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## INTRODUCTION

The complexity of the paranasal sinuses anatomy, as well as their many functions make the sinuses an interesting and rewarding topic of study.  There are a total of four paired sinuses.  They include the frontal, ethmoid, maxillary and sphenoid sinuses.  These sinuses are essentially mucosa-lined airspaces within the bones of the face and skull.  Their development begins in the womb, but results in only two clinically-relevant sinuses by birth--the maxillary and ethmoid sinuses.  The development of the lateral nasal wall begins with a smooth, undifferentiated structure.  The first outgrowth is the maxilloturbinal which will eventually become the inferior turbinate.  Subsequently, another mound of mesenchyme forms which is the ethmoturbinal, destined to become the middle, superior, and supreme turbinates by subdividing into the second and third ethmoturbinals.  This growth is followed by the development of the agger nasi cells, uncinate process, and ethmoid infundibulum.  The sinuses then begin to develop.  The resultant system of cavities, depressions, ostia, and processes is a complex system of structures which must be understood in detail before surgical management of sinus disease can be safe and effective.  The physical anatomy, microscopic anatomy, physiology and function of the sinuses will be explored.

## LATERAL NASAL WALL

The lateral nasal wall includes portions of the ethmoid, the maxilla, the palatine, the lacrimal, the medial pterygoid plate of the sphenoid, the nasal and the inferior turbinate bones.  Three to four turbinates project from the wall; the supreme, superior, and middle turbinates being projections of the ethmoid bone.  The inferior is considered to be an independent structure.  Each of these structures overlies an airspace beneath and lateral to it known as a meatus.  A small slip of bone projects from the ethmoid bone which covers the opening(s) of the laterally placed maxillary sinus and forms a trough behind the middle turbinate.  This thin bony partition is known as the uncinate process.   The superior nasal sidewall consists of ethmoid sinus cells

which laterally border the olfactory epithelium and the fragile cribiform plate.  Superior to the anterior most ethmoid cells lies the frontal sinus which drains between an assortment of air cells.  The posterior-superior aspect of the lateral nasal wall becomes the anterior wall of the sphenoid sinus which nestles below the sella turcica and the cavernous sinus.

## MAXILLARY SINUS

**Development**
       The maxillary sinus (antrum of Highmore) is the first to develop.  These structures are usually fluid-filled at birth.  The growth of these sinuses is biphasic with growth during years 0-3 and 7-12.  During the later phase pneumatization spreads more inferiorly as the permanent teeth take their place.  Pneumatization can be so extensive as to expose tooth roots with only a thin layer of soft tissue covering them.

**Structure**
       The adult maxillary sinus is a pyramid which has a volume of approximately 15 ml (34x33x23mm).  The base of the pyramid is the nasal wall with the peak pointing toward the zygomatic process.  The anterior wall  has the infraorbital foramen located at the midsuperior portion with the infraorbital nerve running over the roof of the sinus and exiting through the foramen.  This nerve can be dehiscent (14%).  The thinnest portion of the anterior wall is just above the canine tooth--the canine fossa.  The roof is formed by the orbital floor and transected by the course of the infraorbital nerve.  The posterior wall is unremarkable.  Behind this wall  is the pterygomaxillary fossa with the internal maxillary artery, sphenopalatine ganglion and the Vidian canal, the greater palatine nerve and the foramen rotundum.  The floor, as discussed above, varies in it's level.  From birth to age nine the floor of the sinus is above that of the nasal cavity.  At age nine the floor is generally at the level of the nasal floor.  The floor continues to sink as the maxillary sinus pneumatizes.  Because of the close relationship with the dentition dental disease can cause maxillary infection, and tooth extraction can result in oral-antral fistulae.

**Vascular supply**
       Branches of the internal maxillary artery supply this sinus.  These include the infraorbital (as it runs with the infraorbital nerve), lateral branches of the sphenopalatine, greater palatine, and the alveolar arteries.  Venous drainage runs anteriorly into the facial vein and posteriorly into the maxillary vein and jugular vs. dural sinus systems.

**Innervation**
       The maxillary sinus is innervated by branches of V2.  Specifically, the greater palatine nerve and the branches of the infraorbital nerve.

**Related structures**

*Nasolacrimal duct*
       The nasolacrimal duct drains the lacrimal sac and runs from the lacrimal fossa in the orbit down the posterior aspect of the maxillary vertical buttress and empties in the anterior aspect of

the inferior meatus.  The duct lies very close to the maxillary ostium.  On average it lies 4mm-9mm anterior to the ostium.

### Natural ostium

The natural maxillary ostium is located at the superior aspect of the medial wall of the sinus.  Intranasally, it is usually in the posterior half of the ethmoid infundibulum, or behind the lower 1/3 of the uncinate process.  The posterior edge of the ostia is continuous with the lamina papyracea, thus a reliable landmark for the lateral limit of surgical dissection.  The ostium size averages 2.4 mm but can vary from 1 to 17mm.  The ostium is much smaller than that actual bony defect, as mucosa fills this area and defines the extent of the opening.  88% of maxillary ostium are hidden behind the uncinate process and therefore cannot be visualized endoscopically.

### Anterior/Posterior Fontanelles/Accessory Ostium

Two bony dehiscences of the lateral nasal wall/maxillary sinus medial wall exist (sometimes there is one large bone dehiscence.  These are usually covered by mucosa.  In some individuals the anterior or posterior fontanelles may be patent which results in an accessory ostium.  They are nonfunctional ostia and serve to drain the sinus only if the natural ostium is blocked and intrasinus pressure/gravity moves material out of the ostium.  Accessory ostium are usually found in the posterior fontanel.

## ETHMOID SINUSES

### Development

The ethmoid sinuses are well-delineated, fluid-filled structures in a newborn child.  During fetal development the anterior cells form first, followed by the posterior cells.  The cells grow gradually and are adult size by age 12.  They are not usually seen on radiographs until age one.  The septa gradually thin and pneumatization spreads as the child ages.  Ethmoid cells are the most variable and can often be found above the orbit, lateral to the sphenoid, into the roof of the maxillary sinus, and anteriorly above the frontal sinus.  These cells have been named.  A cell above the orbit is called a supraorbital cell and is found in 15% of patients.  Invasion of an ethmoid cell into the floor of the frontal sinus is called a frontal bulla.  Extension into the middle turbinate is termed concha bullosa.  Cells in the roof of the maxillary sinus (infraorbital) are called, "Haller's cells," and are found in 10% of the population.  These cells can obstruct the maxillary ostia and narrow the infundibulum and result in disruption of normal sinus function.  Finally, a cell which extends anteriolaterally to the sphenoid sinus is called an Onodi cell (10%).  The common variability of these cells makes preoperative imaging essential to clarify a patient's individual anatomy.

### Structure

Posterior and anterior cells combined have a volume of 15 ml (3.3x2.7x1.4cm).  The ethmoids are shaped like a pyramid and are divided into multiple cells by thin septa.  The roof of the ethmoids is composed of multiple important structures.  The roof slopes both posteriorly (angle of 15 degrees) and medially.  The anterior 2/3 of the roof is thick and strong and is composed of the frontal bone and the foveolae ethmoidalis.  The posterior 1/3 is higher laterally and slopes down medially to the cribiform plate.  The junction between the lateral dense bone and the plate is one-tenth as strong as the lateral roof.  The difference in height between the

lateral and medial roof is variable, but can be as much as 15-17mm.  The posterior aspect of the ethmoid cells borders on the sphenoid sinus.  The lateral wall is the lamina papyracea of the orbit.

## Vascular supply

The ethmoid sinuses are supplied by blood flow originating from both the external and internal carotid arteries.  The Sphenopalatine artery as well as the ophthalmic artery (which branches into the anterior and posterior ethmoid arteries) supply the sinus.  Venous drainage follows arterial supply and thus can track infection intracranially.

## Innervation

Both V1 and V2 innervate this region.  V1 supplies the more superior aspect with V2 innervating the inferior regions.  Parasympathetic innervation is via the Vidian nerve.  Sympathetic innervation is via the cervical sympathetic ganglion and follows the arterial vasculature to the mucosa of the sinuses.

## Related structures

### Basal Lamella (Ground Lamella) of the Middle Turbinate

This structure forms the separation between the anterior and posterior ethmoid cells.  It is the attachment of the middle turbinate and runs in three different planes in it's course from anterior to posterior.  The anterior most portion is vertical and inserts in the crista ethmoidalis and skull base.  The middle third is oblique with insertion in the lamina papyracea.  The final third runs horizontal with insertion in the lamina papyracea.  The space under the middle turbinate is termed the middle meatus into which the anterior ethmoids, frontal sinus, and maxillary sinus drain.  Surgical damage to the anterior or posterior portions of the middle turbinate may destabilize this structure and anteriorly risks disruption of the cribiform plate.

### Anterior vs. posterior Ethmoid cells

The anterior cells are those anterior to the basal lamella.  They drain into the middle meatus via the ethmoid infundibulum.  They include the agger nasi cells, the ethmoid bulla and any other anterior cells.  The posterior cells drain into the superior meatus and border on the sphenoid sinus.  They are generally fewer in number and larger than the anterior cells.

### Agger nasi cell

The cell is found in the lacrimal bone anterior and superior to the junction of the middle turbinate with the nasal wall (often described as the bulge in the lateral nasal wall where the middle turbinate attaches).  It is hidden behind the anterior most aspect of the uncinate process and drains into the hiatus semilunaris.  It is the first cell to pneumatize in the newborn and is prominent through childhood.  There can be from one to three cells.  The posterior wall of the cell forms the anterior wall of the frontal recess.  The roof of the agger nasi cell is the floor of the frontal sinus, and is therefore, an important landmark for frontal sinus surgery.

### Ethmoid Bulla

This is the most constant landmark for surgery.  It lies above the infundibulum and it's lateral/inferior surface and the superior edge of the uncinate process forms the hiatus semilunaris.

It is usually the largest of the anterior ethmoid cells.  The anterior ethmoid artery usually courses across the roof of this cell.  Suprabullar and retrobullar recesses may be formed when the ethmoid bulla does not extend to the skull base.  The suprabullar recess is when there is a cleft between the roof of the ethmoid bulla and the fovea.  The retrobullar space is formed when there is a cleft between the basal lamella and bulla.  This retrobullar space opens into what is known as the "hiatus semilunaris superior."

### Ethmoid infundibulum

The development of the infundibulum precedes that of the sinuses.  This recess, into which the anterior ethmoid sinuses, maxillary sinus and frontal sinus drain, is formed by multiple structures.  The anterior wall is formed by the uncinate process, the medial wall is the frontal process of the maxilla and the lamina papyracea.  It runs anteriorly in continuity with the frontal recess to it's posterior limit where the uncinate process attaches to the lamina.  The opening above the recess is known as the hiatus semilunaris.  The maxillary sinus is found in this area.

### Anterior/Posterior Ethmoid Arteries

The anterior and posterior ethmoid arteries arise from the ophthalmic artery in the orbit.  The anterior artery crosses the medial rectus and penetrates the lamina papyracea.  The artery then courses across the roof the ethmoid sinus in a thin bony mesentery (usually dehiscent), eventually supplying the cribiform plate and anterior septum.  This artery is usually large and singular and may drape inferiorly into a sinus cell.  It's position closely corresponds to the position of the more medial structure, ethmoidal fovea.  The posterior artery crosses the medial rectus, penetrates the lamina papyracea and courses through the posterior ethmoid cells (usually corresponding with the anterior wall of the posterior-most cell) to the septum.  It supplies the posterior ethmoid sinuses, part of the superior and middle turbinates and small amount of the posterior septum.  This artery is usually smaller and branched.  It can be dehiscent and drape down within the sinus cells.  It's position is associated with the position of the optic nerve near the orbital vertex.  Because the development of these structures predate the sinuses their relation to the ethmoid cells can vary.  Their association with the fovea and optic nerve remain constant.

## FRONTAL SINUS

### Development

The frontal sinus is likely formed by the upward movement of the anterior-most ethmoid cells.  Since the frontal bone is membranous at birth there is seldom more than a recess until the bone begins to ossify around age two.  Thus, radiographs seldom show this structure before that time.  True growth begins at age five and continues into the late teens.

### Structure

The volume of the sinus is approximately 6-7 ml (28x24x20mm).  Frontal sinus anatomy is highly variable, but generally there are two sinuses which are funnel shaped and point upward.  The depth of the sinus is the most surgically significant dimension as it determines the limitations of surgical approach.  Both frontal sinuses have their ostia at the most dependant portion of the cavity (posteriomedial).  Many feel this is the reason that these sinuses are rarely involved with infectious disease.  Both the anterior and posterior walls of this sinus are composed of diploe bone.  However, the posterior wall (separates the frontal sinus from the

anterior cranial fossa) is much thinner.  The floor of the sinus also functions as a portion of the orbital roof.

**Vascular supply**
　　　The frontal sinus is supplied by the ophthalmic artery via the supraorbital and supratroclear arteries.  Venous drainage is via the superior ophthalmic veins to the cavernous sinus and via small venulae in the posterior wall which drain to the dural sinuses.

**Innervation**
　　　The frontal sinus is innervated by a branches of V1.  Specifically, these nerves include the supraorbital and supratrochlear branches.

**Related structures**
*Frontal recess*
　　　The frontal recess is the space between the frontal sinus and the hiatus semilunaris into which the sinus drains.  It is bounded anteriorly by the agger nasi cell and superiorly by the frontal sinus, medially by the middle turbinate, and laterally by the lamina papyracea.  The cavity resembles a dumbbell as the frontal sinus narrows to the sinus ostium/channel and then opens again into the wider frontal recess.  Depending on the extent of ethmoid pneumatization, this recess can become tubular resulting in a much longer narrowing of the dumbbell.  Anomalous structures, such as the sinus lateralis (posterior to the frontal recess at the skull base) and frontal bulla (anterior to the recess at the base of the frontal sinus) may be mistaken as the frontal sinus during sinus surgery.

# SPHENOID SINUS

**Development**
　　　The sphenoid sinuses are unique in that they do not arise from outpouchings of the nasal cavity.  These sinuses arise from within the nasal capsule of the embryonic nose.  They remain undeveloped until age three.  By age seven the pneumatization has reached the sella turcica.  By age 18 the sinuses have reached full size.

**Structure**
　　　In the late teen years the sinus reaches it's full size with a volume of 7.5 ml (23x20x17mm).  Pneumatization of this sinus, like that of the frontal sinus, is very variable. Generally these are bilateral structures located at the posteriosuperior aspect of the nasal cavity. Pneumatization can extend as far as the clivus, the sphenoid wings, and the foramen magnum. The walls of the sphenoid vary in thickness with the anterosuperior wall and roof being the thinnest (.1 to 1.5 mm).  The other walls are thicker.  The thinnest part of the anterior wall is 1cm from the fovea ethmoidalis.  The position of the sinus and, therefore, it's anatomic relationships depend on the extent of pneumatization.  The sinus can sit far anterior to, just anterior to, or immediately under the sella turcica (conchal, presellar, sellar/postsellar).  The most posterior position can place the sinus just adjacent to vital structures such as the carotid arteries, optic nerves, maxillary branch of the trigeminal nerve, the Vidian nerve, the pons, sella turcica, and the cavernous sinus.  These structures are often identified as indentions on the roof and walls of the sinus.  A small percentage will have dehiscence of bone over such vital structures as the optic

nerve and carotid arteries.  Care must also be taken when removing sinus septa as these may be in continuity with the carotid and optic canal and can result in death and blindness.

The sphenoid sinus ostium drains into the sphenoethmoidal recess.  The ostium is very small (.5-4mm) and is located about 10mm above the sinus floor.  A 30 degree angle drawn from the anterior nasal floor approximates the location of the ostium on the posteriosuperior nasal wall.  It is noted to be close to the midline at the junction of the upper 1/3 and the lower 2/3 of the anterior sinus wall.  It is generally medial to the supreme/superior turbinate, and is only a few millimeters from the cribiform plate.  This ostium, like that of the maxillary sinus, has a much larger bony dehiscence which is narrowed by a membranous septum.

**Vascular supply**
The posterior ethmoid artery supplies the roof of the sphenoid sinus.  The rest of the sinus is supplied by the sphenopalatine artery.  Venous drainage is via the maxillary veins to the jugular and pterygoid plexus systems.

**Innervation**
The sphenoid sinus is supplied by branches from both V1 and V2.  The nasociliary nerve (from V1) runs into the posterior ethmoid nerve and supplies the roof.  The branches of the sphenopalatine nerve (V2) supply the floor.

**Related structures**

*Sphenoethmoidal recess*
The sphenoethmoid recess is a space behind and above the most superior turbinate.  The boundaries of this space are formed by multiple structures.  The anterior wall of the sphenoid sinus forms the posterior aspect.  The nasal septum and cribiform plate form the medial and superior aspects.  The anteriolateral extent is determined by the most superior turbinate.  The space opens into the nasal cavity inferiorly.  The posterior ethmoid cells, as well as the sphenoid sinus empty into this region.

*Sphenoid rostrum*
This structure is simply the midline projection of the anterior sphenoid sinus wall.  It articulates with the perpendicular plate and the vomer.

*Onodi cell*
As discussed above, these cells are ethmoid cells which are located anteriolateral to the sphenoid sinus.  Vital structures such as the carotid artery and optic nerve may run through this cell.  These structures are often dehiscent.  This requires careful dissection in this area and good preoperative radiographic examination to avoid poor outcomes.

## MICROSCOPIC ANATOMY
The sinuses are lined with pseudostratified ciliated columnar epithelium which is continuity with the mucosa of the nasal cavities.  The epithelium of the sinuses is thinner than that of the nose.  There are four basic cell types.  These include ciliated columnar epithelial cells, noncilliated columnar cells, basal cells, and goblet cells.  The ciliated cells have 50-200 cilia per

cell with the usual structure of 9+2 microtubules with dynein arms. Experimental data shows these cells to beat at 700-800 times a minute, moving mucus at a rate of 9 mm/minute. Noncilliated cells are characterized by microvilli which cover the apical aspect of the cell and serve to increase surface area (likely to facilitate humidification and warming of inspired air). It is interesting to note that there is an increased concentration (up to 50%) at the sinus ostium. The basal cell's function is unknown. They vary in size, shape and number. Some have theorized that they serve as a stem cell which can differentiate as needed. Goblet cells produce glycoproteins which are responsible for the viscosity and elasticity of mucus. They are innervated by the parasympathetic and sympathetic nervous system. Thus, parasympathetic stimulation induces thicker mucus with sympathetic stimulation leading to more watery mucus secretion.

The epithelial layer is supported by a thin basement membrane, lamina propria, and periosteum. Both serous and mucinous glands tract down into the lamina propria. Anatomic studies have shown a general paucity of goblet cells and submucosal glands in the sinuses compared to the nasal mucosa. When comparing the sinuses, the maxillary sinus has the highest density of goblet cells. The ostia of the maxillary, sphenoid, and anterior ethmoid sinuses seem to have an increased number of submucosal serous and mucinous glands.

## MUCOCILIARY CLEARANCE
The ciliated cells in each sinus beat in a specific direction. A resulting pattern of mucus flow results. Since many of the sinuses develop in an outward and inferiorly fashion, the ciliated mucosa often moves material against gravity to the sinus' exit. This means that mucus produced just adjacent to a sinus ostia, if it is on the afferent side, will travel around the entire sinus cavity, often against gravity, before exiting the ostia. This is one reason that creation of accessory ostia at sites outside the physiologic ostium will not significantly improve sinus drainage. In fact, this sometimes results in mucus draining from the natural ostia reentering the sinus via the newly created opening and cycling through the sinus again. Hilding was the first that described each sinuses' mucus flow patterns, and his observations are still valid today. Later researchers described a phenomenon of stagnation which occurs when two ciliated surfaces come into contact (particularly applicable at the osteomeatal complex). This disrupts mucociliary mucus clearance and can result in sinusitis. Clearance of the disease is accomplished when this clearance mechanism has been restored.

## SINUS FUNCTION
The physiology and function of the sinuses has been the subject of much research. Unfortunately, we still are unsure as to all the functions of these air-filled spaces. Multiple theories of function exist. These include the functions of warming/humidification of air, assisting in regulation of intranasal pressure and serum gas pressures (and subsequently minute ventilation), contributing to immune defense, increasing mucosal surface area, lightening the skull, giving resonance to the voice, absorbing shock, and contributing to facial growth. The nose is an amazing humidifier and warmer of air. Even at seven liters/minute of airflow, the nose has not reached it's maximal ability to perform this function. Nasal humidification has been shown to contribute as much as 6.9 mm Hg on serum pO2. Although the nasal mucosa is best adapted to perform this task, the sinuses contribute to mucosal surface area and warming ability.

Some researchers have shown that mouth breathers have a decreased end-tidal $CO_2$ which may increase serum $CO_2$ and contribute to sleep apnea.

Because of the sinuses' copious mucous production they contribute heavily to the immune defense/air filtration performed by the nose.  The nasal and sinus mucosa is ciliated and functions to move mucus to the choanae and the stomach beyond.  The thickened superficial layer of nasal mucus serves to trap bacteria and particulate matter in a substance rich with immune cells, antibodies, and antibacterial proteins.  The underlying *sol* layer is much thinner and serves to provide a thinner substrate in which the cilia are able to beat; their tips essentially grabbing the superficial layer and pushing it in the direction of the beat.  Unless obstructed by disease or anatomical variance, the sinuses move mucous through their cavities and out of their ostia toward the choane.  The most recent research on sinus function has focused on the molecule Nitrous Oxide (NO).  Studies have shown that the production of intranasal NO is primarily in the sinuses.  NO has been shown to be toxic to bacteria, fungi, and viruses at levels as low as 100 ppb.  Nasal concentrations of this substance can reach 30,000 ppb which some researchers have theorized as the mechanism of sinus sterilization.  NO has also been shown to increase ciliary motility.

The physiology and function of the paranasal sinuses is a subject that reflects the complexity of their anatomy.  Continued research may likely reveal that all of these functions are part of a bigger, more involved picture than is now apparent.

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