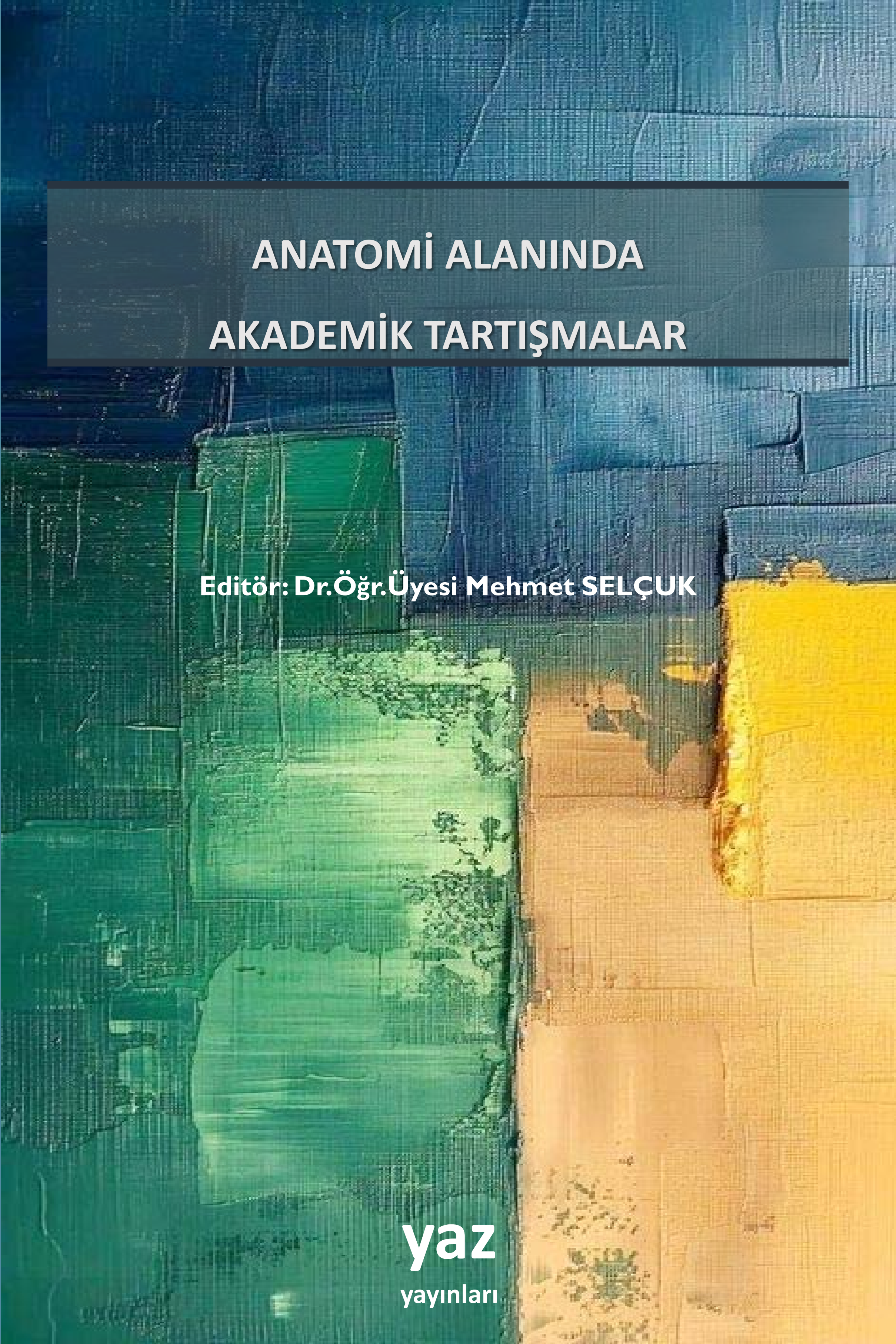

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Editör: Dr.Öğr.Üyesi Mehmet SELÇUK

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www.yazyayinlari.com

yazyayinlari@gmail.com

İÇİNDEKİLER

DEVELOPMENTAL, MORPHOLOGICAL AND CLINICAL ANATOMY OF THE TEMPORAL BONE

Ömer Can KIZILAY[1]

1. INTRODUCTION

The temporal bone is one of the most complex bones of the human skull because it contributes simultaneously to the cranial vault, the cranial base, the external acoustic region, the middle ear, the inner ear, and the temporomandibular joint. It forms part of the lateral wall and base of the cranium and participates in the boundaries of the middle and posterior cranial fossae. Unlike many cranial bones that can be described mainly in terms of external morphology, the temporal bone must be understood as a three dimensional anatomical region containing sensory organs, neurovascular canals, air cell systems, and surgically important landmarks. This complexity explains why the temporal bone is of central importance not only in gross anatomy, but also in otology, neurotology, radiology, neurosurgery, maxillofacial surgery, and skull base surgery (Isaacson, 2018; Juliano, Ginat & Moonis, 2013).

Classically, the temporal bone is described in relation to its squamous, petrous, tympanic, mastoid, and styloid components. These parts differ not only in morphology and anatomical relationships, but also in their developmental origins and clinical relevance. During prenatal development, the temporal bone is composed of five main parts: squamous, styloid,

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[1] MD, Assistant Professor, Department of Anatomy, Faculty of Medicine, Kütahya Health Sciences University, ORCID: 0000-0002-3526-858X.

mastoid, tympanic, and petrous. The squamous part and a portion of the mastoid region are associated primarily with intramembranous ossification, whereas the petrous and mastoid components related to the cranial base develop largely through endochondral ossification. This mixed developmental pattern contributes to the complex architecture of the mature temporal bone and has implications for congenital anomalies, fetal imaging, and the interpretation of developmental defects involving the external, middle, or inner ear (Grzonkowska, Baumgart, Kułakowski & Szpinda, 2023).

From a morphological perspective, the temporal bone provides protection for the organs of hearing and balance, including the cochlea, vestibule, and semicircular canals. It also contains or transmits several important structures, such as the facial nerve, vestibulocochlear nerve, internal carotid artery, sigmoid sinus, jugular bulb, chorda tympani, greater petrosal nerve, and tympanic branch of the glossopharyngeal nerve. Therefore, small anatomical variations or pathological changes within this bone may produce clinically significant symptoms, including conductive or sensorineural hearing loss, vertigo, tinnitus, facial nerve paralysis, otalgia, cerebrospinal fluid leakage, or vascular complications. For this reason, the temporal bone is frequently evaluated with high resolution computed tomography and magnetic resonance imaging in inflammatory, traumatic, congenital, vascular, and neoplastic conditions (Juliano et al., 2013).

The clinical anatomy of the temporal bone is particularly important because many of its structures are arranged in close proximity within a relatively small osseous space. The mastoid air cell system communicates with the middle ear cavity through the aditus ad antrum, making the mastoid region relevant in acute mastoiditis, chronic otitis media, and cholesteatoma. Mastoidectomy, one of the fundamental procedures in otologic surgery, requires detailed knowledge of the mastoid cortex, mastoid antrum, tegmen, sigmoid sinus, lateral semicircular canal, facial canal, and posterior wall of the external acoustic meatus. The variability of mastoid pneumatization further increases the importance of individualized anatomical evaluation before and during surgery (Kennedy & Lin, 2023).

Traumatic lesions of the temporal bone also demonstrate the clinical importance of its anatomy. Temporal bone fractures may involve the external acoustic canal, middle ear, otic capsule, facial canal, carotid canal, or jugular foramen. Depending on the fracture pattern and the structures involved, patients may present with hearing loss, vertigo, facial nerve dysfunction, cerebrospinal fluid otorrhea, vascular injury, or intracranial complications (Johnson, Semaan & Megerian, 2008). Thus, the temporal bone is not merely a passive skeletal element of the skull, but a clinically active anatomical region in which osseous, neural, vascular, and sensory structures are functionally integrated.

The aim of this chapter is to present the temporal bone from developmental, morphological, and clinical perspectives. First, the embryological development and ossification pattern of the temporal bone will be summarized. Then, its major anatomical parts and surface landmarks will be described. Particular attention will be given to the canals, foramina, neurovascular relationships, and air cell systems that make the temporal bone clinically significant. Finally, selected pathological and surgical correlations, including temporal bone fractures, otitis media, mastoiditis, cholesteatoma, mastoidectomy, temporomandibular joint relations, and Eagle syndrome, will be discussed in relation to anatomical landmarks. In this way, the chapter aims to integrate classical anatomical knowledge with clinically relevant interpretation.

2. EMBRYOLOGICAL DEVELOPMENT OF THE TEMPORAL BONE

The temporal bone is not a single developmental unit, but a composite cranial bone formed by the integration of squamous, petrous, tympanic, mastoid, and styloid components. This developmental complexity explains why congenital anomalies of the temporal bone may involve the external ear, middle ear, ossicles, facial nerve canal, otic capsule, mastoid air cell system, or inner ear structures in different combinations. From an anatomical perspective, embryological development is therefore important not only for understanding the mature morphology of the temporal bone, but also for interpreting congenital hearing loss, external auditory canal atresia, ossicular malformations, facial nerve variations, inner ear anomalies, and differences in mastoid pneumatization (Nada, Agunbiade, Whitehead, Cousins, Ahsan & Mahdi, 2021).

The squamous part of the temporal bone develops primarily by intramembranous ossification and contributes to the lateral cranial wall, the temporal fossa, and the root of the zygomatic process. Its early ossification is important for the formation of the lateral skull contour and for the relationship of the temporal region to the developing cranial vault. Fetal morphometric data show progressive growth of the primary ossification center of the squamous part during prenatal life, emphasizing its role in cranial vault development (Grzonkowska, Baumgart, Kułakowski & Szpinda, 2023). If development of this region is deficient or altered, the resulting morphology may contribute to cranial wall defects, abnormal contour of the temporal region, or altered relationships around the temporal fossa and zygomatic arch. Although isolated squamous developmental defects are less frequently discussed than ear canal or inner ear anomalies, the squamous part remains important as the superficial cranial component of the temporal bone.

The petrous part develops in close relationship with the otic capsule and is mainly associated with endochondral ossification. The otic placode appears during the fourth week and gives rise to the otic pit and otocyst. The otocyst subsequently differentiates into the membranous labyrinth, including the cochlear duct, vestibular structures, and semicircular canals. The cartilaginous otic capsule forms around these structures and later ossifies, creating the dense petrous portion that protects the inner ear. Nada et al. (2021) reported that the otic capsule ossifies between the 15th and 23rd weeks, while the major membranous labyrinth structures reach near adult configuration relatively early in fetal life. Developmental arrest or abnormal differentiation in this region may result in inner ear malformations such as labyrinthine aplasia, cochlear aplasia or hypoplasia, common cavity malformation, incomplete partition anomalies, semicircular canal dysplasia, or internal auditory canal hypoplasia. Clinically, these anomalies are commonly associated with sensorineural or mixed hearing loss and may affect cochlear implantation planning.

The tympanic part is closely related to the formation of the external acoustic meatus and tympanic membrane. The cartilaginous portion of the external auditory canal develops from the first pharyngeal groove and pouch between the fourth and eighth weeks, while the bony portion develops from the canalized meatal plug. Except for the tympanic ring, ossification is largely completed by approximately two years of age, and the external auditory canal approaches adult size around nine years of age (Nada et al., 2021). Incomplete development of this region may result in congenital external auditory canal stenosis or atresia. Such defects may be membranous or bony and may coexist with auricular deformity, ossicular hypoplasia or aplasia, abnormal facial nerve course, oval or round window anomalies, and mastoid abnormalities. Therefore, developmental failure of the tympanic component has direct clinical relevance for conductive hearing loss and surgical planning in congenital aural atresia.

The mastoid part has a particularly important postnatal developmental pattern. The mastoid antrum forms during fetal life, whereas pneumatization begins later and continues after birth. Nada et al. (2021) stated that the mastoid antrum forms around the 18th week, pneumatization begins around the 34th week, most mastoid air cells develop by approximately two years of age, and the mastoid process becomes evident after birth. However, the final extent of mastoid pneumatization varies considerably among individuals. A recent scoping review also emphasized that mastoid air cell size changes with age and that growth of the mastoid air cell system may continue beyond puberty, depending on the method of measurement and population characteristics (Aladeyelu et al., 2022). Reduced or abnormal mastoid pneumatization may influence the spread of middle ear infection, the radiological appearance of the mastoid region, and the surgical anatomy encountered during mastoidectomy.

The styloid process differs developmentally from the squamous, petrous, tympanic, and mastoid components. It is associated with Reichert's cartilage of the second pharyngeal arch and forms part of the stylohyoid complex together with the stylohyoid ligament and the lesser horn of the hyoid bone. Variations in the length, angulation, or ossification pattern of this complex may persist into adulthood. When the styloid process is elongated or when the stylohyoid ligament is ossified, patients may develop symptoms related to Eagle syndrome, including cervicofacial pain, dysphagia, otalgia, foreign body sensation in the throat, or vascular symptoms due to close relationships with the carotid arteries and adjacent cranial nerves (Czako, Simko, Thurzo, Galis & Varga, 2020).

In summary, the embryological development of the temporal bone provides a structural explanation for many adult anatomical features and congenital anomalies. The squamous part reflects cranial vault development; the petrous part reflects otic capsule and inner ear development; the tympanic part is linked to the external auditory canal and tympanic membrane; the mastoid part is shaped by fetal formation and postnatal pneumatization; and the styloid process is related to the second pharyngeal arch. This developmental framework is clinically useful because defects in each component tend to produce different anatomical and functional consequences.

3. MORPHOLOGICAL ANATOMY OF THE TEMPORAL BONE

The temporal bone is a paired, irregular cranial bone located on the lateral aspect and base of the skull. It contributes to the lateral cranial wall, middle cranial fossa, posterior cranial fossa, external acoustic region, temporomandibular joint, and cranial base. In addition to its skeletal role, it contains the organs of hearing and balance, transmits important neurovascular structures, and provides attachment for several muscles and ligaments. Therefore, the temporal bone should be evaluated not only as a component of the skull, but also as a compact anatomical region in which cranial, auditory, vestibular, vascular, and neural structures are closely integrated (Dalley & Agur, 2023).

Classically, the temporal bone is divided into five main parts: the squamous part, petrous part, tympanic part, mastoid part, and styloid process. These components differ in shape, density, topographic relationships, and clinical significance. The squamous part forms a thin plate contributing to the lateral cranial wall; the petrous part is a dense pyramidal structure containing the inner ear; the tympanic part contributes to the external acoustic meatus; the mastoid part contains the mastoid process and mastoid air cell system; and the styloid process forms the superior component of the stylohyoid complex. Although these parts are described separately for anatomical clarity, they are continuous in the intact skull and are often involved together in traumatic, inflammatory, congenital, and surgical conditions (Juliano et al., 2013).

3.1. Squamous Part

The squamous part is the thin and plate like superior portion of the temporal bone. It forms part of the lateral wall of the cranium and contributes to the temporal fossa. Its external surface provides attachment for the temporalis muscle, while its internal surface is related to the temporal lobe of the cerebral hemisphere and meningeal vessels. Inferiorly, the squamous part gives rise to the zygomatic process, which extends anteriorly to articulate with the temporal process of the zygomatic bone and forms the zygomatic arch. The zygomatic arch is an important surface landmark because it separates the temporal fossa superiorly from the infratemporal region inferiorly and provides attachment for the masseter muscle (Standring, 2020).

The inferior aspect of the squamous part participates in the formation of the mandibular fossa, which receives the head of the mandible and forms the superior articular component of the temporomandibular joint. Anterior to the mandibular fossa is the articular tubercle, a bony prominence that contributes to the mechanics of mandibular movement. The temporomandibular joint is anatomically adjacent to the external acoustic meatus, with the thin tympanic plate separating the joint region from the external auditory canal. In addition, shared sensory innervation through the auriculotemporal nerve provides an anatomical basis for referred otalgia. Although otologic symptoms have been reported in patients with temporomandibular disorders, current evidence supports an association rather than a proven causal relationship (Hernández-Nuño de la Rosa, Keith, Siegel & Moreno-Hay, 2022). The petrotympanic fissure lies in this region and transmits the chorda tympani nerve from the middle ear toward the infratemporal fossa.

3.2. Petrous Part

The petrous part is the densest and most complex portion of the temporal bone. It has a pyramidal shape and is positioned obliquely between the sphenoid and occipital bones at the cranial base. Its apex is directed anteromedially, while its base is continuous laterally with the squamous and mastoid parts. The petrous part contributes to both the middle and posterior cranial fossae and forms a protective osseous capsule around the structures of the inner ear. It contains the cochlea, vestibule, and semicircular canals and is closely related to the internal acoustic meatus, facial canal, carotid canal, jugular fossa, and petrosal nerve pathways (Standring, 2020).

The anterior surface of the petrous part faces the middle cranial fossa. Important landmarks on this surface include the arcuate eminence, tegmen tympani, trigeminal impression, and hiatuses for the greater and lesser petrosal nerves. The tegmen tympani forms the thin bony roof of the tympanic cavity and mastoid antrum. Because of this relationship, disease processes involving the middle ear or mastoid region may extend superiorly when the tegmen is dehiscent, eroded, or surgically exposed. The posterior surface of the petrous part faces the posterior cranial fossa and contains the internal acoustic meatus, which transmits the facial nerve, vestibulocochlear nerve, and labyrinthine vessels. The inferior surface is irregular and includes the carotid canal, jugular fossa, and structures related to the styloid and mastoid regions (Isaacson, 2018; Juliano et al., 2013).

3.3. Tympanic Part

The tympanic part is a curved plate of bone that forms much of the anterior, inferior, and posterior walls of the bony external acoustic meatus. It surrounds the medial bony portion of the external auditory canal and contributes to the tympanic sulcus, which provides attachment for the tympanic membrane. The external acoustic meatus extends medially to the tympanic membrane, which separates the external ear from the middle ear cavity. In normal anatomy, the lateral third of the external auditory canal is fibrocartilaginous, whereas the medial two thirds are bony and are surrounded mainly by the tympanic part of the temporal bone (Dalley & Agur, 2023).

As discussed in the embryological section, congenital abnormalities of this region may be associated with external auditory canal stenosis or atresia. In the adult skull, however, the tympanic part is primarily important because of its relationships with the external acoustic canal, tympanic membrane, temporomandibular joint, and middle ear. Its anterior relationship with the mandibular fossa and posterior relationship with the mastoid region make it an important anatomical transition zone between otologic and maxillofacial structures.

3.4. Mastoid Part

The mastoid part is located posteroinferior to the squamous part and posterior to the external acoustic meatus. Its most prominent external feature is the mastoid process, a conical projection that provides attachment for several muscles, including the sternocleidomastoid, splenius capitis, and longissimus capitis muscles. Medial to the mastoid process is the mastoid notch, which gives attachment to the posterior belly of the digastric muscle. The occipital groove, located medial to the mastoid notch, transmits the occipital artery. These surface features make the mastoid region an important anatomical landmark in the posterolateral skull base (Dalley & Agur, 2023; Standring, 2020).

Internally, the mastoid part contains the mastoid air cell system, which communicates with the middle ear cavity through the mastoid antrum and the aditus ad antrum. The mastoid antrum is a constant air containing space located posterior to the epitympanic recess and superior to the mastoid air cells. Its roof is formed by the tegmen mastoideum, which separates the mastoid region from the middle cranial fossa. Posteriorly, the mastoid region is related to the sigmoid sinus, and medially it is close to the labyrinthine structures, particularly the lateral semicircular canal. These relationships are essential for understanding the spread of middle ear disease and the anatomical basis of mastoid surgery (Isaacson, 2018).

The degree of mastoid pneumatization is variable among individuals. A well pneumatized mastoid contains numerous air cells extending into the mastoid process and sometimes into adjacent parts of the temporal bone. In contrast, a poorly pneumatized or sclerotic mastoid has fewer air cells and more compact bone. This variation is important in radiological interpretation and surgical planning because the size and extent of mastoid air cells influence the operative corridor, the identification of the mastoid antrum, and the relationship of the surgical field to the sigmoid sinus, tegmen, facial canal, and semicircular canals. As discussed in the embryological section, mastoid pneumatization has a strong postnatal component and may show considerable individual variation (Aladeyelu et al., 2022).

The mastoid region is also closely related to the facial nerve. After passing through the labyrinthine and tympanic segments of the facial canal, the facial nerve turns inferiorly at the second genu and descends as the mastoid segment before exiting the skull through the stylomastoid foramen. This course explains why mastoid surgery requires precise anatomical orientation. The posterior wall of the external acoustic canal, the lateral semicircular canal, the short process of the incus, the digastric ridge, the sigmoid sinus, and the tegmen mastoideum are among the important landmarks used to navigate the mastoid region safely (Juliano et al., 2013).

In clinical anatomy, the mastoid part is particularly relevant in otitis media, mastoiditis, cholesteatoma, temporal bone trauma, and mastoidectomy. Infection or cholesteatoma may extend from the middle ear to the mastoid air cell system through the aditus ad antrum. Erosion of the tegmen may create a route toward the middle cranial fossa, while involvement of the sigmoid plate may create risk for venous sinus related complications. Therefore, the mastoid part should be understood not merely as a posterior projection of the temporal bone, but as a surgically important air containing region situated between the external ear, middle ear, labyrinth, facial nerve, middle cranial fossa, and posterior cranial fossa.

3.5. Styloid Process

The styloid process is a slender, pointed projection extending inferiorly from the inferior surface of the temporal bone. It is located anterior to the mastoid process and lateral to the jugular fossa. Its base lies near the stylomastoid foramen, where the facial nerve exits the skull. Because of this close topographic relationship, the styloid process is an important landmark in the inferior aspect of the temporal bone and in the upper parapharyngeal region (Dalley & Agur, 2023).

The styloid process provides attachment for three muscles and two ligaments. The styloglossus, stylohyoid, and stylopharyngeus muscles arise from the styloid process and pass toward the tongue, hyoid bone, and pharyngeal wall, respectively.

The stylohyoid ligament extends from the styloid process to the lesser horn of the hyoid bone, while the stylomandibular ligament extends toward the angle of the mandible. These structures collectively connect the temporal bone to the tongue, pharynx, hyoid apparatus, and mandible, giving the styloid process functional relevance in swallowing, speech, and movements of the hyoid laryngeal complex.

The anatomical relations of the styloid process are clinically important. Medially, it is related to the pharyngeal wall and tonsillar region. Posteromedially and deeply, it lies near the internal carotid artery, internal jugular vein, and lower cranial nerves. Laterally and anteriorly, it is related to the parotid region and mandibular ramus. These relationships explain why abnormalities of the styloid process or stylohyoid complex may produce symptoms that are not limited to the bone itself, but may be perceived as throat pain, otalgia, dysphagia, facial pain, or vascular discomfort (Czako et al., 2020).

As discussed in the embryological section, variation in the length, angulation, or ossification of the stylohyoid complex may persist into adulthood. An elongated styloid process or ossified stylohyoid ligament may be associated with Eagle syndrome. However, radiological elongation alone does not necessarily indicate symptomatic disease. Clinical significance depends on the presence of compatible symptoms and the relationship of the styloid process to adjacent neurovascular structures. Therefore, the styloid process should be evaluated as part of a regional anatomical complex rather than as an isolated bony projection.

4. CANALS, FORAMINA AND NEUROVASCULAR RELATIONS

The temporal bone contains a complex network of canals, foramina, fissures, aqueducts, clefts, and grooves that transmit or accommodate important neurovascular structures. These small anatomical pathways connect the cranial cavity, middle ear, inner ear, mastoid region, infratemporal fossa, carotid canal, jugular region, and posterior cranial fossa. Although some of these structures are minute and may be difficult to identify even on thin section computed tomography, they have considerable anatomical and clinical importance. They may be overlooked, mistaken for fracture lines or pathological lesions, or involved by developmental, inflammatory, infectious, traumatic, or neoplastic processes (Benson et al., 2020). Therefore, understanding these structures as part of an integrated three dimensional anatomical system is essential for temporal bone imaging, otologic surgery, skull base surgery, and the interpretation of neurovascular complications.

The internal acoustic meatus is located on the posterior surface of the petrous part and transmits the facial nerve, vestibulocochlear nerve, and labyrinthine vessels toward the inner ear. At its lateral end, the fundus of the internal acoustic meatus is divided into compartments for the facial, cochlear, superior vestibular, and inferior vestibular nerves. This arrangement is clinically important in vestibular schwannoma, facial nerve pathology, congenital nerve deficiency, and cochlear implantation planning (Nada et al., 2021).

The facial canal is one of the most clinically important canals of the temporal bone. It begins at the fundus of the internal acoustic meatus and carries the facial nerve through labyrinthine, tympanic, and mastoid segments before the nerve exits the skull through the stylomastoid foramen. Along this course, the facial nerve is closely related to the cochlea, geniculate ganglion, oval window, lateral semicircular canal, pyramidal eminence, mastoid antrum, and posterior wall of the tympanic cavity. These relationships explain the vulnerability of the facial nerve in temporal bone fractures, middle ear disease, cholesteatoma, congenital anomalies, and mastoid surgery (Gupta, Mends, Hagiwara, Fatterpekar & Roehm, 2013).

The carotid canal begins on the inferior surface of the petrous part and transmits the internal carotid artery and its sympathetic plexus into the cranial cavity. The artery first ascends vertically and then turns anteromedially within the petrous temporal bone. Its proximity to the middle ear, cochlea, Eustachian tube, and petrous apex is clinically relevant because congenital or acquired dehiscence, aberrant vascular anatomy, trauma, infection, or surgical drilling in this region may place the internal carotid artery at risk (Juliano et al., 2013). Similarly, the jugular fossa accommodates the superior bulb of the internal jugular vein and lies near the jugular foramen, through which the glossopharyngeal, vagus, and accessory nerves pass. Variations such as a high riding or dehiscent jugular bulb may alter the anatomy of the hypotympanum and increase the risk of vascular injury in middle ear or cochlear implant surgery (Ueda, Yamazaki, Michida, Shinohara & Naito, 2024).

Smaller canals and fissures of the temporal bone also have important functional and clinical implications. The petrotympanic fissure transmits the chorda tympani nerve from the tympanic cavity to the infratemporal fossa. The canaliculus tympanicus transmits the tympanic branch of the glossopharyngeal nerve, which contributes to the tympanic plexus on the promontory. The canaliculus mastoideus transmits the auricular branch of the vagus nerve and is related to sensory innervation of the external acoustic region. The hiatus for the greater petrosal nerve transmits the greater petrosal nerve from the facial canal region toward the middle cranial fossa. The vestibular aqueduct contains the endolymphatic duct and is clinically important in enlarged vestibular aqueduct and other congenital inner ear disorders. The cochlear aqueduct connects the perilymphatic space near the basal turn of the cochlea with the subarachnoid space and may be relevant in inner ear fluid dynamics and skull base pathways (Benson et al., 2020).

The following table summarizes the principal canals, foramina, fissures, and aqueducts of the temporal bone and their major transmitted or related structures (Table 1).

In anatomical and clinical practice, these structures should be interpreted together rather than memorized as isolated openings. The temporal bone is a compact region in which the facial nerve, vestibulocochlear nerve, internal carotid artery, jugular bulb, sigmoid sinus, middle ear cavity, inner ear, and mastoid air cells are separated by thin bony partitions. This explains why small congenital variations, inflammatory erosion, traumatic fracture lines, or surgical drilling may produce significant neurological, vascular, auditory, or vestibular consequences.

5. CLINICAL AND SURGICAL ANATOMY OF THE TEMPORAL BONE

The clinical importance of the temporal bone arises from the close spatial relationship between its osseous structures, the external and middle ear, the inner ear, the facial nerve, the vestibulocochlear nerve, the internal carotid artery, the jugular bulb, the sigmoid sinus, and the dura of the middle and posterior cranial fossae. Because many of these structures are separated only by thin bony partitions, relatively small pathological processes may cause significant auditory, vestibular, neural, vascular, or intracranial complications. Therefore, the temporal bone is a central region in otology, neurotology, radiology, skull base surgery, maxillofacial surgery, and clinical anatomy.

5.1. Temporal Bone Fractures

Temporal bone fractures are clinically important because fracture lines may involve the external acoustic canal, ossicular chain, otic capsule, facial canal, carotid canal, jugular foramen, or mastoid air cell system. Traditionally, these fractures were classified as longitudinal or transverse according to their orientation relative to the long axis of the petrous temporal bone. However, from a clinical perspective, the distinction between otic capsule sparing and otic capsule violating fractures is particularly useful because otic capsule involvement is more strongly associated with sensorineural hearing loss, vestibular dysfunction, cerebrospinal fluid leakage, and facial nerve injury (Johnson et al., 2008).

The clinical presentation depends on the structures involved. Conductive hearing loss may result from hemotympanum, tympanic membrane injury, external acoustic canal disruption, or ossicular chain dislocation. Sensorineural hearing loss and vertigo are more suggestive of labyrinthine or otic capsule involvement. Facial nerve dysfunction may occur when the fracture line crosses the facial canal, especially near the geniculate ganglion or tympanic and mastoid segments. Fractures extending toward the carotid canal or jugular foramen may also create risk for vascular injury or lower cranial nerve involvement. Thus, temporal bone trauma should be evaluated as a regional injury involving osseous, neural, vascular, and sensory structures rather than as an isolated skull fracture (Kennedy, Avey & Gentry, 2014).

5.2. Otitis Media, Mastoiditis and Cholesteatoma

The temporal bone is also clinically important in inflammatory and infectious diseases of the middle ear and mastoid region. The middle ear cavity communicates with the mastoid antrum and mastoid air cells through the aditus ad antrum. This anatomical continuity explains why middle ear infection may extend into the mastoid air cell system and cause mastoiditis. In uncomplicated cases, the disease may remain limited to the mucosa of the tympanic cavity and mastoid cells. However, progression may result in bony erosion, subperiosteal abscess, facial canal involvement, labyrinthine complications, sigmoid sinus thrombosis, or intracranial spread through the tegmen tympani or tegmen mastoideum (Cassano, Ciprandi, & Passali, 2020).

Cholesteatoma is another important condition in which anatomy directly determines clinical behavior. Although it is histologically benign, cholesteatoma may enlarge and erode adjacent bony structures. The ossicles, scutum, tegmen tympani, lateral semicircular canal, facial canal, and mastoid air cells may be affected. Erosion of the ossicles may produce conductive hearing loss, while involvement of the lateral semicircular canal may cause vertigo or labyrinthine fistula. Facial canal dehiscence or erosion increases the risk of facial nerve dysfunction, especially during surgery. Therefore, detailed knowledge of the epitympanum, aditus ad antrum, mastoid antrum, facial recess, sinus tympani, and lateral semicircular canal is essential in both diagnosis and surgical management (Rosito, Canali, Teixeira, Silva, Selaimen, & Costa, 2019).

5.3. Mastoidectomy and Surgical Landmarks

Mastoidectomy is one of the most important surgical procedures demonstrating the applied anatomy of the temporal bone. The procedure requires orientation within a compact region bordered by the tegmen superiorly, sigmoid sinus posteriorly, external acoustic canal anteriorly and laterally, middle ear anteriorly, labyrinthine structures medially, and digastric ridge inferiorly. Important landmarks include the mastoid cortex, spine of Henle, posterior wall of the external acoustic canal, mastoid antrum, tegmen mastoideum, sigmoid sinus, lateral semicircular canal, short process of the incus, facial canal, facial recess, chorda tympani, and digastric ridge (Isaacson, 2018; Kennedy & Lin, 2023).

The degree of mastoid pneumatization may significantly affect the operative field. A well pneumatized mastoid usually provides a wider air cell system and more recognizable landmarks, whereas a sclerotic mastoid may make surgical dissection more difficult. As discussed previously, mastoid pneumatization shows considerable individual variation and age related growth patterns (Aladeyelu et al., 2022). The facial nerve is particularly important because its mastoid segment descends within the facial canal and exits through the stylomastoid foramen. Injury to the facial nerve may cause significant functional and cosmetic morbidity. Similarly, the sigmoid sinus and tegmen are relevant because excessive drilling or disease related erosion may lead to venous injury, dural exposure, cerebrospinal fluid leakage, or intracranial complications. For this reason, mastoid surgery depends not only on knowledge of named anatomical structures, but also on the ability to interpret their three dimensional relationships during dissection (Isaacson, 2018; Kennedy & Lin, 2023).

5.4. Temporomandibular Joint Relations and Eagle Syndrome

The temporal bone is also relevant to clinical conditions outside the classical field of otology. The mandibular fossa and articular tubercle of the squamous part form the temporal component of the temporomandibular joint. Because the joint is located close to the external acoustic meatus and shares regional sensory innervation through the auriculotemporal nerve, patients with temporomandibular disorders may report otalgia, ear fullness, tinnitus, or other otologic complaints. However, the available evidence supports an association rather than a clearly proven causal relationship. Therefore, otologic symptoms in patients with temporomandibular disorders should not automatically be attributed to the joint; appropriate otolaryngological evaluation and differential diagnosis remain necessary (Hernández-Nuño de la Rosa et al., 2022).

The styloid process and stylohyoid complex represent another clinically relevant region of the temporal bone. Elongation of the styloid process or ossification of the stylohyoid ligament may be associated with Eagle syndrome. Depending on the direction and length of the styloid process and its relationship with adjacent neurovascular structures, patients may present with throat pain, dysphagia, otalgia, foreign body sensation in the pharynx, cervicofacial pain, or vascular symptoms. However, radiological elongation alone is not sufficient for diagnosis, because asymptomatic elongation may also occur. Clinical correlation is therefore essential when interpreting styloid process morphology (Czako et al., 2020).

5.5. Vascular Variations and Surgical Risk

Vascular relationships are among the most critical aspects of temporal bone anatomy. The internal carotid artery passes through the carotid canal within the petrous temporal bone, while the jugular bulb occupies the jugular fossa inferiorly (Standring, 2020). Variations such as aberrant internal carotid artery, dehiscent carotid canal, high-riding jugular bulb, dehiscent jugular bulb, or jugular bulb diverticulum may alter the expected surgical anatomy of the middle ear and skull base. These variations are important because they may mimic middle ear masses, produce pulsatile tinnitus or conductive symptoms, and create risk for severe bleeding during otologic procedures (Nada et al., 2021; Ueda et al., 2024).

High resolution computed tomography is particularly valuable for defining these bony and vascular relationships before surgery. For example, a high riding or dehiscent jugular bulb may protrude into the tympanic cavity and obscure surgical access to the round window or hypotympanum. In cochlear implantation or middle ear surgery, failure to recognize such a variation may result in hemorrhagic complications or alteration of the surgical plan. Therefore, preoperative imaging should be evaluated systematically with attention to the carotid canal, jugular bulb, sigmoid sinus, facial canal, round window niche, mastoid pneumatization, and middle ear cavity (Ueda et al., 2024).

6. CONCLUSION

The temporal bone is a highly complex cranial bone in which developmental, morphological, neurovascular, and clinical features are closely integrated. Its squamous, petrous, tympanic, mastoid, and styloid components differ in origin, structure, density, anatomical relationships, and clinical relevance. This composite organization explains why temporal bone anatomy cannot be fully understood by surface morphology alone.

From a developmental perspective, the temporal bone reflects the interaction of the cranial vault, cranial base, otic capsule, external auditory canal, middle ear cavity, mastoid air cell system, and pharyngeal arch derivatives. From a morphological perspective, it contains and protects the organs of hearing and balance, forms part of the temporomandibular joint, and transmits several critical neurovascular structures. Its canals, foramina, fissures, and aqueducts provide pathways for the facial nerve, vestibulocochlear nerve, internal carotid artery, jugular bulb, petrosal nerves, chorda tympani, and other small but clinically important structures.

Clinically, the temporal bone is involved in a wide range of conditions, including congenital anomalies, temporal bone fractures, otitis media, mastoiditis, cholesteatoma, facial nerve disorders, vascular variations, temporomandibular joint-related symptoms, and Eagle syndrome. Many of these conditions are explained by the close spatial relationships between the middle ear, inner ear, mastoid air cells, facial canal, carotid canal, jugular fossa, sigmoid sinus, and cranial fossae. Therefore, a detailed understanding of temporal bone anatomy is essential not only for anatomical education, but also for radiological interpretation, otologic surgery, neurotology, skull base surgery, and the prevention of neurovascular complications.

Table 1. Principal Canals, Foramina, Fissures, and Aqueducts of the Temporal Bone

Canal / Foramen / Fissure	Main Location	Transmitted Or Related Structures	Clinical Relevance
Internal acoustic meatus	Posterior surface of the petrous part	Facial nerve, vestibulocochlear nerve, labyrinthine vessels	Vestibular schwannoma, facial nerve pathology, congenital nerve deficiency, cochlear implantation planning
Facial canal	Petrous and mastoid parts	Facial nerve, geniculate ganglion, greater petrosal nerve, nerve to stapedius, chorda tympani	Facial paralysis, temporal bone fracture, cholesteatoma, middle ear disease, mastoid surgery
Stylomastoid foramen	Between styloid and mastoid processes	Facial nerve exit, stylomastoid artery	Facial nerve block, parotid region surgery, facial nerve injury
Carotid canal	Inferior surface of petrous part to petrous apex	Internal carotid artery, sympathetic plexus	Vascular injury, aberrant internal carotid artery, skull base surgery
Jugular fossa / jugular foramen region	Inferior surface of petrous part	Superior bulb of internal jugular vein; cranial nerves IX, X, XI pass through jugular foramen	High riding or dehiscent jugular bulb, glomus jugulare tumors, lower cranial nerve deficits, vascular injury risk
Petrotympanic fissure	Between mandibular fossa and tympanic region	Chorda tympani, anterior tympanic vessels	Taste pathway, middle ear and infratemporal fossa connection

Canal / Foramen / Fissure	Main Location	Transmitted Or Related Structures	Clinical Relevance
Hiatus for greater petrosal nerve	Anterior surface of petrous part	Greater petrosal nerve	Lacrimal secretomotor pathway, facial nerve lesions, perineural tumor spread
Canaliculus tympanicus / inferior tympanic canaliculus	Inferior petrous surface / pars nervosa region of jugular foramen	Tympanic branch of glossopharyngeal nerve (Jacobson's nerve)	Tympanic plexus, glomus tympanicum, middle ear neurovascular anatomy
Canaliculus mastoideus / mastoid canaliculus	Jugular fossa and mastoid region	Auricular branch of vagus nerve (Arnold's nerve)	Arnold nerve reflex, cough reflex, referred otalgia from external ear stimulation
Vestibular aqueduct	Posterior surface of petrous part	Endolymphatic duct and endolymphatic sac	Enlarged vestibular aqueduct, sensorineural or mixed hearing loss, Pendred syndrome
Cochlear aqueduct	Inferior petrous region near round window and petrous apex	Perilymphatic duct; communication between scala tympani and subarachnoid space	Inner ear pressure regulation, labyrinthitis ossificans pathway, possible CSF related communication
Petromastoid canal / subarcuate canaliculus	From subarcuate fossa to medial mastoid antrum	Dura mater, subarcuate artery and vein	Potential route for infectious spread from mastoid air cells to cranial cavity; pediatric normal variant when prominent
Singular canal	From posterior margin of internal auditory canal to posterior semicircular canal	Posterior ampullary nerve / singular nerve	May mimic fracture on imaging; landmark in posterior fossa transmeatal approaches and singular neurectomy
Mastoid foramen	Mastoid or occipitomastoid region	Mastoid emissary vein, meningeal branch of occipital artery	Emissary venous communication, bleeding risk, potential route of infection spread

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SEX ESTIMATION USING CRANIAL PARAMETERS IN THE TURKISH POPULATION

Beyza ÇELİK[1]

Seda SERTEL MEYVACI[2]

1. INTRODUCTION

In forensic anthropology, the identification process is based on the construction of an individual's biological profile from skeletal remains. The main components of this biological profile include sex, age, stature, and population origin (Krishan et al., 2016; Spradley, 2016). Sex estimation is considered one of the first and most important steps in identification studies, as it directly affects the assessment of other biological parameters. Particularly in incomplete, fragmented, burned, or severely decomposed human remains, accurate sex estimation contributes to narrowing the pool of possible identities and enables the forensic process to proceed more reliably (Wang et al., 2024).

1.1. The Role of the Cranium in Sex Estimation

The cranium is an important structure in sex estimation due to its durability and the presence of many sexually dimorphic anatomical features (Spradley and Jantz, 2011). It includes dimorphic regions such as muscle attachment sites,

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[1] PhD Student, Bolu Abant Izzet Baysal University, Faculty of Medicine, Department of Anatomy, ORCID: 0000-0003-4401-8678.

[2] Assoc. Prof. Dr., Bolu Abant Izzet Baysal University, Faculty of Medicine, Department of Anatomy, ORCID: 0000-0002-9450-145X

facial skeletal structures, frontal and occipital morphology, orbital region, mastoid process, and mandible. Male crania generally show larger dimensions, thicker cortical structure, more prominent muscle attachments, and developed supraorbital, mastoid, and occipital prominences, whereas female crania tend to be more gracile, with sharper supraorbital margins, a more vertical frontal region, and a more delicate facial skeleton (Mello-Gentil and Souza-Mello, 2021; Musilová et al., 2016). Craniometric measurements provide valuable metric data for sex estimation. These measurements may differ significantly between sexes, and population-specific standards are essential for reliable evaluation (Zaafrane et al., 2018; Zhan et al., 2019).

2. ANATOMICAL STRUCTURE OF THE CRANIUM

The cranium refers to the entirety of the bony structures that form the skeleton of the head. Anatomically, it is a complex skeletal structure closely associated with the brain, meninges, sensory organs, and the initial parts of the upper respiratory and digestive tracts. The skull should not be regarded merely as a bony box that protects the brain; it is also a functional structure that forms the basic shape of the face and constitutes the bony boundaries of the orbit, nasal cavity, and oral cavity (Arıncı and Elhan, 2010; Moore et al., 2018). The cranial bones can be preserved for a longer period than some soft tissues and skeletal regions despite trauma, burning, decomposition, or environmental effects causes the cranium to be frequently evaluated in identification studies. In this respect, the cranium can provide important information in the assessment of an individuals age, sex, and some morphological characteristics (Ozan, 2014; Mello-Gentil and Souza-Mello, 2021).

2.1. Divisions of the Cranium

2.1.1. Neurocranium

Anatomically, the cranium is examined in two main divisions: the neurocranium and the viscerocranium. The neurocranium is the part of the cranium that surrounds and protects the brain. This division forms the superior and posterior parts of the skull and creates the cranial cavity, called the cavitas cranii. The neurocranium consists of the frontal, parietal, temporal, occipital, sphenoid, and ethmoid bones. The anatomical importance of the neurocranium does not arise solely from its protection of the brain. The frontal bone, parietal bones, temporal bones, and occipital bone located in this division are also important in morphological evaluations due to their external surface shapes, muscle attachment areas, and cranial prominences (Arıncı and Elhan, 2010; Moore et al., 2018; Ozan, 2014; Arifoğlu, 2021).

2.1.2. Viscerocranium

The viscerocranium is the part of the cranium that forms the facial skeleton. This division contributes to the formation of the bony boundaries of structures such as the orbit, cavitas nasi, and cavitas oris. The viscerocranium consists of bones such as the maxilla, zygomatic bone, nasal bone, lacrimal bone, palatine bone, inferior nasal concha, vomer, and mandible. The maxilla and mandible play a role in mastication because they are the bony structures in which the teeth are located; the nasal bones and surrounding structures are involved at the beginning of the respiratory tract; and the orbital bony structures serve to protect the eyeball (Moore et al., 2018; Arifoğlu, 2021). The importance of the viscerocranium in forensic anthropology arises from the fact that the facial skeleton may show individual and sex-related morphological differences (Arıncı and Elhan, 2010; Mello-Gentil and Souza-Mello, 2021).

3. SEX ESTIMATION STUDIES CONDUCTED USING NEUROCRANIAL REGIONS

3.1. Frontal Bone

The frontal bone is an important cranial structure used in sex estimation, particularly through the glabella, supraorbital region, and frontal sinus morphometry. In the Turkish population, studies have mainly focused on frontal sinus dimensions and related morphological features. Tatlisumak et al. reported that frontal sinus width, height, and anteroposterior length may vary according to age and sex (Tatlisumak et al., 2017). Türk et al. found that bilateral frontal sinus width, anteroposterior depth, and total width were significantly higher in males on Cone-Beam Computed Tomography (CBCT) images (Türk et al., 2019). Similarly, Boyacioglu et al. emphasized the importance of frontal sinus volume, especially right frontal sinus volume, in sex estimation in the Turkish sample (Boyacioglu et al., 2020). Durum Polat et al. also reported that frontal and maxillary sinus diameters could assist sex estimation (Durum Polat et al., 2020). Frontal sinus morphometry has also been evaluated in archaeological and radiographic materials. Demiralp et al. showed that frontal sinus parameters could be assessed in ancient skulls, although their discriminative ability was limited (Demiralp et al., 2019). Emekli reported that frontal sinus height and width on direct skull radiographs were significantly higher in males and could provide moderate accuracy in sex estimation (Emekli, 2023). Morphological criteria have also been investigated; Yaşar and Sağır stated that the glabella showed marked sexual dimorphism, while Apaydın and İçöz reported that the glabella was one of the strongest dimorphic features on 3D CBCT reconstructions (Yaşar and Sağır, 2023; Apaydın and İçöz, 2025). In addition, Kalkan and Kalkan found that frontal sinus measurements were significantly higher in males when evaluated together with mandibular ramus length (Kalkan and Kalkan, 2026). Overall, frontal bone studies in the Turkish population mainly emphasize frontal sinus morphometry and glabellar morphology.

3.2. Occipital Bone

The occipital bone and cranial base are frequently evaluated in sex estimation, especially through the foramen magnum, occipital condyles, posterior cranial fossa openings, external occipital protuberance, and nuchal crest. In Turkish studies, foramen magnum morphometry is the most commonly examined parameter. Uysal et al. reported that foramen magnum diameter, area, and circumference were higher in males on 3D computed tomography (CT) images (Uysal et al., 2005). İlgüy et al. showed that foramen magnum parameters contributed to sex estimation, although better classification was achieved when combined with mandibular measurements (İlgüy et al., 2014). Meral et al. similarly found that foramen magnum length, width, area, and circumference were higher in males and useful in discriminant analysis (Meral et al., 2020). Recent studies have also incorporated computational and broader cranial base approaches. Kartal et al. compared discriminant analysis and artificial neural networks using foramen magnum measurements and reported higher accuracy with artificial neural networks (Kartal et al., 2022). Depreli et al. evaluated posterior cranial fossa openings, including the foramen magnum, jugular foramen, and internal acoustic opening, and reported that these structures may show significant sexual dimorphism in the Turkish population (Depreli et al., 2025). Overall, occipital bone studies indicate that foramen magnum and posterior cranial fossa measurements are useful parameters for sex estimation.

3.3. Sphenoid Bone

The sphenoid bone has been evaluated mainly through sphenoid sinus morphometry due to its location at the cranial base. Kaplanoglu et al. reported that some surgically relevant sphenoid sinus measurements were longer in males and should be considered in clinical interventions (Kaplanoglu et al., 2013). Koç found that right, mean, and total sphenoid sinus volumes were higher in males, with right sphenoid sinus volume being the strongest parameter for sex estimation (Koç, 2020). Özeren Keşkek and Aytuğar reported that sphenoid sinus pneumatization types did not differ significantly by sex, although clival extension and some anterior clinoid process pneumatization types may show sex-related differences (Özeren Keşkek and Aytuğar, 2021). Gurlek Celik and Akman found that sphenoid sinus volumes, particularly left sphenoid sinus volume, were significantly greater in males (Gurlek Celik and Akman, 2024). Keleş et al. also reported that sphenoid sinus volume was higher in males and that sphenoid sinus shape may show anthropometric differences between sexes (Keleş et al., 2024). Thus, sphenoid sinus volume appears to be a useful cranial base parameter in sex estimation.

3.4. Ethmoid Bone

The ethmoid bone is a complex structure related to the orbit, nasal cavity, and anterior cranial base. In the Turkish population, direct sex estimation studies on the ethmoid bone are limited; available studies mostly focus on ethmoid sinus volume, ethmoid cells, agger nasi cell, ethmoid bulla, Haller cell, Onodi cell, and lamina papyracea variations. Borahan et al. evaluated paranasal sinus variations on CBCT images and examined ethmoid-related structures such as agger nasi, infraorbital ethmoid, and Onodi cells (Borahan et al., 2019). Bora et al. assessed sinonasal variations in 1532 CT cases and reported that the Onodi cell was more common in females, while ethmoid bulla and some variations differed by age (Bora et al., 2021). Gruszka et al. compared Polish and Turkish Cypriot populations and found that the agger nasi cell was one of the most common variations in the Turkish Cypriot group (Gruszka et al., 2022). Overall, the ethmoid region is not as strong as the sphenoid sinus for sex estimation, but it provides valuable anatomical variation data for evaluating the orbit, nasal cavity, and paranasal sinus complex.

4. SEX ESTIMATION STUDIES CONDUCTED USING VISCEROCRANIAL REGIONS

4.1. Mandible

The mandible is an important structure in forensic anthropology due to its robust morphology, prominent muscle attachment areas, and ease of radiological measurement. İnci et al. reported that mandibular ramus measurements, particularly vertical ramus parameters, showed marked sexual dimorphism on 3D CT images (İnci et al., 2016). Acar et al. found that corpus length, corpus height, ramus height, ramus width, and bicondylar width were significantly higher in males using multidetector computed tomography (MDCT) (Acar et al., 2017). Direk et al. reported that the gonial angle was higher in females, whereas some mandibular foramen-related distances and lingula height were higher in males (Direk et al., 2018). Apaydın et al. showed that mental foramen-related distances were higher in males, while gonial and antegonial angles were larger in females on panoramic radiographs (Apaydın et al., 2018). Studies based on CBCT also support the value of mandibular measurements in sex estimation. İçöz and Akgünlü found that condylar length, coronoid length, bigonial width, and bicondylar width were significantly higher in males (İçöz and

Akgünlü, 2019). Okkesim and Sezen Erhamza stated that all ramus-related measurements differed significantly between sexes in the Central Anatolian Turkish population (Okkesim and Sezen Erhamza, 2020). Sertel Meyvaci et al. found significant sex differences in mandibular angular parameters, including gonial, mentomandibular, α, and β angles (Sertel Meyvaci et al., 2021). Recent studies also confirmed that coronoid length, condylar length, bigonial width, condylar measurements, sigmoid notch depth, and general mandibular linear measurements are useful for sex estimation (Çelebi et al., 2025; Doğan et al., 2025; Mutlu et al., 2025). Overall, ramus height, condylar length, coronoid length, bigonial width, bicondylar width, mandibular length, and symphysis height are among the most dimorphic mandibular parameters in the Turkish population.

4.2. Maxilla and Maxillofacial Measurements

Sex estimation studies related to the maxilla and maxillofacial region in the Turkish population have mostly focused on maxillary sinus morphometry, although the hard palate, bizygomatic breadth, bigonial width, craniofacial diameters, and skeletal patterns have also been evaluated. Teke et al. reported that maxillary sinus dimensions may support sex estimation but have limited accuracy when used alone (Teke et al., 2007). Ekizoğlu et al. found that all maxillary sinus measurements were significantly smaller in females than in males on thin-slice MDCT images (Ekizoğlu et al., 2014). Studies on maxillary sinus volume have produced different findings. Güleç et al. found no significant relationship between maxillary sinus volume and age or sex in a Turkish subpopulation (Güleç et al., 2020). Kolak et al. found that some maxillary sinus height and width values were higher in males, with right maxillary sinus height being the most discriminative parameter (Kolak et al., 2024). Doğan and Uluışık also reported significantly higher right and left maxillary sinus volumes in males (Doğan and Uluışık, 2024).

4.3. Zygomatic Bone and Arch

In Turkish sex estimation studies, the zygomatic bone and arch have generally been assessed through bizygomatic diameter or breadth rather than as independent structures. Ekizoğlu et al. reported that bizygomatic diameter was one of the most prominent sexually dimorphic craniofacial parameters and was higher in males (Ekizoğlu et al., 2016). Meral et al. found that maximum cranial length, maximum cranial breadth, bimastoid diameter, bizygomatic diameter, and bigonial width could contribute to sex estimation (Meral et al., 2022). Kalkan et al. evaluated several linear craniometric parameters and reported that all measurements were higher in males, with bizygomatic breadth showing one of the most notable sex differences (Kalkan et al., 2025). Alkan also found that bizygomatic breadth was higher in males in direct cephalometric measurements, although it was recommended to use this parameter together with other craniofacial measurements (Alkan, 2025). Overall, bizygomatic breadth appears to be a valuable and commonly used indicator of craniofacial sexual dimorphism in the Turkish population.

4.4. Orbit and Surrounding Region

Orbital studies in the Turkish population have evaluated orbital breadth, orbital height, orbital index, biorbital and interorbital breadth, orbital aperture dimensions, globe volume, optic nerve measurements, and medial orbital wall morphology. Kaya et al. reported that left orbital breadth was more discriminative in males and left orbital height in females, but orbital measurements alone were not sufficiently reliable for sex estimation (Kaya et al., 2014). Özer et al. found significant sex differences in orbital aperture dimensions, axial globe length, globe volume, optic nerve diameter, and right optic nerve length (Özer et al., 2016). Meral et al. reported that orbital measurements could be used in discriminant analysis, although their overall accuracy was moderate (Meral et al., 2022). Can et al. showed that orbit-related parameters, especially biorbital width, may contribute to sex estimation and become more effective when combined with zygomatic and maxillofacial widths (Can et al., 2022). Erdem et al. evaluated orbital width, height, depth, and volume using 3D MDCT and reported that orbital measurements were generally higher in males, while side differences should also be considered (Erdem et al., 2023). Overall, orbital parameters have auxiliary value and are more effective when combined with other craniofacial measurements.

4.5. Nasal Bones and Piriform Aperture

The nasal bones and piriform aperture are midfacial structures that have been evaluated less frequently than the mandible and orbit in Turkish sex estimation studies. Karadağ et al. reported that nasal bone length was higher in males, while piriform aperture width alone was not a strong parameter for sex differentiation (Karadağ et al., 2011). Yüzbaşıoğlu et al. found that most nasal bone and piriform aperture measurements were higher in males on MDCT images, supporting the value of this region in sexual dimorphism (Yüzbaşıoğlu et al., 2014). Sertel Meyvaci et al. measured piriform aperture dimensions and adjacent cranial structures and found significant sex differences in most parameters, except for vertex–rhinion distance, rhinion–supraorbital foramen distances, and piriform aperture width at the infraorbital foramina level (Sertel Meyvaci et al., 2019). Kabakcı et al. also reported that piriform aperture height and width were generally higher in males (Kabakcı et al., 2020). Parlak et al. used 3D CT and machine learning methods and showed that piriform aperture measurements provided moderate accuracy with discriminant analysis, while machine learning, especially ensemble methods, improved classification performance (Parlak et al., 2025). Overall, nasal bones and piriform aperture measurements have supportive value and should be evaluated together with other craniofacial parameters.

4.6. Palatine Region

The palatine region and hard palate may provide auxiliary morphometric data for sex estimation in the Turkish population. Studies have mainly focused on hard palate length, width, height/depth, palatal index, palatal vault angle, greater palatine foramen, and nasopalatine canal measurements. Ortug and Uzel evaluated the greater palatine foramen together with palatal index and sex variables (Ortug and Uzel, 2019). Ayyildiz and Dursun reported that hard palate asymmetry and sex-related differences may be present in the Turkish population (Ayyildiz and Dursun, 2021). Tassoker et al. found that palatal width, length, and depth were higher in males, whereas palatal vault angle did not differ significantly between sexes (Tassoker et al., 2024). Overall, palatine measurements should not be used alone for definitive sex estimation, but may support evaluation when combined with other craniofacial parameters.

4.7. Vomer, Lacrimal Bone, and Inferior Nasal Concha

The vomer, lacrimal bone, and inferior nasal concha have limited direct use in sex estimation studies in the Turkish population. The vomer has mostly been evaluated indirectly through nasal septum and nasal cavity morphology. Okumuş reported that bony nasolacrimal canal measurements may show sex-related variation, particularly in the angle between the canal and nasal floor (Okumuş, 2020). Açar et al. examined inferior concha-related variations and reported that inferior concha thickness did not differ significantly by sex (Açar et al., 2025). Overall, these structures do not appear to be strong independent markers for sex estimation, but they may provide supportive morphometric data in the holistic evaluation of the nasal cavity, orbit, maxilla, and sinonasal complex.

5. CONCLUSION

Studies on sex estimation from the cranium in the Turkish population show that cranial and maxillofacial structures provide valuable information for forensic identification. The mandible, bizygomatic breadth, foramen magnum, and some sinus measurements stand out in sex differentiation. However, the most reliable results are obtained not from a single measurement, but from the combined evaluation of multiple cranial and maxillofacial parameters. CT, CBCT, three-dimensional imaging, and machine learning methods contribute to more objective and reproducible assessments.

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OS HYOİDEUM: EMBRİYOLOJİSİ, ANATOMİSİ, KLİNİK ÖNEMİ VE ADLİ ANTROPOLOJİDEKİ YERİ

Yaşam VERDİ[1]
İsmail MALKOÇ[2]

1. GİRİŞ: Os Hyoideum'un Aksiyel İskelet Sistemi İçerisindeki Yeri

İnsan iskeleti, topografik ve fonksiyonel özelliklerine göre aksiyel ve appendiküler iskelet olmak üzere iki ana bölümde incelenir. Aksiyel iskelet; baş, boyun ve gövdenin merkezi iskelet çatısını oluşturan kemikleri içerirken, appendiküler iskelet üst ve alt ekstremiteler ile bunların aksiyel iskelete bağlantısını sağlayan kemer yapılarından meydana gelir. Os hyoideum'un anatomik sınıflandırılması literatürde tam bir görüş birliği göstermemektedir. Bazı kaynaklarda kemiğin serbest hareketli yapısı ve kas-tendon kompleksleri içerisindeki konumu nedeniyle sesamoid benzeri bir yapı olarak değerlendirildiği görülürken, bazı anatomik sınıflandırmalarda ise belirgin bir kategori içerisinde ele alınmadığı dikkat çekmektedir. Bununla birlikte modern anatomik yaklaşımda os hyoideum; baş-boyun bölgesinin orta hattında yer alması, embriyolojik olarak faringeal arkus sisteminden gelişmesi, suprahyoid ve infrahyoid kas kompleksinin merkezi bağlantı noktası olması ve üst solunum–

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[1] Dr., Düzce Üniversitesi, Tıp Fakültesi, Anatomi Anabilim Dalı, ORCID: 0000-0002-7738-5565.

[2] Prof. Dr., Düzce Üniversitesi, Tıp Fakültesi, Anatomi Anabilim Dalı, ORCID: 0000-0002-9221-510X.

sindirim sistemlerinin fonksiyonel bütünlüğüne katkı sağlaması nedeniyle aksiyel iskeletin bir bileşeni olarak kabul edilmektedir.

Os hyoideum, aksiyel iskeletin baş-boyun bileşkesinde yer alan özgün anatomik yapılardan biridir. Halk arasında "dil kemiği" olarak da bilinen bu kemik, diğer iskelet elemanlarından farklı olarak hiçbir kemikle doğrudan eklem yapmaması nedeniyle insan anatomisinde istisnai bir konuma sahiptir. Boynun ön orta hattında yer alan os hyoideum; mandibula, processus styloideus, larynx ve scapular bölge ile ilişkili kas ve ligamentler aracılığıyla askıda tutulur.

Fonksiyonel açıdan os hyoideum; yutma, fonasyon, solunum ve üst hava yolu stabilitesinde merkezi rol oynar. Suprahyoid ve infrahyoid kas grupları için önemli bir tutunma noktası oluşturmasının yanı sıra, dil kökü ve larengeal kompleks arasında biyomekanik bir bağlantı görevi üstlenir. Bu nedenle os hyoideum, yalnızca lokomotor sistemin bir parçası olarak değil; aynı zamanda üst solunum ve sindirim sistemlerinin fonksiyonel bütünlüğüne katkı sağlayan dinamik bir anatomik yapı olarak değerlendirilir (Arifoğlu, 2021; Snell, 2007; Moore & Dalley, 2007).

2. OS HYOİDEUM EMBRİYOLOJİSİ VE GELİŞİMSEL TARTIŞMALAR

Baş ve boyun bölgesinin prenatal gelişimi, intrauterin yaşamın 4. ve 5. haftalarında ortaya çıkan faringeal arkus sistemine (arcus pharyngei) dayanır. Faringeal arkuslar; yüz, boyun ve üst solunum–sindirim sisteminin morfolojik organizasyonunda temel rol oynayan embriyolojik yapılardır. Her arkus, dışta ektoderm ve içte endoderm kökenli epitel ile çevrili mezenşimal bir çekirdekten oluşur. Mezodermal bileşenler kas yapılarının gelişimine katkı sağlarken, göç eden nöral krista hücreleri her arkusa özgü kıkırdak, vasküler yapı ve kranyal sinir komponentlerinin oluşumunda görev alır.

Os hyoideum'un embriyolojik kökeni konusunda farklı görüşler bulunmaktadır. Klasik embriyolojik yaklaşıma göre os hyoideum, ikinci ve üçüncü faringeal arkusların ventral segmentlerinden gelişir. Bu modele göre Reichert kıkırdağı olarak da bilinen ikinci arkus; cornu minus ile corpus hyoidei'nin superior bölümünü oluştururken, üçüncü faringeal arkus ise cornu majus ve corpus'un inferior kısmının gelişimine katkı sağlar (Moore et al.,2002; Sadler, 2018).

Buna karşın modern embriyolojik çalışmalar, corpus hyoidei'nin gelişiminde ikinci ve üçüncü arkusların doğrudan belirleyici olmayabileceğini ileri sürmektedir. Rodriguez-Vazquez ve ark.'nın tanımladığı bu yaklaşıma göre corpus hyoidei; faringeal arkusların tabanında yer alan hipobranşiyal eminens kaynaklı bağımsız bir mezenşimal kondensasyondan gelişmektedir. Aynı modele göre cornu minus Reichert kıkırdağının kaudal segmentinden, cornu majus ise üçüncü faringeal ark kıkırdağından köken alır (Rodríguez-Vázquez et al., 2011).

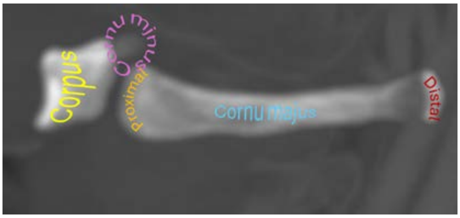
Os hyoideum'un çok merkezli embriyolojik gelişimi; erişkin dönemde gözlenen morfolojik asimetri, boynuz uzunluğu varyasyonları ve füzyon anomalilerinin olası gelişimsel temelini açıklayabilir.

3. OS HYOİDEUM'UN MAKROSKOBİK ANATOMİSİ VE TOPOGRAFİSİ

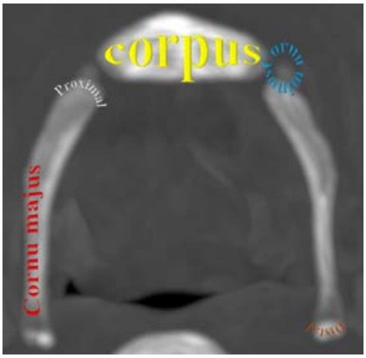
Os hyoideum, boynun ön orta hattında, cartilago thyroidea'nın superiorunda ve corpus'u yaklaşık üçüncü servikal vertebra (C3) seviyesinde yer alan, at nalı veya "U" harfi şeklinde bir kemiktir. İsmini, şekil benzerliği nedeniyle Yunanca “upsilon” harfinden türeyen *hyodeides* ifadesinden alır (Snell, 2007; Moore et al., 2002). Ortalama uzunluğu erkeklerde 40,5 mm, genişliği ise 47,2, kadınlarda uzunluğu 34,3mm, genişliği 42,6’ mm’dir (Verdi, 2025). Kemiğin konkav yüzü posteriora, konveks yüzü ise anteriora bakar.

Os hyoideum; mandibula, processus styloideus, sternum, scapula ve larengeal yapılarla ilişkili kas ve ligament kompleksleri aracılığıyla boyun bölgesinde askıda tutulur. Bu suspansiyonel organizasyon, os hyoideum’a geniş hareket kabiliyeti kazandırır ve yutma ile fonasyon sırasında larengeal kompleksin dinamik hareketlerine katkı sağlar. Ayrıca bu hareketlilik, künt servikal travmalarda kemiğin kırık gelişimine karşı göreceli korunmasında rol oynayabilir.

Anatomik olarak os hyoideum üç ana bölümden oluşur (Şekil 1.1–1.2):



a) Şekil1.1



b) Şekil 1.2

1. Corpus ossis hyoidei (Gövde): Kemiğin anterior bölümünde yer alan merkezi ve quadrilateral yapıdaki segmenttir. Anterior yüzü hafif konveks olup suprahyoid ve infrahyoid kasların tutunmasına olanak sağlayan transvers kristalar içerir. Posterior yüzü ise konkav ve daha düzgün yapıdadır; membrana thyrohyoidea ile komşuluk gösterir.

2. **Cornua majora (Büyük boynuzlar):** Corpus'un lateral uçlarından posteriora ve hafif superiora doğru uzanan çift kemik çıkıntılarıdır.

3. **Cornua minora (Küçük boynuzlar):** Corpus ile cornua majora birleşim bölgesinin superiorunda yer alan küçük, konik çıkıntılardır. Ligamentum stylohyoideum bu yapılara tutunarak os hyoideum'un kafa tabanı ile bağlantısına katkı sağlar. Cornua minora'nın küçük boyutları ve morfolojik değişkenliği nedeniyle osteometrik çalışmalarda her zaman güvenilir şekilde değerlendirilemeyebileceği bildirilmiştir (Urbanová et al., 2013).

4. ARTERİYEL BESLENMESİ

Os hyoideum ve ilişkili kas yapıları, temel olarak arteria carotis externa'nın dalları tarafından beslenir. Bu damarlar boyun ön bölgesinde geniş bir arteriyel anastomoz ağı oluşturur.

Arteria lingualis: Os hyoideum'un superior komşuluğunda seyrederek dil kökü ve suprahyoid kas gruplarına dallar verir.

Arteria submentalis: Arteria facialis'in bir dalıdır. Submental bölgede ilerleyerek suprahyoid kasların ve os hyoideum'un anterior bölümünün vaskülarizasyonuna katkı sağlar.

Ramus infrahyoideus: Arteria thyroidea superior'un bir dalı olup infrahyoid kasları ve corpus ossis hyoidei'nin inferior kısmını besler (Waschke et al., 2016; Moore & Dalley, 2007; Arifoğlu, 2021).

5. FONKSİYONEL KAS VE LİGAMENT BAĞLANTILARI

Os hyoideum, boyun ön bölgesindeki suprahyoid ve infrahyoid kas grupları için merkezi bir tutunma noktası oluşturur. Bununla birlikte m. sternothyroideus, os hyoideum'a doğrudan tutunmayan tek infrahyoid kastır. Os hyoideum; superior tarafta ligamentum stylohyoideum aracılığıyla kafa tabanına, inferior tarafta ise membrana thyrohyoidea aracılığıyla larengeal komplekse bağlanır (Arifoğlu, 2021; Garg et al., 2025; Moore et al., 2020; Moore & Dalley, 2007; Ozan, 2004; Pınar, 2019; Snell, 2007; Standiring, 1998; Urbanová et al., 2013; Waschke et al., 2016).

Suprahyoid ve infrahyoid kas grupları birlikte çalışarak yutma, fonasyon, mandibular hareketler ve üst hava yolu stabilitesinde önemli rol oynar. Suprahyoid kaslar genel olarak os hyoideum'u superiora taşırken, infrahyoid kaslar kemiğin stabilizasyonu ve inferiora çekilmesinden sorumludur.

6. KLİNİK VE ADLİ TIP AÇISINDAN ÖNEMİ

Os hyoideum; respirasyon, fonasyon ve deglutisyon fonksiyonlarının mekanik kesişim noktasında yer alan önemli bir anatomik yapıdır. Dil tabanına destek sağlamasının yanı sıra yutma, konuşma, hava yolu açıklığının sürdürülmesi ve mandibular hareketlerin koordinasyonunda görev alır. Bu nedenle anatomi, otorinolaringoloji, maksillofasiyal cerrahi, uyku cerrahisi ve adli tıp gibi birçok disiplin açısından klinik önem taşır (Ito et al., 2012).

Herhangi bir kemikle doğrudan artikülasyon yapmamasına rağmen os hyoideum; mandibula, basis cranii, lingua, larynx ve scapular kompleks ile fonksiyonel bağlantılar içerisindedir. Bu özellik, kemiğin dinamik hareket kapasitesinin yanı sıra üst hava yolu biyomekaniğindeki merkezi rolünü de açıklar (Auvenshine & Pettit, 2020).

6.1. Os Hyoideum Postürü ve Temporomandibular Bozukluklar

Os hyoideum'un uzaysal pozisyonu ve bu pozisyonun kas tonusu ile korunması "hyoid postürü" olarak tanımlanır. Sabit kemiksel artikülasyonunun bulunmaması nedeniyle bu denge tamamen çevre kas sisteminin fonksiyonel bütünlüğüne bağlıdır (German et al., 2011).

Temporomandibular bozukluklar ile os hyoideum ve servikal omurga pozisyonu arasında biyomekanik ilişkiler olduğu bildirilmiştir (Opris et al., 2022). Uzun süreli oklüzal splint tedavileri ve fizyoterapi uygulamalarının, hyoid pozisyonunda değişikliklere ve alt orofaringeal hava yolu boyutlarında farklılıklara yol açabileceği radyolojik çalışmalarla gösterilmiştir (Derwich & Pawlowska, 2022).

Nadir olgularda, uzamış cornu majus'un karotis arterler üzerinde bası oluşturarak tekrarlayan serebrovasküler olaylara neden olabileceği bildirilmiştir (Xia & Li, 2024).

6.2. Os Hyoideum İnsersiyon Tendiniti (Os Hyoideum Sendromu)

Os hyoideum'un özellikle cornu majus bölgesindeki kas tutunma alanlarında gelişen enflamatuar süreç "hyoid sendromu" veya "insersiyon tendiniti" olarak tanımlanır. Klinik olarak yutma ve boyun hareketleriyle artan kronik boyun ağrısı ile karakterizedir. Ağrı temporal bölgeye, kulağa, posterior farinks duvarına veya m. sternocleidomastoid boyunca yayılım gösterebilir.

Tanı çoğunlukla fizik muayene ve lokal hassasiyet bulgularına dayanır. Görüntüleme yöntemleri ayırıcı tanı amacıyla kullanılmaktadır. Tedavide konservatif yaklaşımlar, nonsteroid antiinflamatuar ilaçlar ve lokal enjeksiyonlar ön plandadır; dirençli olgularda cerrahi tedavi uygulanabilir (Aydil et al., 2007).

6.3. Eagle Sendromu ve Stilohiyoid Kompleks İlişkisi

1937 yılında Dr. Watt Eagle tarafından tanımlanan Eagle sendromu; processus styloideus'un uzaması veya ligamentum stylohyoideum'un ossifikasyonu sonucu gelişen semptomatik bir klinik tablodur (Eagle, 1937; Eagle, 1958). Stilohyoid kompleksin anormal ossifikasyonu, boyun ağrısı, disfaji, otalji ve farengeal rahatsızlık hissi gibi semptomlara yol açabilir. Bununla birlikte ligamentum stylohyoideum ossifikasyonu asemptomatik bireylerde tesadüfi radyolojik bulgu olarak da saptanabilmektedir (Öztaş & Orhan, 2012; Mahdian et al., 2014).

6.4. Obstrüktif Uyku Apnesi ve Üst Hava Yolu Kollapsı

Obstrüktif uyku apnesi, uyku sırasında üst hava yolunun tekrarlayan kollapsı ile karakterize kronik bir solunum bozukluğudur (Heinzer et al., 2015; Peppard et al., 2013; Punjabi, 2008). Os hyoideum'un inferior ve posterior yerleşimi, farengeal hava yolu daralması ile ilişkilendirilmiştir. Suprahyoid ve infrahyoid kas grupları arasındaki tonus dengesizlikleri üst hava yolu kollapsibilitesini artırabilir (Sforza et al., 2000; Tantawy et al., 2018). Cerrahi tedavi seçeneklerinden biri olan hyoidothyroidopexy, os hyoideum'u anterosuperior yönde stabilize ederek hava yolu açıklığını artırmayı amaçlar (Tantawy et al., 2018).

6.5. Adli Antropoloji ve Otopsi Bulgularında Os Hyoideum

Os hyoideum, adli antropolojide yaş ve cinsiyet tahmini açısından önemli morfolojik veriler sunar. Hyoid morfometrisine dayalı diskriminant analiz ve lojistik regresyon modellerinin cinsiyet tayininde yüksek doğruluk oranlarına ulaşabildiği bildirilmiştir (Fisher et al., 2016), (Balseven-Odabasi et al., 2013). Ayrıca kemik yoğunluğu ve cornu majus–corpus füzyon derecesinin yaş tahmini açısından potansiyel parametreler olduğu ifade edilmektedir. Bununla birlikte füzyon zamanlamasında belirgin bireysel varyasyon bulunduğu ve gecikmiş füzyonun travmatik kırık ile karıştırılmaması gerektiği vurgulanmaktadır.

Adli patolojide ise os hyoideum ve larengeal kıkırdak kompleksinin değerlendirilmesi; elle boğma, ligatür strangülasyonu ve ası vakalarında önemli postmortem bulgular sağlar. Boyun bölgesine uygulanan kompresif kuvvetler os hyoideum ve ilişkili yapılarda kırık ve hemorajik lezyonlara neden olabilir (Ito, K., et al. 2012; Garg et al., 2025).

7. OS HYOİDEUM'UN OSSİFİKASYON DİNAMİKLERİ VE FÜZYON KRİTERLERİ

Os hyoideum, endokondral ossifikasyon paterni gösteren bir kemiktir ve toplam altı primer ossifikasyon merkezinden gelişir. Bunların ikisi corpus ossis hyoidei'de, ikisi cornua majora'da ve ikisi cornua minora'da yer alır. Ossifikasyon odakları fetal dönemin sonlarına doğru ilk olarak cornua majora'da, kısa süre sonra ise corpus bölgesinde ortaya çıkar. Cornua minora'daki ossifikasyon ise genellikle postnatal dönemde, yaşamın ilk 1–2 yılı içerisinde başlar (Arifoğlu, 2021; Elhan & Arıncı, 2006; By & Parsons, 1909; Waschke, 2016).

Yaş ilerledikçe bu ossifikasyon merkezleri giderek birleşir ve tek kemik yapısı hâline gelir. Bununla birlikte corpus ile cornua majora arasındaki füzyonun derecesi ve zamanlaması bireyler arasında belirgin farklılık gösterebilir. Bazı bireylerde ileri yaşlarda tam kemiksel ankiloz gelişirken, bazı olgularda sinkondrotik yapı yaşam boyunca korunabilmektedir (Balseven-Odabasi et al., 2013; Parsons, 1909; Gupta et al., 2008; Porrath, 1969).

Literatürde, bilateral tam füzyonun genç erişkinlerde nadir olduğu; füzyon sıklığının yaşla birlikte arttığı ve erkeklerde kadınlara göre daha erken ortaya çıkma eğiliminde olduğu bildirilmektedir Ito, K., et al. 2012; Gupta et al., 2008). Bununla birlikte os hyoideum'un ossifikasyon dinamikleri üzerine yapılan çalışmaların sınırlı sayıda olduğu ve populasyonlar arasında belirgin varyasyon bulunduğu vurgulanmaktadır.

7.1. Antropolojik Füzyon Sınıflaması

Corpus ossis hyoidei ile cornua majora arasındaki füzyon derecesinin değerlendirilmesinde standart kriter eksikliği, yaş ve cinsiyet çalışmalarında bildirilen farklılıkların temel nedenlerinden biri olarak kabul edilmektedir. Bu nedenle literatürde, füzyonun derecelendirilmesi amacıyla dört basamaklı bir sınıflama sistemi önerilmiştir (Fisher et al., 2016):

Derece 0 (Non-füzyon / Açık eklem):
Corpus ile cornu majus arasındaki mesafe ≥2.5 mm'dir.

Derece 1 (Erken evre yaklaşma):
Eklem aralığı 2.5 mm'nin altındadır; ancak kemiksel köprü oluşmamıştır.

Derece 2 (Parsiyal füzyon):
Kemiksel birleşme başlamıştır; ancak rezidüel eklem hattı izlenebilmektedir.

Derece 3 (Tam füzyon / Ankiloz):
Corpus ve cornu majus tamamen birleşmiştir; ayırt edilebilir eklem aralığı bulunmaz.

Bazı araştırmacılar derece 0 ve 1'i birlikte değerlendirerek füzyonu; non-füzyon, parsiyal füzyon ve tam füzyon olmak üzere üç ana grupta incelemektedir.

8. BİLGİSAYARLI TOMOGRAFİ TABANLI HYOİD MORFOMETRİSİ VE YAPAY ZEKÂ UYGULAMALARI

Os hyoideum'un kırılgan yapısı ve postmortem süreçte kolaylıkla kaybolabilmesi, geleneksel osteometrik incelemelerde güvenilir ölçüm elde edilmesini güçleştirmiştir. Günümüzde yüksek çözünürlüklü Bilgisayarlı Tomografi (BT) görüntüleme yöntemleri ve üç boyutlu (3D) rekonstrüksiyon teknikleri, hyoid morfometrisinin değerlendirilmesinde yaygın olarak kullanılmaktadır. Bu yöntemler, kemiğe zarar vermeden yüksek doğrulukta ölçüm yapılmasına ve geniş veri setlerinin dijital ortamda analiz edilmesine olanak sağlamaktadır.

BT tabanlı morfometrik analizlerde; total hyoid uzunluğu ve genişliği, corpus ossis hyoidei'nin boyutları, cornua majora uzunlukları, distal uç yükseklikleri ve intercornual açı gibi parametreler değerlendirilmektedir. Özellikle corpus genişliği, total hyoid boyutları ve cornu majus distal uç vertikal parametrelerin cinsiyet ayrımında yüksek diskriminatif değere sahip olduğu bildirilmiştir.

Geleneksel istatistiksel yöntemler arasında yer alan doğrusal diskriminant analizi ve lojistik regresyon modelleri, hyoid morfometrisine dayalı cinsiyet tahmininde yüksek doğruluk oranları sağlayabilmektedir. Bununla birlikte os hyoideum'un anatomik varyasyonları, bilateral asimetrileri ve yaşa bağlı füzyon farklılıkları; doğrusal olmayan veri örüntülerinin değerlendirilmesini gerektirmektedir. Bu nedenle son yıllarda makine öğrenmesi (machine learning) ve derin öğrenme (deep learning) tabanlı yaklaşımlar ön plana çıkmıştır.

Literatürde, Random Forest, Support Vector Machine, XGBoost ve k-nearest neighbors gibi cinsiyet tahmininde kullanılan farklı makine öğrenmesi algoritmalarının geleneksel istatiksel analiz yöntemlerine kıyasla benzer veya daha yüksek sınıflandırma performansı gösterebildiği bildirilmiştir (Abdelkader et al., 2025; Mutlu et al., 2024; Ferraz et al., 2024; Nikita & Nikitas, 2020; Tyagi et al., 2021). Özellikle Türk popülasyonu üzerinde gerçekleştirilen çalışmalarda, BT tabanlı hyoid morfometrisinin makine öğrenmesi algoritmalarıyla (Logistic regression, Linear Discriminant Analysis, Decision Tree, Random Forest, Support Vector Machine, k-Nearest Neighbors, ve Gaussian Naive Bayes) birlikte kullanıldığında adli antropoloji standartları açısından yüksek doğruluk oranlarına ulaşabildiği gösterilmiştir (Verdi, 2025).

Derin öğrenme tabanlı yaklaşımlar ise doğrudan piksel veya voxel verileri üzerinden analiz yapabilmeleri nedeniyle dikkat çekmektedir. DenseNet121 gibi konvolüsyonel sinir ağı mimarilerinin kullanıldığı çalışmalarda, hyoid kemik görüntülerinden dengeli duyarlılık ve özgüllük değerleri elde edildiği bildirilmiştir (Bakici et al., 2024).

Sonuç olarak, BT tabanlı üç boyutlu hyoid morfometrisinin yapay zekâ destekli analiz yöntemleriyle birlikte kullanımı; adli kimliklendirme, iskelet kalıntılarının incelenmesi ve postmortem analizlerde objektif ve yüksek doğruluklu değerlendirmeler sunan modern bir yaklaşım hâline gelmiştir.

9. SONUÇ

Os hyoideum, insan iskeletinde başka bir kemikle doğrudan eklem yapmayan tek kemik olması nedeniyle anatomik açıdan özgün bir konuma sahiptir. Yutma, fonasyon, solunum ve üst hava yolu stabilitesindeki kritik rolü nedeniyle yalnızca baş-boyun anatomisinin bir bileşeni olarak değil, aynı zamanda fonksiyonel bir biyomekanik merkez olarak değerlendirilmelidir.

Embriyolojik gelişim sürecindeki çok merkezli yapısı, erişkin dönemde gözlenen morfolojik varyasyonların ve füzyon farklılıklarının anlaşılmasına katkı sağlamaktadır. Bunun yanında os hyoideum; temporomandibular bozukluklar, obstrüktif uyku apnesi, Eagle sendromu ve çeşitli boyun patolojileri ile ilişkisi nedeniyle klinik açıdan da önem taşımaktadır.

Son yıllarda bilgisayarlı tomografi tabanlı üç boyutlu görüntüleme yöntemlerinin yaygınlaşması, os hyoideum morfolojisinin ayrıntılı ve tekrarlanabilir biçimde incelenmesine olanak sağlamıştır. Özellikle adli antropoloji alanında gerçekleştirilen çalışmalar, hyoid morfometrisinin yaş ve cinsiyet tahmininde güvenilir parametreler sunabildiğini göstermektedir.

Makine öğrenmesi ve derin öğrenme tabanlı yapay zekâ uygulamalarının gelişmesiyle birlikte os hyoideum analizlerinin daha objektif, hızlı ve yüksek doğrulukla gerçekleştirilebilmesi mümkün hâle gelmiştir. Gelecekte farklı popülasyonlardan elde edilecek geniş veri setleri ve otomatik görüntü analiz sistemleri sayesinde os hyoideumun klinik ve adli uygulamalardaki kullanım alanlarının daha da genişlemesi beklenmektedir.

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ANATOMİ ALANINDA

AKADEMİK TARTIŞMALAR

yaz

yayınları

YAZ Yayınları
M.İhtisas OSB Mah. 4A Cad. No:3/3
İscehisar / AFYONKARAHİSAR
Tel : (0 531) 880 92 99
yazyayinlari@gmail.com • www.yazyayinlari.com