Abstract

Objective: The objective of this presentation is to display a series of new anatomical concepts and terms regarding the frontal sinus, its drainage pathway and cells vs. spaces of the anterior ethmoid, based on Three-Dimensional Computer X-ray Tomography Stereoscopic Imaging (3DCTSI) and contrast these concepts to those reported in the current literature.

Methods: Given the new anatomic observations provided by 3DCTSI, and the widespread anatomic variations a small sample was initially selected to describe our observations. Six exemplary cases according to the “Classification of Fronto-Ethmoidal cells” by Kuhn, Bent et al., Lee et al., expanded by Wormald et al., and adopted by Ramakrishnan et al., Huang et al., and Void et al. (1-7) were chosen to illustrate our detailed anatomic observations. Additional observations and data of prevalence identified in a larger series will follow.

Results and Conclusion: Conceptually, the anterior ethmoid “cells” are in essence “spaces” with openings that communicate with the middle meatus and/or the ethmoidal infundibulum. The frontal sinus and frontal recess are a united and continuous three-dimensional, irregularly shaped space, the Frontal Sinus/Recess Space (FSRS). The uncinate process has two segments: the Ethmoidal Uncinate Process (EUP), which encompasses the Infundibular Space of the EUP (IS-EUP), currently known as the Agger Nasi cell; and the Turbinal Uncinate Process (TUP), which borders the Turbinal Infundibulum (TI) medially. The superior attachment of the EUP will be detailed in each of the six cases (Table 2). The middle meatus and infundibular passages are the drainage pathways from the frontal sinus and maxillary sinus to the nasal cavity.

Key words: frontal sinus, frontal recess, frontal sinus drainage pathway, uncinate process, infundibulum, ethmoid, 3D CT stereoscopic imaging

Introduction

The introduction of Endoscopic Sinus Surgery (ESS) was aided by the improved imaging of X-ray polytomography, which was then replaced by planar X-ray Computed Tomography (CT) in 1985 (8-9). In the late 1980s, the introduction of CT Multiplanar Reconstruction, advanced Functional Endoscopic Surgery and Image-Guided Surgery improved our understanding of the detailed sinus anatomy (Figure 1) (10-11). Observations of the anatomical subunits, introduced in the late 1800s (12-22), and the movement towards less invasive, "precision surgery", and highlight the importance of continuing to improve our anatomic knowledge of the Frontal Sinus Drainage Pathway, as well as, most recently the posterior ethmoid and sphenoid sinus anatomy (23-35).
The perceived complexity and variability of this region largely stems from the limitations of endoscopic visualization and 2-dimensional tri-planar CT imaging (23-48,54,55). In the past two decades, the potential advantages of 3D imaging techniques were addressed, but without the necessary depth perception, and manageability to achieve the needed displays of the regional anatomy (49-53). A new perspective is provided by the evolving Three-Dimensional CT Stereoscopic Imaging (3DCTSI) technology, which combines volume rendering with depth perception (56,57). Furthermore, it can be used as a virtual surgical tool for selective removal of structures in the imaging volume, which simulates a surgical dissection, enhancing surgical planning, and improved understanding of the frontal sinus outflow tract and anterior ethmoid spaces, paving the way for innovative surgical approaches. In this study, we will present six examples according to the previously published “Classifications of Fronto-Ethmoidal cells” (1-7), and describe the frontoethmoidal communicating passage(s) with the anterior ethmoid sinus. More particularly, we will demonstrate the following anatomical concepts and terms illuminated by 3-DCTSI:

1. The concept of cells vs. spaces
2. The frontal sinus and frontal recess as a united space
3. The frontal sinus drainage pathway
4. The attachment of the superior Ethmoid Uncinate segment in the six cases demonstrated (Table 2).
5. The two-part segments of the uncinate process S. The multiple spaces of the infundibulum

Materials and methods
Imaging instrumentation
Axial sinus CT scans were performed on a Siemens CT scanner using a 0.7 mm thickness without administering intravenous contrast.
An advanced evolution of the Dextroscope imaging device was used to create 3D CT Stereoscopic Imaging displays (3DCTSI) \(^{(56,57)}\). The device provides an “en bloc” 3D display of the imaging data, which can be manipulated to display the information from any plane or direction. A “cut-away” planar view can be shifted into any angled plane to “cut” into the image volume and reveal the anatomy from any orthogonal or oblique plane. The device has a “virtual surgery” capability that can remove structures which obstruct the visualization of specific anatomic detail. Furthermore, it has a “replace function” to restore inadvertently removed anatomy. Furthermore, a 3D display of the air within the frontal/ethmoid spaces may be extracted or superimposed on the bony anatomy of the sinuses (Figure 1).

The 3DCTSI created by the Dextroscope imaging device are displayed on a stereoscopic monitor and are viewed with 3D electronic glasses. The stereoscopic display provides depth perception showing a structure, just as it would appear in nature. The challenge is to display the 3D stereoscopic formatted image on a “flat” surface. In this case only a “partially simulated” depth perception is retained. An alternative (“poor man’s”) 3D stereoscopic display is available with the unit’s anaglyph 3D. Here, a left/right pair of images are created in a specific colour pair combination, with red/green or red/cyan, so that left-eye image is printed in a red colour, and the right-eye image is printed using a green or cyan colour. The colour printed hard copy, when viewed using corresponding colour filter glasses, will create a binocular pair separation effect, allowing binocular vision necessary for 3D perception/stereoscopic perception.

Source of information
Six examples were selected to illustrate the “Agger nasi Cell” and the 4 types of frontal cells previously reported in the “Classification of Fronto-Ethmoidal Cells” to describe our observations \(^{(1-7)}\). Our evaluation includes: the frontal sinus, and the frontal recess outline; the bony architecture of the uncinate process; the relationship of these structures to the bulla lamella, the middle meatus and infundibulum; as well as the superior attachment of the Ethmoidal Uncinate Process segment (EUP).

Results based on anatomic observations
The concept of “cells” vs. “spaces”
Traditional anatomical concepts of ethmoidal “cells” are an oversimplification of the actual situation. We found that the anterior ethmoidal anatomy is composed of enclosed spaces, which lack ostia in the traditional sense (‘a mouthlike opening in a bodily part’). We found, in all six cases, round/oval/slit-like, single or multiple openings that enable intercommunication between the spaces, with direct communication to the middle meatus and/or the infundibular passages, providing air exchange and mucociliary flow (Figures 2-12).

The frontal sinus drainage pathway shown in examples relating to “fronto-ethmoidal cells classification systems”

I. The “Agger Nasi Cell”

The frontal sinus/recess space (FSRS) - The fronto-ethmoidal transition region:

3DCTSI, reveals that the frontal sinus and the frontal recess spaces are continuous and unite completely, without an exactly definable anatomic landmark, which distinguishes the separation between these two spaces (Figures 2 a-e, h). Both spaces, the Frontal Sinus and the Frontal Recess, appear to be two compartments of a single space. It has often been noted that bony ridges are present within the perimeter of the frontal sinus, which, if included in the sagittal CT plane, would appear as an “hourglass”-like narrowing. However, this is not the case when the anatomy is observed with 3DCTSI in the axial perspective from above, in which the spatial volume can be observed in its entirety (Figures 2 a, b). In this case, the bony ridge present in the floor of the frontal sinus splits the volume of the frontal sinus into two separate compartments. Each compartment, and jointly, having its communication with the frontal recess (Figures 2 a, b). At the coronal plane where both openings have a joint communication with the frontal recess, there is a distinct concentric narrowing between frontal sinus and frontal recess spaces. The location of this coronal plane is undefined by specific anatomic landmarks and variations are seen from case to case.

Consequently, we refer to this three-dimensional cuboidal space (Figure 2 a), as the Frontal Sinus/Recess Space (FSRS). The FSRS is bordered antero-superiorly by the frontal bone, the skull base; laterally by the lamina papyracea and parts of the lacrimal bone; medially by the middle turbinate/middle meatus; and posteriorly by the bulla lamella, an extension of the uncinate lamella, or the fusion of uncinate and bulla lamellae known as the common lamella.

In the configuration, we refer to as the “Agger Nasi Cell” (ANC) the superior portion of the uncinate process extends laterally creating a “horizontal shelf”, which fuses with the lamina papyracea. It extends: anteriorly to fuse with the Nasal Process of the
Frontal Bone ("nasal beak"); and extends posteriorly to fuse with the bulla lamella. The "horizontal shelf", which is the roof of the space contained within the Ethmoid Uncinate Process (EUP) and is also the floor of the Frontal Recess (FR) (Figures 10 h-j).

The FSRS may have a variety of communications with the anterior ethmoid. It may communicate with the anterior ethmoid through a direct opening shared by the middle meatus and the ethmoidal infundibulum (Figures 10 i, j). It is located in the teromedial floor of the space, just anterior to the bulla lamella (Figure 10 i) Less commonly (but not in Figure 10 i) the FSRS may communicate directly with the IS-EUP.

The uncinate process

Embryologically, a series of ethmo-turbinals form on the lateral nasal wall, above the maxillo-turbinal, which are composed to two segments. The more anterior segment, which angles ventro-cranial (anterior-superior) is designated the Pars Ascendens and the posterior-inferior segment, which remains parallel to the nasal floor is designated as the Pars Descendens.

It is commonly held that the 1st Embryonic Ethmo-Turbinal (ET), shaped as a "boomerang/bent hook" or hockey stick shape (11),
Figure 5. Three-dimensionality of the two-component uncinate process: from the sagittal and axial perspective. The sagittal perspective: In (a-e) oblique sagittal displayed images, with the sagittal plane to the left of the black dashed line, and the coronal display to the right of the line. (a) Reveals the partially resected middle turbinate (MT, gold color) fusing antero-superiorly with the ethmoidal uncinate process (EU, greenish gold). The outline of the EU is separated from the turbinal uncinate process (TU)(darker green). Note the relationship with the partially resected ethmoid bulla (EB), and the bulla lamella (blue outline); maxillary sinus (MS). The ethmoidal infundibulum is outlined with white arrows, and the turbinal infundibulum with green arrows; blue arrow represents the visible end of the turbinal uncinate process at the posterior fontanelle. In (b), a more pronounced angulation of the sagittal plane to the left demonstrating the fusion between the turbinal uncinate process (TU) and the ethmoidal uncinate process (EU). Note the laterally turned EU (*), revealing the anterior surface of the ethmoid infundibulum (white arrows). Note the opening created at the inferior edge of the laterally turned uncinate lamella (yellow arrow) providing a communication between the ethmoidal and turbinal infundibulum, and the infundibular space of the EU (IS-EUP). In (c), similar to (a) with additional removal of medial sagittal image data, partially removing the medial wall of the ethmoidal uncinate process (EU), revealing the infundibular space within the EU (IS-EUP), and the relationship with the frontal sinus/recess space. Note the fusion between the uncinate lamella (gold outline) and bulla lamella (blue outline) to create the common lamella (C); turbinal uncinate process (TU); turbinal infundibulum (green arrows). (d, and e) Displays the posterior plane of separation between the turbinal uncinate process (TU, light green surface) and the ethmoidal uncinate process (EU) (gold surface)/common lamella (C, red outline), and the opening between the IS-EUP and the TI (yellow arrow); primary ostium of maxillary sinus (red arrow); turbinal infundibulum (green arrows, light green outline).

The axial perspective:

Figures (f-i): slightly obliqued 3DSI axial/sagittal images. The sagittal plane is to the left of the dashed black line and the axial plane is to the right of the line in all images. The information of interest is primarily on the axial planes viewed from above, (f) is most inferior and (i) the most superior. (f-h) Reveal the fusion of the TU (light green surface) with the lacrimal bone (L) and the lamina papyracea (P). The fusion between all three bony structures is within the area of the yellow oval on (f). The turbinal infundibulum (TI dark green), is the space between the TU and the lamina papyracea (P) and the medial maxillary sinus wall (M). The TI space is enclosed anteriorly (yellow “circle”) and is open posteriorly, as it communicates with the middle meatus (orange arrow). The oval wedge-like opening in the base of the TI (+, anteriorly) represents the primary ostium of the maxillary sinus. More superiorly, in (h,i) note that the posterior superior ethmoidal uncinate process (EU) turns laterally to merge with the bulla lamella (red outline) and create a common lamella (red outline, C). The common lamella, in turn, fuses with the lamina papyracea (P), enclosing the infundibular space of the ethmoidal uncinate process (IS-EUP) and defines the inferior extent of the ethmoidal infundibulum best shown on sagittal fig. (b), (yellow arrow). Ethmoidal bulla (EB), middle turbinate (MT); curved dashed arrow shows the continued extension of the TI, as well as its communication with the ethmoidal infundibulum under the fusion of the EU with the common lamella fig. (i): in figs. (c, d), the primary ostium of maxillary sinus (+).
regresses to form the uncinate process, with its pars ascendens believed to become the Agger Nasi Cell and the pars descendens to become the uncinate process (UP) \textsuperscript{17-19}. Therefore, the precedent has been set for considering that these two joined segments will become dissimilar, but joined structures. They are already named differently in embryologic terms.

Schaeffer, however, demonstrated in 1916 that the 1st ET becomes the middle turbinate and that two secondary or accessory Middle Meatal Turbinals (MMT) develop “under cover of the middle turbinate.” The UP develops from the first of these MMTs, and the second develops into the ethmoid bulla lamella. The two MMTs are separated by a groove, which becomes the Infundibulum and each MMT has two joined segments, a pars ascendens.
and a pars descendens. We acknowledge the continuous and joined nature of the Uncinate Process, but have chosen to name the two segments separately to clarify their origin and developmental function. Our evaluation with 3DCTSI supports Schaeffer’s suggestion that the UP has two segments, with the following caveat: the pars descendens of the first MMT develops into the Turbinal Uncinate segment (TUP) and the pars ascendens becomes the Ethmoidal Uncinate segment (EUP). In Figure 3, we demonstrate the 3DCTSI appearance of the lateral nasal wall status post septectomy (Figures 3 a, b), and the location of the uncinate process and ethmoid bulla status post virtual partial middle turbinectomy in (Figures 3 c, d). Furthermore, in Figure 4, we show the “segmented” uncinate process, coloured in red: its relationship to the bordering anatomy, as well as the two segments of the uncinate process.

The turbinal uncinate process segment (TUP)
The infero-posterior horizontal component of the uncinate process is a planar structure, developed from the pars descendens of the first MMT, which becomes the TUP (Figures 4 a-e, 5 a-h, 6 a-g). It is attached anteriorly to the lacrimal bone and ascending extensions of the inferior turbinate. It is attached to the medial maxillary sinus wall and visibly extends posteriorly along the inferior turbinan to the posterior fontanelle in 80% of cases. In the remaining 20%, Yoon et al. describe that TUP fibres extend further posteriorly and attach to: inferior turbinate, lower portion of the ethmoid bulla, and the perpendicular plate of the palatine bone.

Antero-superiorly, the TUP fuses with the lacrimal bone to the suture between the lacrimal bone and inferior tip of the frontal process of the maxilla (FPM) (Figures 4 b, c, f; 5 f; 6 e-g). This focal point is also shared with fusion of the lamina papyracea laterally and the ethmoidal uncinate process medially to the inferior tip of the FPM. This shared point of fusion between the four structures represents the anterior site of the plane of separation between the TUP and Ethmoidal Uncinate Process segment (EUP). Posteriorly this plane is angled supero-posteriorly to reach the inferior extent of the common lamella and the inferior point of the ethmoidal infundibulum. This posterior focal point also marks the superior extent of the TUP (Figures 4 e; 5 b, c, h; 6 a, e, f). From this point, the TUP tapers infero-posteriorly along the antero-inferior border of the bulla lamella to visibly end at the posterior fontanelle (Figures 4 d; 5 a-d; 6 g). As the TUP tapers posteriorly, it creates a space between the TUP and the median surface of the maxillary sinus, and the lamina papyracea, the Turbinal Infundibulum (TI) earlier referred to by Schaeffer as “a pocket.”

The ethmoidal uncinate process segment (EUP)
From the plane of separation between the TUP and the EUP, the ethmoid segment of the uncinate process, the EUP, extends superiorly and fuses antero-medially with the medial border of the frontal process of maxilla (Figures 4 f, h; 5 f; 6 d).
Figure 8. “K1 cell”,”Frontal cell, type 1”, “Supra agger cell”: described as a single anterior-lateral ethmoid cell, above the ANC, without penetrating the frontal sinus. (a-c), are images in the sagittal plane viewed from medially, with (a) being most medial, and (c) being most lateral. Note two spaces within the EUP bony surround (1,2) with space #2 pneumatizing into the frontal recess (R) fusing: supero-laterally with the lamina papyracea; posteriorly with the bulla lamella; anteriorly with the Nasal Process of the Frontal Bone (NPFB), and medially with the middle turbinate. Space #2 “opens” into the superior ethmoid infundibulum fig. (b) (blue outline), (curved yellow arrow). (c-f), (c), a lateral sagittal image; (d) a segmented, and displayed sagittal image viewed from lateral (coronal, axial and sagittal planes shown within dashed black lines) which reveals the continuity of the EUP (gold) and TUP (green) bony framework; (e) a sagittal image viewed from laterally; and (f) a sagittal image viewed from medially displaying the 3 dimensionality of the air within the anterior ethmoid spaces and FSRs. (c-f) reveal the outline of the common lamella (red); the communication of space #1 with the turbinal infundibulum (light green outline); the communication of space #2 with the ethmoid infundibulum (yellow arrows) and the inter-communication between the inferior ethmoid infundibulum/turbinal infundibulum/IS-EUP (red oval).

Superiorly, the EUP attaches horizontally along the suture between the frontal bone/frontal process of the maxilla/nasal process of frontal bone (NPFB), creating a horizontal plate, which fuses laterally with the lamina papyracea, and posteriorly with the bulla lamella/common lamella, creating a polyhedral space contained within the EUP, the Infundibular Space of the Ethmoid Uncinate Process segment (IS-EUP), which is commonly referred to as the Agger Nasi Cell (Figures 4 b, d, e, f, h, j; 5 b-e, g-i; 6 a, d-g).

Inferiorly at the plane of separation between the IS-EUP and the Turbinal Infundibulum (TI), the polyhedral space narrows to create a "wedge-like" oval or round opening. Notably, the posterior portion of the opening communicates with the inferior Ethmoidal Infundibulum (EI), and the dorsal TI. The anterocentral portion of the opening communicates with the TI and in turn the primary ostium of the maxillary sinus (Figures 4 h, j; 5 h, i; 6 d; 7 e).

The common lamella

Posteriorly, the EUP angles laterally and becomes the anterior surface of the ethmoid infundibulum with simultaneous lateral angulation of the bulla lamella which becomes the posterior surface of the ethmoid infundibulum (Figures 4 d, e; 5 b). The posteriorly angled EUP and anteriorly angled BL fuse to create a common partition/wall/lamella between the IS-EUP and EB which we refer to as the Common Lamella (CL) (Figures 5 c-e, i; 6 g),(55). The Common Lamella’s orientation/angulation, as well as its extent, varies considerably. Its medial surface is at the depth
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of the ethmoidal infundibulum, and laterally, it fuses with the lamina papyracea (Figures 5 d, e; 6 f, g).

Drainage channels within the anterior ethmoid sinus
The ethmoid infundibulum is the conventional term for the space between the entire length of the uncinate process and the ethmoid bulla lamella. It now appears, based upon the 3-DCTSI findings that this space is more complex than we previously realized.

The infundibular space appears to be made up of three interconnected spaces, each named for the uncinate subdivision associated with it:

1. The Ethmoidal Infundibulum (EI) (Figures 7 c, d) – is between the ethmoidal uncinate anteriorly and the bulla lamella, posteriorly. Its medial extent is the hiatus semilunaris, and its depth is the medial surface of the common lamella (CL) (Figures 2 h-j; 4 d, g; 5; 7 c).
2. The turbinal infundibulum (TI) – is defined medially by the turbinal uncinate process and laterally by the medial surface of the maxillary sinus, and lamina papyracea. It extends from the lacrimal bone anteriorly, under the ethmoid bulla to communicate with the middle meatus through the hiatus semilunaris at the posterior fontanelle. This space communicates with the IS-EUP superiorly, with the ethmoidal infundibulum supero-posteriorly and the maxillary sinus inferiorly (Figures 4 b-e; 5, 6, 7).
3. The infundibular space of the ethmoidal uncinate process (IS-EUP), the polyhedral space enclosed by the EUP, described above, inferiorly directly communicates with the TI, and infero-posteriorly with the EI, and is currently referred to as the Agger Nasi Cell (ANC) (Figures 4 f, h; 5 a-e, l; 6 a-e; 7). Our use of the descriptor IS-EUP is meant to more accurately name the space we currently refer to as the ANC, and avoid the confusing relationship between the ANC and the uncinate process. Given that the IS-EUP space is one and the same as the "agger nasi space", the terms could be used interchangeably with the understanding that both re-
Figure 10. “K3 cell”, “Frontal cell type 3”: a single cell above the ANC, extending from the frontal recess into the frontal sinus with superior wall inserting into the inner surface of the anterior frontal sinus. (a) is a coronal image just posterior to the anterior frontal sinus wall, revealing a “bulging” structure(*) with near occlusion of the Frontal Sinus Recess Space (FSRS): superolateral and superomedial spaces afford communication between the frontal sinus and frontal recess(yellow arrows). (b) is a coronal image revealing that the “bulging structure” represents a pneumatization of the superiorly extending uncinate lamella into the FSRS, fusing medially to the frontal septum, and laterally to the lamina papyracea. On sagittal images (c-e), viewed from medially and noted to extend from medial to lateral reveal a close relationship between the bulla lamella (blue outline), the ethmoid uncinate process (gold coloured structure) and the emerging pneumatized space (greenish/yellow colour) extending into the frontal recess, as well as the posterior frontal sinus space, as it adheres to the posterior floor of the frontal sinus. Sagittal images in (f-h) are viewed from laterally, and specifically in (g) contributions from the uncinate (gold) and bulla lamella (blue) shows their joint “contribution” in the creation of the superiorly extending pneumatized space (*), which is the terminal ending of the ethmoid infundibulum, and a “terminal recess” space.

fer to the polyhedral space created by the ethmoid Uncinate segment and its fusion with the FPM, LP, BL, and CL.

Superiorly, the ethmoid infundibulum may terminate: 1) into the FSRS (as in this case) (Figures 2 i, j; 5 a, b; 7 b-d; 11 e, f, h); 2) directly into the IS-EUP (Figures 8 g; 9 c, d; 12 c, d); 3) a space created by the coalescence of the uncinate and bulla lamellae, at or near the skull base (Figures 10 b-h).

II. The “K 1” / “Type 1 Frontal Cell” (Figure 8)
The FSRS, has a bony ridge in the floor of the frontal sinus, creating two separate components within the frontal sinus (Figure 8 a). The plane of separation between the frontal sinus and frontal recess is just dorsal to the opening of the more lateral space. There is no evidence of a specific landmark establishing a separation between frontal sinus and frontal recess, and the FSRS is continuous and uninterrupted. The opening of the FSRS is in the postero-medial frontal recess directly into the middle meatus, and indirectly into the ethmoid infundibulum (Figures 8 b, c, e). The EUP bony architecture surrounds two separate infundibular spaces with the more superior space pneumatized into the frontal recess volume, without adhering to the skull base (Figures 8 b-g). The roof of the superior EUP fuses laterally with the lamina papyracea, anteriorly with the NPF, medially with the middle turbinate, and posteriorly with the superior common lamella at its junction with the bulla lamella. The superior IS-EUP space has a direct individual communication with the superior ethmoid infundibulum (Figure 8 c).
The inferior IS-EUP space has a direct communication with the TI through an oval opening extending from: anteriorly, at the junction of the lacrimal bone/FPM inferior tip/anterior EUP and lamina papyracea; posteriorly, to the inferior ethmoid infundibulum/common lamella (Figures 8 d, g). The TUP visibly, extends posteriorly to the posterior fontanelle (Figures 8 d, g).
The TI communicates directly with the primary ostium of the maxillary sinus (Figure 8 e).

III. The “K 2” / “Type 2 Frontal cell” (Figure 9)
The FSRS is a single uninterrupted space posteriorly bordered
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by the bulla lamella (Figures 9 a-f), medially; by the middle turbinate and the frontal intersinus septum; laterally by the lamina papyracea; superiorly, by the skull base/orbital plate; and inferiorly by the roof of the EUP, which pneumatizes into the frontal recess volume. The superiorly pneumatized EUP extends transversely across and into the floor of the frontal recess and displaces the floor of the frontal recess superiorly, as the indentation into frontal recess space extends from middle turbinate to lamina papyracea. There are two openings affording communication between FSRS and anterior ethmoid: a postero-lateral opening into the middle meatus (Figures 9 a, b); and a lateral opening into a space created by the uncinate lamella and bulla lamella (Figures 9 c-e). The opening from the frontal recess is into the superior portion of the space, as a second opening is present anterio-inferiorly affording communication with the infundibulum (Figures 9 c-e). The anterior border of this “common” space spanning between the two openings, represents the common lamella.

The EUP bony architecture surrounds: a single apical space, which communicates postero-medially with the middle meatus;
two additional incompletely walled off spaces, which converge to communicate with the Ethmoidal Infundibulum. The TUP is in direct communication with the IS-EUP and the maxillary sinus (Figure 9 c).

The superior EUP fuses anteriorly with the NPFB, posteriorly with the common lamella (above described), medially with the middle turbinate and laterally with the lamina papyracea.

IV. The “K3” / “Type 3 frontal cell” (Figure 10)

In this example, an expansile pneumatized space arising from the anterior ethmoid region superiorly displaces the floor and compresses the volume of the anterior frontal recess and posterior frontal sinus. The bony perimeter of the pneumatized volume fuses anteriorly to the posterior floor of the frontal sinus, and the superiorly extending uncinate lamella. Its roof adheres to the FSRS roof, and tapers laterally to fuse with the lamina papyracea and medially to the frontal inter-sinus septum creating a narrow space medially and laterally affording communication between the frontal sinus and the posterior frontal recess spaces. Its posterior rim is continuous with the bulla lamella and common lamella. Medially, the pneumatized space fuses to the frontal inter-sinus septum, and borders the middle meatus (Figure 10 b). The FSRS has a postero-medial opening which communicates with the middle meatus (Figure 10 h).

Note that the ethmoid bulla “space” extends anteriorly to narrow the EUP and the TUP. The ethmoid Infundibulum extends superiorly to terminate in a space, which is pneumatized jointly by the bulla and uncinate lamellae (Figures 10 b-h). In effect, the resultant pneumatized space occupying the majority of the frontal recess and the posterior frontal sinus is a “Terminal Recess” in direct communication with the ethmoid infundibulum (Figures 10 b, d-h).

V. Variation of “K3” / “Type 3 frontal cell” (Figure 11)

The FSRS is a continuous and uninterrupted space which antero-medially extends laterally from the frontal sinus septum, to “wrap” around the superiorly extending EUP, and a space between the EUP and the bulla lamella, terminating posteriorly at the bulla lamella (Figure 11 a). The floor of the frontal recess extends further inferiorly than usual to the infero-laterally extending EUP and bulla lamella. The opening of the frontal recess is antero-laterally directly into the infundibulum, which curves in the shape of a semicircle around the anteriorly extending tip of the ethmoid bulla (Figures 11 e, f, h).
The EUP is an incompletely enclosed space with the appearance of an ANC present above the TUP (Figure 11 b). More laterally, this space combines with a larger superior space. Both spaces are within the EUP enclosure and represent the IS-EUP (Figures 11 c, d). Note, that on the standard, more medial, sagittal CT image (Figure 11 i), the two spaces appear to be separate. The bony perimeter of the EUP enclosing the combined spaces (IS-EUP) extends superiorly to fuse superiorly with the skull base and the middle turbinate medially. At the skull base the bony outline of the EUP assumes a steeple shaped configuration with its anterior attachment extending to the floor of the anterior frontal sinus where it extends postero-laterally to fuse with the lamina papyracea (Figures 11 a, h). The postero-lateral extension of the frontal recess narrows the volume of the superior EUP/IS-EUP and is associated with a “gap/opening” in the lateral bony framework of the EUP which affords a direct communication between the frontal recess and the IS-EUP (Figures 11 b-d, h). The ascending uncinate lamella “wraps around” a space between the uncinate lamella and the bulla lamella. This space is medially bordered by the middle turbinate, and therefore the created space may be considered: a concha bullosa, or an interlamellar space (Figures 11 a-d, f-h). Nevertheless, it’s lateral wall is a continuation of the uncinate lamella which fuses with the bulla lamella infero-posteriorly and may be considered to be a sagitally oriented common lamella (Figures 11 a, f, h). Note the prominent antero-inferior indentation of the IS-EUP into the frontal process maxilla (FPM) considered by Layton to represent an ANC (Figures 11 b-d, i) (20).

VI. The “K4” / “Type 4 frontal cell” (Figure 12)
This entity has had a variety of descriptions, the most common being, that it appears as an isolated “cell” in the frontal sinus on coronal CT (1,2), which may be the case if the entity is viewed with selective coronal images. However, as this example shows that it is a pneumatized/partially pneumatized space with its antero-inferior border adherent to the floor of the frontal sinus and in this case its superior border is adherent to the roof of the frontal sinus/frontal recess. Openings are present primarily along its posterior and/or inferior margins which afford communication with the middle meatus and the IS-EUP (Figures 12 a-d). Lee et al. provide a less commonly mentioned associated finding – the appearance similar to an “air bubble” and a “balloon on a string” (19). 3DCTSI demonstrates their description, and in this example one notes that the uncinate lamella has a “lamellar extension”, which could be construed to look like a “string” connecting the postero-inferior border of the “bullous” pneumatization within the frontal sinus with the uncinate lamella and that the two entities together resemble a “balloon on a string” (Figures 12 c, d).

The “bulla” as well as the FSRS communicates with the IS-EUP and the middle meatus (Figure 12).

Discussion
Our individual and collective understanding of sinus anatomy and its development is based upon anatomic and embryologic investigation by early investigators (14-22), the experience gained from more recent adult dissection (9,13,23-52), and the information provided more recently by sinus CT individual orthogonal and MPR images (1,13,23-34,37-54). Several attempts to show the value of this regional anatomy in 3D were proposed (49-51).

Recent advances of 3DCTSI and its application to sinus CT anatomy seem to be the most likely solution to an intuitive 3D perception of the complex, varied anatomy of the paranasal sinuses (55,56) (Figure 1). Given the newness of this technology’s anatomic display, we selected six examples of the “Classification of Fronto-ethmoid cells” by Kuhn and expanded by Wormald et al., and adopted by Huang et al., Ramakrishnan et al; and Void et al., to illustrate our findings and contrast our observations with those reported in the current literature (1-7). The study focused on the following observations:

Cells vs. spaces within the ethmoid sinuses
Zukerkandl, Seydel, and Van Alyea described the anatomy of the ethmoid sinus as a “labyrinth” enclosed in a “capsule,” and that lamellae within the “capsule” served to separate groups of cells, each group retaining its original drainage channels (14-16). Schaeffer, in 1916, concluded that the frontal sinus may originate from “one or more of the cellulae ethmoidales anterior,” and was one of the first to refer to the compartments within the anterior ethmoid sinus as “cells” (18). Terrier reported that the ethmoidal compartments had the external appearance of a “centrifugal” arrangement of balloons with proximal ostia in each case, inferring a distinction between the “cellular concept” and the “space concept” (186). Marquez et al., stated that an “air space” must have two features to be defined as an ANC: it has been a cell, which is a sphere-like air space with a drainage ostium smaller than the space diameter (191). Pianta et al. adopted this concept in establishing their ABC classification of the frontal sinus drainage pathway and referred to the compartments within the anterior ethmoid sinuses as spaces, not cells (29). Arun et al., stated that “the frontal recess is a three-dimensional space connecting the frontal sinus superiorly with the nasal cavity inferiorly” (249). We realize that the traditionally mentioned anatomical concept of “ethmoidal cells” represents a simplified observational explanation. In essence, what we currently call “ethmoidal cells” are “spaces” with slit-like or round openings, varying in size and in the traditional sense, are not “ostia.” Each space individually, or in combination with other spaces, communicates with the infundibulum, which, in turn, communicates with the middle meatus, thus allowing air exchange and mucociliary clearance to occur (Figure 7).
The frontal sinus recess space (FSRS) nomenclature

Schaeffer states that the middle meatus extends ventro-cephalically, where it becomes the ‘anlage’ of the frontal recess and represents the first step in the formation of the frontal sinus. Lund et al. reported that the frontal recess is “the most anteroinferior part of the ethmoid,” and is synonymous with the “frontal sinus drainage pathway.” Furthermore, they state that the terms “frontal sinus” and “frontal recess” refer to two separate entities and that the opening of the frontal sinus is best defined on a sagittal CT section; and the contours between the frontal sinus and frontal recess form an hourglass shape, with the narrowest point at the frontal sinus opening. Furthermore, they state that then frontal recess “is a term that has been defined in various ways over many decades and remains disputed”

Daniels et al. described the drainage of the frontal sinus through the frontal recess to be complex, as it is altered by air cells within the frontal recess and the varied attachment of the uncinate process. Stammberger et al. described the opening of the frontal sinus to be an hourglass-like narrowing formed between the frontal sinus and the frontal recess, and that the frontal recess has the appearance of an inverted funnel-shaped structure, synonymous with the frontal sinus drainage pathway. Wor- mald et al. described the frontal ostium as being in a plane that is anteriorly defined by the frontal sinus beak, and posteriorly by the skull base.

Evaluation with 3DCTSI shows the frontal sinus and frontal recess to be a united and continuous irregular volume, with no evidence of specific anatomic landmarks, which create an hourglass-like narrowing that separate the two spaces. The concept of the hourglass-shaped narrowing is largely based on the information provided by CT MPR images.

The frontal sinus and the frontal recess (the latter understood here as the whole anterior-superior part of the unilateral anterior ethmoid, incorporating specific cells or spaces) is comprised of two confluent spaces. In a variety of cases, the impression of a defined “narrow-pass” between the two cavities is envisioned. However, irrespective to the relative expansion of the anterior-superior frontal sinus and the obvious narrowing as the frontal sinus space “joins” the frontal recess space, a defined anatomic landmark to precisely locate an “opening” / “ostium” / or plane of separation between these two spaces is absent. Contrasting views in the literature are based on virtual geometric calculations and illustrations disregarding 3D anatomy. As such the combined uninterrupted space is more accurately referred to as the Frontal Sinus/Recess Space (FSRS).

The uncinate process anatomy

Regarding the Uncinate Process anatomy, confusion has been disseminated by a multitude of publications. The EPOS ma-
still exists about how this upward continuation of the uncinate relates to the Agger Nasi and if present, the frontal ethmoid cells" (24,46). Wormald and Kim et al. tried to resolve the "confusion" with the following statement: "Most of the agger nasi cell is anterior to the uncinate, but the posterior half of the agger nasi cell has an intimate relationship with the upward extension of the uncinate process" (24,46). Nevertheless, a distinction between these two structures remains without explanation. Similarly, Zhang et al. failed to define a distinct separation between the two structures (47). Layton's opinion on the subject is: "In this collection I have only classed as agger nasi cells those which hollow out to some extent the nasal process of the superior maxilla" (20). This definition, however, needs to consider the fact that, in virtually every case, we encountered the pneumatization into the frontal process of the maxilla, it was in communication with the IS-EUP (Figure 11). Even though the medial surface of the ANC is the "mound", it is the EUP that lines the medial surface of the polyhedral space, currently referred to as the ANC, and therefore would more accurately be named the Infundibular Space of the Ethmoid Uncinate Process (IS-EUP). The superior attachment of the superior Ethmoid Uncinate Process segment in the six cases demonstrated in this manuscript are presented in Table 2.

Our detailed description of the Uncinate Process segments and particularly the description of the polyhedral shaped IS-EUP, is meant to clarify the origin of the polyhedral space commonly referred to as the ANC, and clarify the confusion concerning the relationship between the ANC and the uncinate process. Given that the IS-EUP space is one and the same as the "agger nasi space", the terms could be used interchangeably with the understanding that both refer to the polyhedral space created by the ethmoid Uncinate segment and its fusion with the FPM, LP, BL, and CL.

The infundibulum

The tortuous course of the infundibulum, its complex association with the uncinate process and the ethmoidal bulla, and its pronounced segmentation by CT MPR images, are all part of the challenge in understanding its full extent and relationship with its neighbouring spaces.

Both Zukerkandl and Schaeffer considered the infundibulum to be the "conduit" between the FSRs, the anterior ethmoid spaces, and the maxillary sinus (15,16).

3DCTSI evaluation reveals the following intercommunications provided by the infundibulum:

1. The FSRS communicates with the anterior ethmoid sinus directly into the middle meatus, directly or indirectly into the EI and rarely directly into the IS-EUP.
2. The IS-EUP opens directly into the EI and the TI.

Table 1. Key to abbreviations.

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Definitions</th>
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<tbody>
<tr>
<td>ANC</td>
<td>AggerNasi cell</td>
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<tr>
<td>BL</td>
<td>Bulla Lamella</td>
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<tr>
<td>CT</td>
<td>X-ray Computed Tomography</td>
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<tr>
<td>CTMPR</td>
<td>X-ray Computed Tomography with Multiplanar Reconstructions</td>
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<tr>
<td>3DCTSI</td>
<td>Three-D. Computed Tomography with Stereoscopic Imaging</td>
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<tr>
<td>EUP</td>
<td>Ethmoidal Uncinate Process</td>
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<tr>
<td>FESS</td>
<td>Functional Endoscopic Sinus Surgery</td>
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<tr>
<td>FSRS</td>
<td>Frontal Sinus/Recess Space</td>
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<tr>
<td>EI</td>
<td>Ethmoidal Infundibulum</td>
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<tr>
<td>ET</td>
<td>Embryonic Ethmo-Turbinal</td>
</tr>
<tr>
<td>FPM</td>
<td>Frontal Process Maxilla</td>
</tr>
<tr>
<td>FSRS</td>
<td>Frontal Sinus/Recess Space</td>
</tr>
<tr>
<td>IS-EUP</td>
<td>Infundibular Space of the Ethmoidal Uncinate Process</td>
</tr>
<tr>
<td>MMT</td>
<td>Middle Meatal Turbinals</td>
</tr>
<tr>
<td>TUP</td>
<td>Turbinal Uncinate Process</td>
</tr>
<tr>
<td>Ti</td>
<td>Turbinal Infundibulum</td>
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3. The TI communicates with the IS-EUP superiorly, the EI superiorly-posteriorly, and with the middle meatus postero-laterally, as its free margin extends to the posterior fontanelle under the ethmoidal bulla. Inferiorly, it communicates directly with the maxillary sinus.

Conclusions

As the potential for minimally invasive surgery grows, increased recognition of the sinus anatomy and its common variations becomes increasingly important, and 3DCTSI provides the opportunity to clearly define the anatomy and variations which previously, were not appreciated. We present our observations of the normal 3D anatomy as displayed with 3DCTSI of the anterior ethmoid and fronto-ethmoidal transition zone in six exemplary cases, representative of the "Classification of the Fronto-ethmoidal cells" by Kuhn and expanded by Wormald et al., and adopted by Huang et al.; Ramakrishnan et al; and Void et al. (1-7). The cases are pathology-free. These cases demonstrate the common anatomic variations within the frontal and anterior ethmoid structures, spaces, and drainage pathways. An attempt to clarify the confusion relating to the association between the ANC and the Ethmoid Uncinate Process segment is provided. The spaces appearing to be within the frontal recess and frontal sinus are pneumatized spaces originating from the anterior ethmoid. Also of note are the following observations:

1. The compartments within the anterior ethmoid sinus,
previously referred to as “cells,” are, in essence, spaces with an opening, which, if unaffected by pathology, afford air exchange and mucociliary clearance.

2. The frontal sinus and frontal recess are a united and uninterrupted three-dimensional cuboidal space, the Frontal Sinus/Recess Space (FSRS), without identifiable landmarks showing the separation between Frontal Sinus and Frontal recess. A narrowing between the two spaces is occasionally present, however, its location varies. The opening, “draining” the FSRS is primarily directly into the middle meatus, and, less frequently directly into the ethmoidal infundibulum, and even less frequently directly into the IS-EUP.

3. The uncinate process has two structural segments: the Ethmoidal Uncinate Process segment (EUP), creating a polyhedral shaped pneumatized space, the Infundibular Space of the Ethmoid Uncinate Process segment (IS-EUP); and the Turbinal Uncinate Process segment (TUP), creating a vertically shaped space, the Turbinal Infundibulum (TI).

4. The middle meatus and the ethmoidal and turbinal infundibular channels are the principal draining channels that enable air exchange and mucociliary drainage of the anterior ethmoid spaces, the frontal sinus and the maxillary sinus.

New anatomic details are described and nomenclature created to fit these observations. Our objective is to clarify the confusion resulting from previous less-than-optimal imaging technology and provide an introduction to an improved understanding of the frontal sinus outflow tract and anterior ethmoid spaces, with implications for facilitating surgery and fostering future innovative approaches, as we are repeatedly reminded that understanding the anatomy of this area directly influences the surgical success.

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Authorship contribution
SJZ, FAK wrote and edited the manuscript; WH, DK, NJL contributed to the writing and addressed anatomic detail where clarity was needed; MS assisted in creating the needed images.

Conflict of interest
DK is a consultant for Medtronic and Fiagon companies. WH Hosemann is a consultant for Karl Storz. The other authors have no conflict of interest.

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