Choanal Atresia and Craniosynostosis: Development and Disease

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Summary: A number of textbooks, review articles, and case reports highlight the potential comorbidity of choanal atresia in craniosynostosis patients. However, the lack of a precise definition of choanal atresia within the current craniosynostosis literature and widely varying methods of detection and diagnosis have produced uncertainty regarding the true coincidence of these conditions. The authors review the anatomy and embryologic basis of the human choanae, provide an overview of choanal atresia, and analyze the available literature that links choanal atresia and craniosynostosis. Review of over 50 case reports that describe patients diagnosed with both conditions reveals inconsistent descriptions of choanal atresia and limited use of definitive diagnostic methodologies. The authors further present preliminary analysis of three-dimensional medical head computed tomographic scans of children diagnosed with craniosynostosis syndromes (e.g., Apert, Pfeiffer, Muenke, and Crouzon) and typically developing children and, although finding no evidence of choanal atresia, report the potentially reduced nasal airway volumes in children diagnosed with Apert and Pfeiffer syndromes. A recent study of the *Fgfr2c*[+/C342Y] Crouzon/Pfeiffer syndrome mouse model similarly found a significant reduction in nasal airway volumes in littermates carrying this *FGFR2* mutation relative to unaffected littermates, without detection of choanal atresia. The significant correlation between specific craniosynostosis syndromes and reduced nasal airway volume in mouse models for craniosynostosis and human pediatric patients indicates comorbidity of choanal and nasopharyngeal dysmorphologies and craniosynostosis conditions. Genetic, developmental, and epidemiologic sources of these interactions are areas particularly worthy of further research.   (*Plast. Reconstr. Surg.* 141: 156, 2018.)

W e present a review of case reports that link craniosynostosis and choanal atresia to highlight the uncertainty of a choanal atresia diagnosis in pediatric craniosynostosis patients and provide anatomical data from human and mouse to more fully define choanal and associated dysmorphologies. The lack of a precise definition of choanal atresia in the current craniosynostosis literature results in an unclear set of standards for the diagnosis of choanal dysmorphologies. The developmental genetic significance of the association of choanal atresia and craniosynostosis and the implications for developing appropriate therapeutics require a clear understanding of these anomalies.

THE HUMAN CHOANAE

In humans, the choanae are defined in several ways. Osteologically, the choanae are the posterior openings of the right and left nasal passages that are bordered medially by the posterior border of the vomer, superiorly by the sphenoid body, laterally by the medial pterygoid plates, and inferiorly by the horizontal plate of the palatine bones[1] (Fig. 1). An anatomical definition includes these osteologic borders of the choanae, or posterior nares, while incorporating the surrounding

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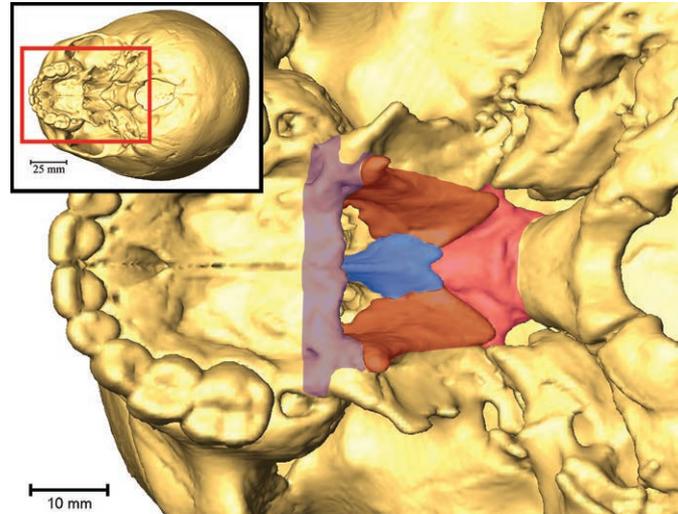
Fig. 1. Three-dimensional computed tomographic reconstruction of the cranium of a typically developing child viewed from below showing the osteologic borders of the choanae: vomer (*blue*), sphenoid body (*pink*), medial pterygoid plates (*red*), and horizontal plates of the palatine bones (*purple*).

soft tissues: the choanae are the pair of posterior apertures of the nasal cavity that open into the nasopharynx. Each choana can be defined functionally, as an internal nostril, connecting the nasal air space and the posterior roof of the pharyngeal cavity (Fig. 2). Study of extant jawed fishes and fossil vertebrates shows that choanae evolved from a condition in which anterior and posterior external nostrils functioned without a connection between the nasal sac and the oral cavity.[2] The tetrapod choanae ("internal nostrils") are homologous to the posterior external nostrils of jawed fishes[2] and are a key feature of the evolution of tetrapods, a group that includes, reptiles, mammals, and humans. The tetrapod respiratory system appeared with the evolution of the palate separating the nasal and oral respiratory systems. Only tetrapods possess choanae.[2]

Embryogenesis of the choanae is complex, characterized by several distinct developmental
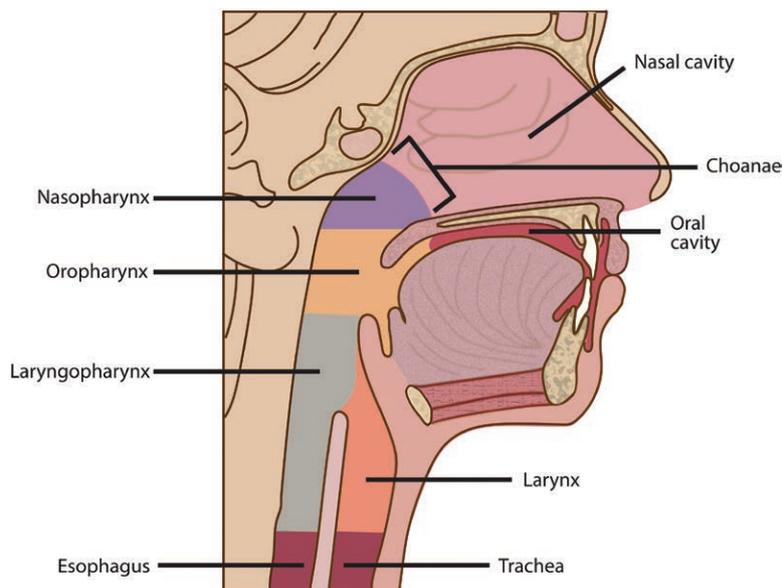
Fig. 2. Midsagittal section of an adult human showing the position of the choanae relative to the human nasal, oral, and pharyngeal airways.

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periods, each requiring the precise spatiotemporal coordination of the development of diverse tissues and functioning spaces before the final structure and function are reached (Fig. 3). At the end of the seventh week of prenatal ontogeny, the medial nasal prominences fuse,[3] providing the foundation for the primary palate.[3,4] The posterior portion of the intermaxillary process becomes the oro-olfactory, oronasal, or nasobuccal membrane, which separates the developing olfactory sac from the oral cavity.[3,5] When this membrane ruptures, the *primary choanae* are formed, permitting communication between the nasal and oral cavities.[3,6] At this stage, the lateral palatal shelves are still oriented vertically.[3,6] As these shelves transition downward to their final horizontal position, the remnants of the primary choanae become the incisive foramen, the primary palate fuses to the secondary palate posteriorly, the right and left lateral shelves of the secondary palate fuse along the midline, and the posterior or *secondary choanae* are formed and shifted posteriorly following this progressive fusion.[3,5–8] During this time, the nasal septum has formed from the roof of the nasal cavity to meet the superior surfaces of the primary and secondary palates along the midline, dividing the left and right nasal cavities.[3] The completion of this process results in separation of the right and left nostrils and separation of the nasal and oral cavities, with the secondary choanae defining the posterior aspect of the left and right nasal cavities immediately rostral to the nasopharynx. For the purposes of this article, the secondary choanae are referred to generally as the choanae.

CHOANAL ATRESIA: DEFINITION, DEVELOPMENT AND DIAGNOSIS

Errors in timing, organization, or development of the palate can give rise to numerous dysmorphic conditions, including various degrees of clefting of the hard and/or soft palate.[4] Choanal atresia is a less common, though medically significant, anomaly associated with errors of development of the nasal cavity and palate. Choanal atresia is defined as the complete obstruction of the posterior nasal apertures (choanae) by osseous tissue, either alone or in combination with nonosseous tissue.[1,9–11] This blockage may occur unilaterally or bilaterally and results in a lack of communication of the nasal cavity with the pharyngeal cavity by means of the nasopharynx,[1] thereby preventing inhalation and exhalation of air through the affected nasal passage(s). Two major osteologic deformities have been described in choanal atresia: (1) a medialization of the medial pterygoid plates and (2) a thickening of the posterior vomer.[9,10,12,13] Either of these deformations can lead to a narrowing of the choanae, potentially resulting in complete obstruction of the choanae. Several developmental theories are commonly cited in the formation of choanal atresia: (1) persistence of the buccopharyngeal membrane from the foregut; (2) persistence or abnormal location of mesoderm-forming adhesions in the nasochoanal region; (3) persistence of the nasobuccal membrane of Hochstetter; and (4) misdirection of neural crest cell migration and subsequent flow of mesoderm.[1,5,9–11,14] However, none of these provides a precise explanation
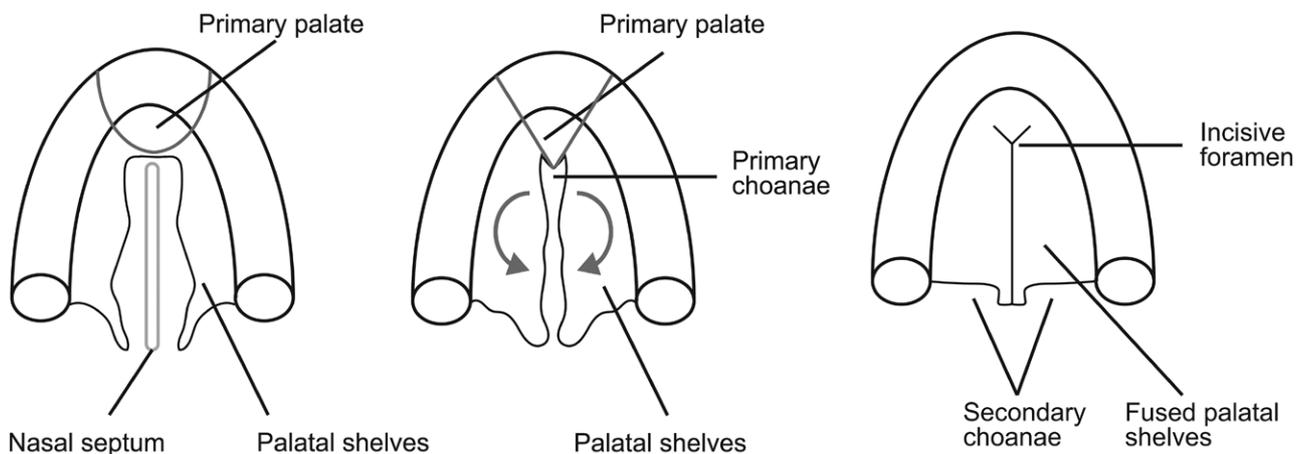
Fig. 3. Formation of the secondary palate and choanae. Inferior view of the forming palate showing (*left*) vertically oriented palatal shelves, (*center*) the palatal shelves as they rotate downward into a horizontal position and begin to approximate one another to form the primary choanae, and (*right*) fused palatal shelves in their final orientation, with the incisive foramen at the intersection of the primary and secondary palate and the secondary, or definitive, choanal openings at the posterior end of the palate. (Adapted from Jankowski R. *The Evo-Devo Origin of the Nose, Anterior Skull Base and Midface*. Paris: Springer Paris; 2013.[3])

for obstruction or minimization of the size of the choanal openings by developmental processes, and to date, there has been no definitive evidence supporting one theory over the others.

Significantly, choanal atresia must be differentiated from choanal stenosis, a diagnosis defined as the narrowing of the posterior choanae without complete obstruction,[15] and from nasal pyriform aperture stenosis, which involves narrowing of the skeletal borders of the anterior nasal cavity.[1,16,17] Precise definitions are required to correct common errors that incorporate narrowing or incomplete obstruction of the choanae within the definition of choanal atresia or that conflate choanal atresia with choanal stenosis (e.g., Corrales and Koltai,[10] Ramsden et al.,[18] Meyers et al.,[19] and Wilkes et al.[20]). The potential for the misdiagnosis of choanal atresia has been recognized in pediatric patients with major craniofacial anomalies because these conditions routinely include some form of midfacial retrusion. Airway obstruction is common in craniofacial syndromes because of potential maldevelopment of the palate (floor of the pyriform aperture), the nasal airway, the nasopharynx, or the entire midfacial skeleton in the production of midfacial dysmorphogenesis.[1,21–23]

Choanal atresia is typically suspected in infants exhibiting respiratory distress, particularly when feeding.[12,13] Bilateral choanal atresia in neonates presents an emergent situation, as infants are obligate nasal breathers. Bilateral choanal atresia leads to cyclic cyanosis relieved by crying, which facilitates mouth breathing.[1,10,11] Although truly complete obstruction of the posterior choanae can be confirmed only through diagnostic imaging or endoscopy, choanal atresia is often diagnosed by the inability to cannulate the nasal passage with a small catheter, a procedure that cannot definitively distinguish partial stenosis from complete obstruction of the choanae.[9,12,17,22,24] The incidence of choanal atresia ranges from one in 5000 to 8000 live births, with a 2:1 higher occurrence in females.[9,10,13,24,25] Unilateral choanal atresia is slightly more common than bilateral atresia, whereas bilateral atresia is more common when other craniofacial malformations are present.[9,10,13,24]

In an early review, Durward and colleagues defined choanal atresia as a very rare condition and concluded that the association between choanal atresia and other syndromic craniofacial dysmorphologies was no more than spurious.[26] Improvements in diagnostic imaging and neonatal care have permitted researchers to make the explicit link between choanal atresia and a number of craniofacial disorders, most notably CHARGE syndrome, with an estimated 7 to 29 percent of choanal atresia patients also being diagnosed with CHARGE syndrome.[10] Syndromic craniosynostosis patients make up another core subset of patients diagnosed with choanal atresia, with specific associations made between choanal atresia and Antley-Bixler, Apert, Beare-Stevenson, Crouzon, Crouzonodermoskeletal (Crouzon with acanthosis nigricans), Jackson-Weiss, and Pfeiffer syndromes.[1,10,15,17,18,27–29]

CHOANAL ATRESIA AND SYNDROMIC CRANIOSYNOSTOSIS IN PEDIATRIC PATIENTS

Craniosynostosis is a condition with a complex cause that always involves the premature fusion of one or multiple cranial sutures and includes various anomalies of the soft and hard tissues of the head.[30] In cases of syndromic craniosynostosis, the closed suture occurs as part of a suite of symptoms or features, and mutations in a number of genes have been identified as being associated with these syndromes (e.g., Flaherty et al.,[30] Heuzé et al.,[31] and Lattanzi et al.[32]). The nearly 200 identified craniosynostosis syndromes account for approximately 15 percent of all craniosynostosis cases.[30] Recent work stresses the complexity of craniosynostosis phenotypes even in cases of nonsyndromic (isolated) craniosynostosis, emphasizing that craniosynostosis conditions need to be defined not simply by premature suture closure, but more broadly as growth disorders that affect many different cell and tissue lineages.[30,31,33–35] Consequent to the broad developmental impact of the genes on which craniosynostosis-causing mutations are located (e.g., fibroblast growth factor receptors, TWIST), many craniofacial tissues are affected in craniosynostosis syndromes, including skeletal (bone and cartilage), muscular, neural, and circulatory structures. Facial dysmorphologies potentially associated with craniosynostosis syndromes include maxillary dysmorphogenesis resulting in a reduced midface, hypertelorism, exophthalmos, depressed or low nasal bridge, mandibular prognathism, cleft palate, and highly arched and/or constricted palate.[27,36–40] Any one of these structural anomalies has the potential to contribute to altering the position, size, shape, or patency of the choanae.

Craniosynostosis has been explicitly linked with choanal atresia in one of the seminal texts on the diagnosis and evaluation of craniosynostosis, noting that atresia or stenosis is an "expected" clinical finding in craniosynostosis syndromes,

particularly where there have been structural rearrangements in the cranial base,[27] a region of the skull that forms endochondrally from a complex series of cartilages that underlie the brain. Additional links between syndromic craniosynostosis and choanal atresia can be found in review and research articles throughout the clinical literature (e.g., Adil,[1] Corrales and Koltai,[10] Lowe et al.,[15] Keller and Kacker,[17] Ramsden et al.,[18] Hehr and Muenke,[29] and Cunningham et al.[37]). Table 1 lists published case reports that have explicitly reported choanal atresia in patients diagnosed with syndromic craniosynostosis. Craniosynostosis cases reporting only choanal stenosis are not included.

Of the 54 case reports reviewed, none included a definition of choanal atresia, and several provide descriptions suggesting that the condition may have more likely been choanal stenosis.[19,20,79] For example, various authors reported (emphases added):

- "all four of our patients exhibited choanal atresia (*narrowed* nasal passage)."[19]
- "*incomplete* choanal atresia led to respiratory difficulties."[20]
- condition was first labeled "choanal atresia" and later as "choanal *hypoplasia*,"[79] the former being a diagnostic category and the latter being a description that suggests the developmental basis of this anomaly.

In addition, the methods of evaluation and diagnosis were often not indicated, and the fundamental differences among diagnostic tools were not discussed by these authors. Only eight cases reported the use of computed tomographic imaging to confirm the choanal atresia diagnosis,[43,44,59,62,64,65,67,75] whereas others cited Doppler evidence,[42] choanography,[48] inability to pass a nasogastric tube through the posterior choanae,[49] simple reference to "imaging,"[44] and pharyngography[66]. Although computed tomographic imaging was mentioned in seven additional case reports, those reports did not include an indication of whether the scan was used in the choanal atresia diagnosis.[54–56,66,76,77,80] Another nine reports mentioned various types of surgical intervention in which direct visualization may have been possible, but no explicit description of the surgical evaluation was given.[45,50,53,54,61,68,71,73,76] These reports also varied widely in the detail of the description of co-occurring facial anomalies that might contribute to respiratory difficulties. It is important to note that, unless the above-referenced case

reports included images of the diagnostic scans, it is impossible to say for certain whether the suggested choanal atresia was correctly diagnosed.

LOOKING FORWARD

The clear implication of the case reports (Table 1) is the need for a consistent application of an invariant clinical definition of choanal atresia that is distinct from choanal stenosis. The term "choanal atresia" was used in a number of these case reports, yet the condition described may actually be choanal stenosis. Without review of each described patient's medical records and associated diagnostic images and results, we are only able to note that the diagnosis is not well supported based on the published information and cannot definitively state whether any of these choanal atresia diagnoses are truly erroneous. Other reports simply group the conditions together and report a finding of "choanal stenosis/atresia." Although options may be similar from a treatment perspective, understanding choanal stenosis and atresia as potentially different pathologic conditions with distinct causes requires more precise descriptions and further research. While several craniofacial textbooks and journal articles provide clear definitions of choanal atresia,[1,9–11,16] many authors either omit a definition from published case reports or fail to explicitly match a given definition to their clinical observations and reports. In addition, although medical computed tomography is acknowledged to be the gold standard for the diagnosis of choanal atresia,[1,11,15,17,18,81] the vast majority of published case reports either fail to report the use of this preferred diagnostic methodology or use less reliable techniques that may erroneously lead to a choanal atresia diagnosis when choanal stenosis or an other choanal or nasal dysmorphology is present. Sculerati and colleagues' previous study of over 250 pediatric patients with major craniofacial anomalies produced results that support our observations, finding that choanal atresia was often misdiagnosed when respiratory difficulties were actually being caused by nasal obstructions secondary to midfacial retrusion.[21] In addition to the need for a better understanding of the facial dysmorphologies associated with midfacial retrusion (e.g., hypoplasia, flattening, dysgenesis), further research should be directed toward the investigation of the relationship between choanal stenosis and choanal atresia and whether they are distinct abnormalities or represent unique conditions along a continuum of choanal dysmorphogenesis. Given the

Table 1. Case Reports That Explicitly Diagnose Syndromic Craniosynostosis and Choanal Atresia

| Gene	Mutation	Diagnosis	Calvarial Sutures	Choanal Atresia/Stenosis	Method of Evaluation	Citation
NR	NR	Antley-Bixler	Lambdoid	Unilateral atresia	NR	41
NR	NR	Antley-Bixler	Metopic	Choanal atresia	Doppler; autopsy	42
NR	NR	Antley-Bixler	NR	Unilateral right atresia and left stenosis	CT	43
NR	NR	Antley-Bixler	Coronal	Bilateral atresia	CT	44
NR	NR	Antley-Bixler	Coronal	Unilateral atresia	Imaging	44
NR	NR	Antley-Bixler	Coronal, metopic	Bilateral atresia	Surgical intervention	45
NR	NR	Apert	Coronal	Unilateral atresia and stenosis	NR	46
NR	NR	Apert	Coronal	Bilateral atresia	NR	47
NR	NR	Apert	Coronal	Unilateral atresia	Choanography; surgical intervention	48
NR	NR	Apert	Multiple	Bilateral atresia	Inability to cannulate	49
FGFR2	NR	Apert	Coronal	Bilateral atresia	Surgical intervention	50
FGFR2	S252W	Apert	NR	"Choanal stenosis/atresia"	NR	51
FGFR2	S252W	Apert	Coronal, lambdoid	Choanal atresia	NR	52
FGFR2	S252W	Apert	NR	Choanal atresia	NR	52
FGFR2	S252W	Apert	NR	Choanal atresia	NR	52
FGFR2	P253R	Apert	NR	Choanal atresia	NR	52
FGFR3	P253R	Apert	NR	"Choanal stenosis/atresia"	NR	47
FGFR2	Alu insertion	Apert	NR	Choanal atresia	Surgical intervention	53
NR	NR	Beare-Stevenson	Coronal, lambdoid, squamous	Choanal atresia	NR	54
NR	NR	Beare-Stevenson	Coronal, lambdoid, sagittal	Bilateral atresia	Surgical intervention	54
NR	NR	Beare-Stevenson	Coronal, lambdoid, sagittal	Choanal atresia	NR	54
NR	NR	Beare-Stevenson	Coronal, lambdoid, sagittal	Choanal atresia	NR	54
NR	NR	Beare-Stevenson	Cloverleaf	Choanal atresia	NR	55
NR	NR	Beare-Stevenson	Cloverleaf	Choanal atresia	NR	56
NR	NR	Beare-Stevenson	NR	Choanal atresia	NR	57
NR	NR	Beare-Stevenson	NR	Choanal atresia	NR	58
NR	NR	Beare-Stevenson	Cloverleaf	Bilateral atresia	CT	59
NR	NR	Beare-Stevenson	Cloverleaf	Unilateral atresia	NR	59
NR	NR	Beare-Stevenson	Cloverleaf	Choanal atresia	NR	60
NR	NR	Beare-Stevenson	Coronal, sagittal, lambdoid	Bilateral atresia	Surgical intervention	61
FGFR2	Tyr375Cys	Beare-Stevenson	Cloverleaf	Choanal stenosis with possible atresia	CT	62
FGFR2	Tyr375Cys	Beare-Stevenson	Multiple	Choanal atresia	NR	63
FGFR2	Tyr375Cys	Beare-Stevenson	None	Bilateral atresia	CT	64
FGFR2	Tyr375Cys	Crouzon	NR	Unilateral right atresia and left stenosis	CT	65
FGFR2	Tyr375Cys	Crouzon	Cloverleaf	Bilateral atresia	Pharyngiography	66
FGFR2	Tyr375Cys	Crouzon	NR	Bilateral atresia	CT	67
NR	NR	Crouzon	NR	Unilateral right atresia and left stenosis	Surgical intervention	68
FGFR2	Cys342Tyr	Crouzon	Coronal, lambdoid, sagittal	Unilateral atresia	NR	69
FGFR2	Cys342Tyr	Crouzon	Coronal	Choanal atresia	NR	63
FGFR2	Ser351Cys	Crouzon	Cloverleaf	Bilateral atresia	NR	70
NR	NR	Crouzon with acanthosis nigricans	Coronal, sagittal	Bilateral atresia	Surgical intervention	71
NR	NR	Crouzon with acanthosis nigricans	Coronal	Choanal atresia	NR	72
NR	NR	Crouzon with acanthosis nigricans	Coronal, sagittal	Choanal atresia	NR	72
FGFR3	Ala391Glu	Crouzon with acanthosis nigricans	Coronal	"Incomplete" choanal atresia	NR	20
FGFR3	Ala391Glu	Crouzon with acanthosis nigricans	NR	Choanal atresia (narrowed nasal passage)	NR	19
FGFR3	Ala391Glu	Crouzon with acanthosis nigricans	Cloverleaf/multiple sutures	Unilateral atresia and stenosis	Surgical intervention	73

(Continued)

Table 1. (Continued)

Gene	Mutation	Diagnosis	Calvarial Sutures	Choanal Atresia/Stenosis	Method of Evaluation	Citation
FGFR3	Ala391Glu	Crouzon with acanthosis nigricans	Multiple	Unilateral atresia and stenosis	Surgical intervention	[73]
FGFR3	Ala391Glu	Crouzon with acanthosis nigricans	Coronal	Choanal atresia	NR	[74]
FGFR3	Ala391Glu	Crouzon with acanthosis nigricans	Cloverleaf	Bilateral atresia	CT	[75]
NR	NR	Pfeiffer	Coronal, lambdoid, sagittal	Bilateral atresia	NR	[76]
NR	NR	Pfeiffer	Cloverleaf	Choanal atresia	NR	[77]
NR	NR	Pfeiffer	NR	Choanal atresia/stenosis	NR	[78]
NR	NR	Pfeiffer	Cloverleaf	Choanal atresia/hypoplasia	NR	[79]
FGFR2	Ser351Cys	Pfeiffer	Coronal	Choanal atresia	NR	[80]

NR, not reported; CT, computed tomography.

state of the existing literature, it is recommended that case reports and research articles focusing on choanal atresia provide both an explicit definition of the condition, and details regarding the methodology used to detect and diagnose the condition. Recent caution regarding radiation exposure when using computed tomography as a primary diagnostic tool[82] provides a timely opportunity to refine both the clinical definition of choanal atresia and to develop a new standard for detection and diagnosis.

Research focused on choanal development, structure, and morphology in humans (especially within the pediatric craniosynostosis syndrome population) and animal models is needed to better understand the true incidence of choanal atresia within this patient population. Several studies have reported nasal airway volume or morphology in pediatric choanal atresia patients,[12,13] but little work has been done to quantify or describe choanal or nasal airway morphology in syndromic craniosynostosis patients. Perhaps more importantly, there have been few serious attempts to tie craniosynostosis conditions to choanal atresia developmentally or by molecular causation.

A recent analysis of three-dimensional medical computed tomographic scans comprising children diagnosed with Apert, Pfeiffer, Muenke, or Crouzon syndrome and typically developing children (aged 0 to 23 months) without craniosynostosis who underwent computed tomographic imaging for unrelated conditions (e.g., seizures) provides information about differences in facial skeletal shape among craniosynostosis syndromes.[40] The three-dimensional isosurfaces were reconstructed from the set of Digital Imaging and Communication in Medicine (DICOM) images,[40] and these three-dimensional computed tomographic scans were evaluated visually for the presence of choanal atresia. Of 33 individuals diagnosed with syndromic craniosynostosis, none had choanal atresia. Nasopharyngeal volume, including the ethmoidal air cells, was estimated for each patient using the segmentation editor of the software package Avizo 6.3 (Visualization Sciences Group, Burlington, Mass.). The nasal vestibule defined the anterior end of the nasal cavity, with the borders defined by soft tissue when present in individual three-dimensional computed tomographic slices or by manually closing the nostrils when soft tissue was not present (Fig. 4, *above* and *below, left*). Posteriorly, only the nasopharyngeal lumen that was present anterior to or coincident with a line connecting the most posterior points on the right and left medial plates of the pterygoid was included

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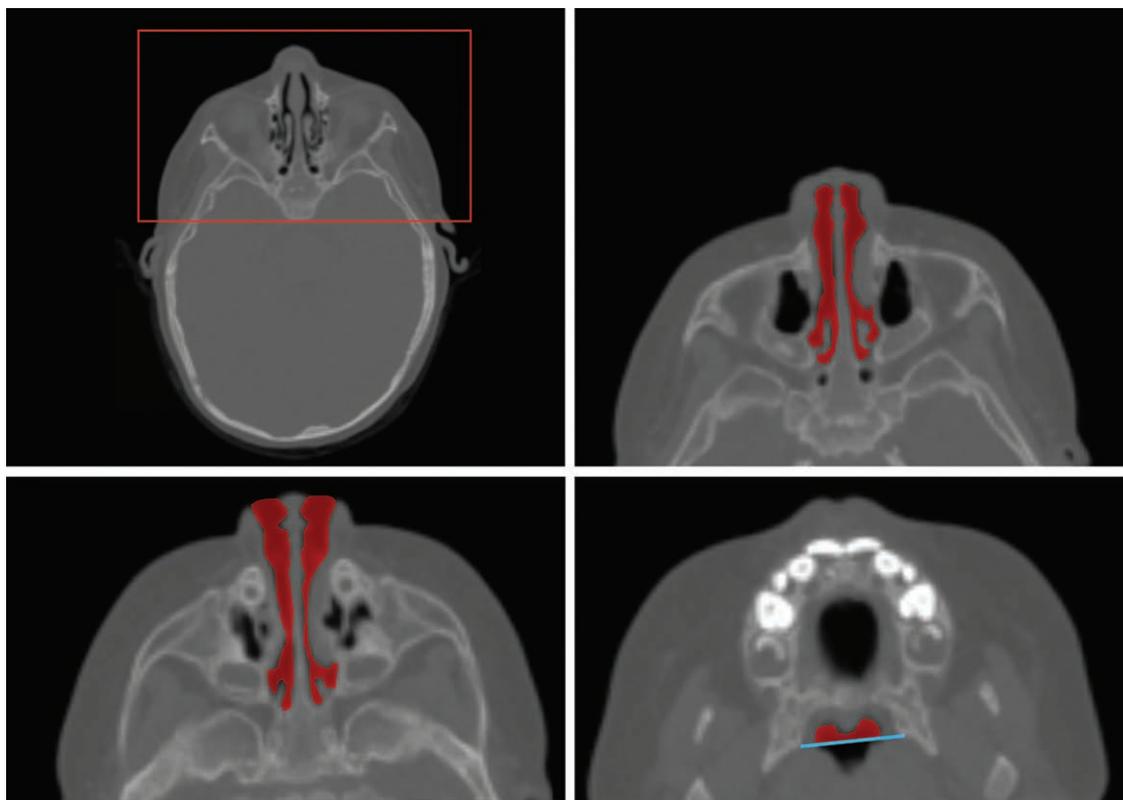
Fig. 4. Nasal airway segmented from a computed tomographic image of a typically developing child at 10 months, as an example of how the nasal airway volume data presented in Figure 5 were collected. (*Above*, *left*) Axial computed tomographic image at the level of the orbits indicating area of close-up (*red box*) for three additional anatomical levels, including (*above*, *right*) the nasal cavity (*red*) with soft tissue of the nose bordering the anterior nares at the level of the maxillary sinuses; (*below*, *left*) midnares level with partial soft-tissue border of the anterior nares; and (*below*, *right*) at the level of the alveolar processes of the maxillae showing the nasopharyngeal lumen (*red*) anterior to a line (*blue*) connecting the most posterior points on the medial plates of the pterygoid bone.

in the segmented volume (Fig. 4, *below*, *right*). Comparisons between unaffected children and those diagnosed with syndromic craniosynostosis reveal potentially reduced nasal airway volumes in children diagnosed with Apert and Pfeiffer syndromes (Figs. 5 and 6). Analysis of cross-sectional data representing nasal airway volumes of varying groups from birth to approximately 30 months of age shows that children diagnosed with Apert and Pfeiffer syndromes appear to share similar nasal airway volumes with children diagnosed with Muenke syndromes and their typically developing peers at birth. Although the sample size is small, the results also indicate that children diagnosed with Crouzon syndrome may have reduced nasal airway volumes at birth. Based on this analysis using limited samples, children diagnosed with Apert and Pfeiffer syndromes may experience an early postnatal developmental divergence that results in smaller overall nasal airways within the first year of life (Fig. 5).

The distinction between true choanal atresia and more diffuse nasal airway stenosis that is often present in syndromic craniosynostosis is important for both clinical and basic research reasons. Although it is essential that researchers in the field have a clear understanding of the correct terminology to ensure appropriate communication and reporting, there are also potential clinical ramifications to consider. Choanal atresia in the newborn is a condition that is very amenable to early surgical intervention, which can often obviate the need for tracheostomy, prolonged neonatal intensive care unit hospitalization, and continued respiratory monitoring. Nasal airway obstruction in the newborn with syndromic craniosynostosis may not be as readily surgically correctable in early life. Incorrect terminology may lead a surgeon down an errant pathway and may lead the child's family to have unrealistic expectations. Knowledge of associations between craniosynostosis and choanal
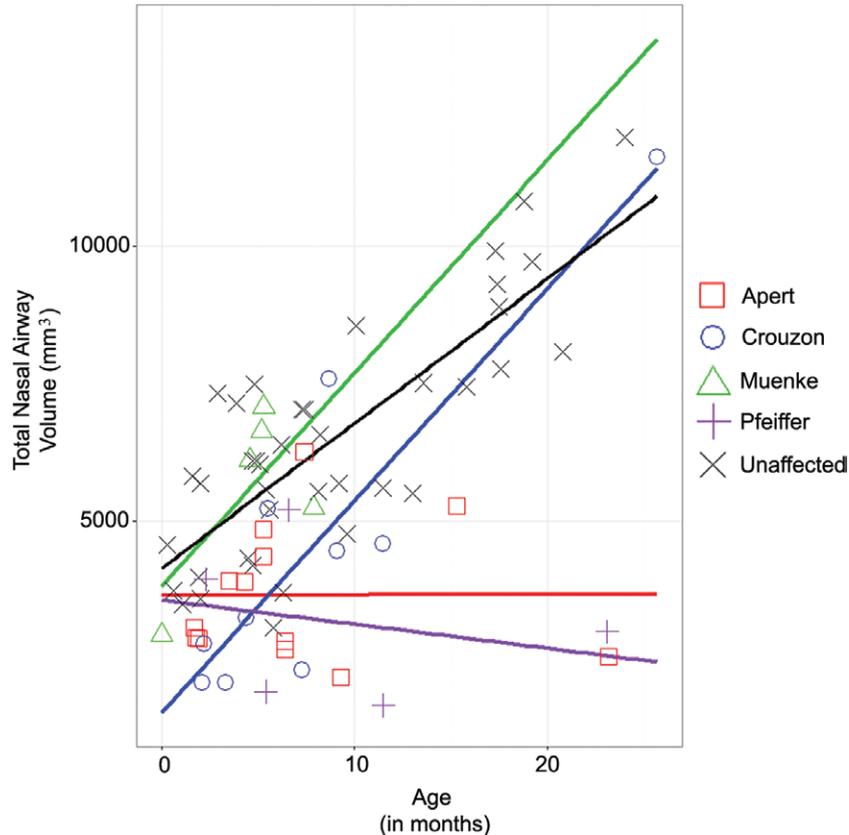
Fig. 5. Scatterplot of total nasal airway volume and age (in months) of individuals diagnosed with various craniosynostosis syndromes and typically developing individuals. Sample sizes are as follows: Apert syndrome (*n* = 13), Crouzon syndrome (*n* = 10), Muenke syndrome (*n* = 5), Pfeiffer syndrome (*n* = 5), and unaffected (*n* = 39). *Lines* represent the results of regression analysis showing the relationship between age and total nasal airway volume (including the ethmoidal air cells) for each group. It is important to note that this plot and the regression lines estimated from the cross-sectional data are used to demonstrate the variation in nasal airway volumes among craniosynostosis syndromes. As the nasal airway volume data are based on cross-sectional data sets for each diagnostic category, these regression lines do not necessarily indicate growth patterns or growth trajectories.

atresia will require development of standards of diagnosis and application of those standards.

Mouse models have been developed for a number of craniosynostosis syndromes that replicate the genetic cause and the skeletal and soft-tissue phenotypes seen in human patients, including midfacial hypoplasia.[83–89] Several of these models have also been used to investigate nasal airway volumes. A recent study of the soft-tissue phenotype of the *Fgfr2c+/C342Y* Crouzon/Pfeiffer syndrome mouse model found a significant reduction in nasal airway volumes in littermates carrying this mutation relative to unaffected littermates.[35] The C342Y mutation is equivalent to the most common mutation associated with human patients diagnosed with Crouzon syndrome. The

human Crouzon syndrome phenotype has been associated with a number of craniofacial dysmorphologies related to both hard and soft tissues, such as premature closure of the coronal suture, midfacial hypoplasia/retrusion, and alterations to nasopharyngeal morphology.[27,38] Skeletal phenotypic correspondences between human patients with Crouzon syndrome and the *Fgfr2c+/C342Y* mouse model of Crouzon syndrome have been demonstrated, and this mouse model also mimics the altered human nasopharyngeal phenotype.[35] On the day of birth, heterozygous *Fgfr2c+/C342Y* littermates exhibited a statistically significant restriction in nasal airway volume (2.81 ± 0.17 mm³) compared with their unaffected littermates (3.28 ± 0.13 mm³; *p* = 0.012).[35] However, choanal atresia

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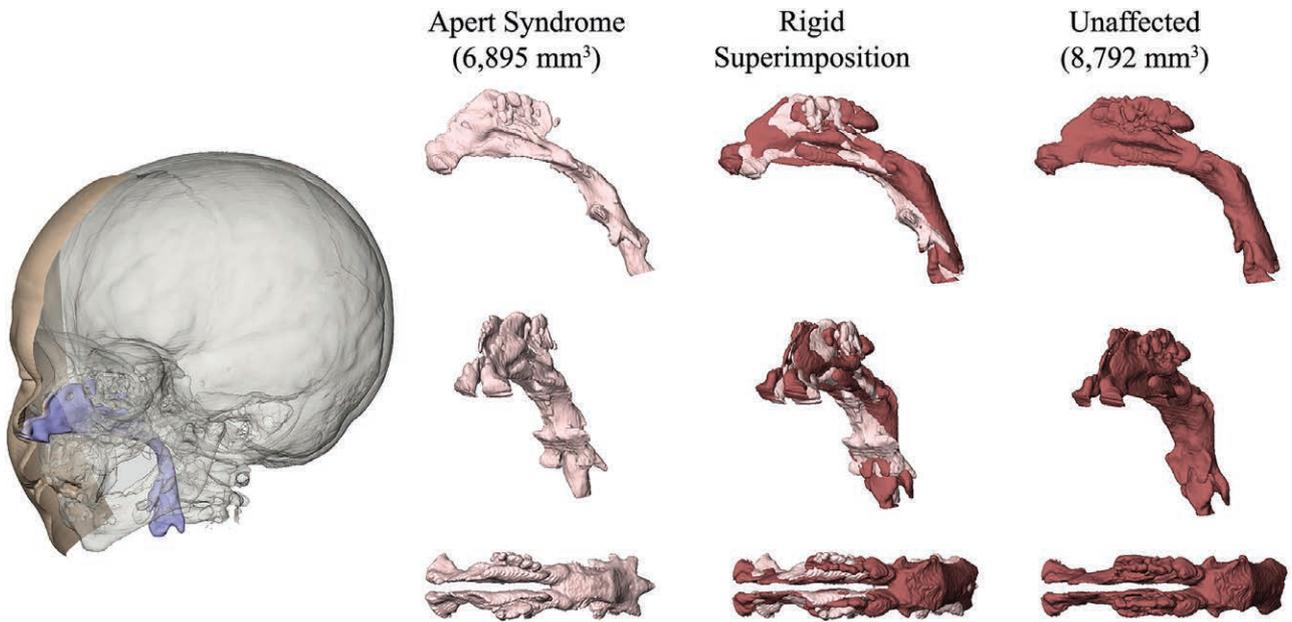
Fig. 6. Three-dimensional computed tomographic reconstruction of a typically developing child (*left*) showing superimposed segmentations of skin surface (*beige*), brain surface (*gray*), and upper airway lumen (*blue*). At *right* are "virtual endocasts" of the nasopharynx of a child with Apert syndrome (*pink*, *left*) and a typically developing child (*maroon*, *right*) as segmented from high resolution three-dimensional computed tomographic reconstruction. Superimposition of the two virtual endocasts (*second from right*) shows local areas of greatest shape difference. This comparison is not a statistical comparison of the nasopharyngeal anatomy of patients with Apert syndrome and typically developing individuals; rather, this superimposition provides an example of how nasopharyngeal morphology of craniosynostosis patients may differ from typically developing individuals.
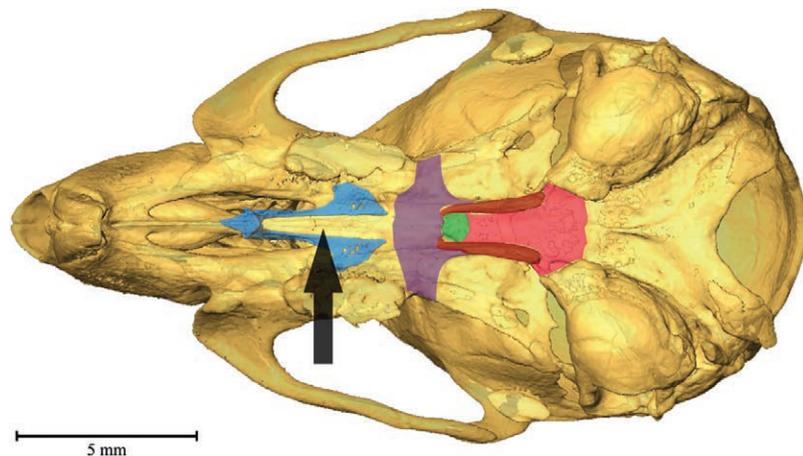
Fig. 7. Three-dimensional computed tomographic reconstruction of the cranium of a 6-week-old C57BL/6J mouse showing the bones that form the osteologic borders of the choanae in the human skull: vomer (*blue*), basisphenoid (*pink*), medial pterygoid plates (*red*), and horizontal plates of the palatine bones (*purple*). The vomer (which is ghosted in this illustration) lies deep to the maxillae and so is hidden in an inferior view. The presphenoid is shown in *green*. Note the anatomical separation of these bones compared to the human skull in Figure 1. The *black arrow* indicates the position of the choanae in mice at the soft-tissue intersection of the posterior nasal cavity and nasopharynx.

was not reported in any of the mice studied. As of this date, there have been no published reports of definitive choanal atresia in any mouse models of syndromic craniosynostosis.

While murine data provide valuable information about the molecular and developmental mechanisms that produce the choanae, significant differences in human and murine craniofacial anatomy and development must be taken into consideration when evaluating the comorbidity of choanal atresia and craniosynostosis using cross-species comparisons. Because of the rostral-caudal elongation of the murine premaxillae, maxillae, palatine bones, and the soft palate, different osteologic and soft-tissue boundaries define the murine choanae relative to humans. In humans, choanal atresia has been attributed to a combination of a thickening of the posterior vomer with medialization of the pterygoid plates of the sphenoid. Although useful murine models of choanal atresia have recently been produced and will be critical to determining the molecular and developmental basis of choanal atresia,[90] species-specific differences including the anatomical separation of the vomer and pterygoid plates along the rostrocaudal axis in mice suggests an alternate structural foundation for murine choanal atresia (Fig. 7). While mouse models are an excellent tool for understanding the cause of human craniofacial disorders such as craniosynostosis, given the tremendous number of genetic mutations implicated in craniosynostosis conditions, each model can represent only a single development pathway to the craniosynostosis phenotype. We propose that there are potentially as many ways to produce choanal atresia.

The significant correlation between specific craniosynostosis syndromes and reduced nasal airway volume in mouse models for craniosynostosis and human pediatric patients indicates comorbidity of choanal and nasopharyngeal dysmorphologies and craniosynostosis conditions. Genetic, developmental, and epidemiologic sources of these interactions are areas particularly worthy of further research.

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