Forensic Anthropology
DOI: 10.5744/fa.2023.0016

RESEARCH ARTICLE

Age-Related Changes to Frontal Sinus Traits and Implications for Forensic Identification

Naeema Abdulrazak[a] • Lauren Nicole Butaric[a*] • Heather Marie Garvin[a]

ABSTRACT: Forensic studies on frontal sinus identification are often limited to adult samples or utilize static, simulated antemortem images, which overlook any potential temporal changes in sinus morphology. Further, studies on frontal sinus growth typically utilize lateral radiographs and/or are cross-sectional. The current study utilizes a longitudinal sample of frontal radiographs to determine the age at which forensically relevant frontal sinus traits stabilize during growth and development. The sample includes 1500 radiographs of 141 individuals (66F/75M) ranging from three to 56 years of age (yoa). For each individual, trait age-of-stabilization was recorded by identifying the year at which each coded trait became consistent across images.

Our results demonstrate that frontal sinus traits stabilize on average 10–15yoa, with sinus presence being the first to stabilize and arcade counts the last. Females generally stabilized earlier (9–14yoa) versus males (10–15yoa). However, sex differences were generally not statistically significant. Further, traits displayed a high degree of variation with wide standard deviations (~3 years). However, by 21yoa almost all individuals displayed stabilization in all traits, suggesting that little change should be expected with later-aged postmortem radiographs. Still, given the amount of variation, forensic practitioners should be cautious using frontal sinus identification methods in subadults, especially when years may have elapsed between images. When conducting a radiographic comparison that involves a subadult antemortem image, the results of this study may help the practitioner interpret whether the differences between antemortem and postmortem radiographs can be explained by age and time elapsed between radiographs.

KEYWORDS: Forensic anthropology; personal identification; RADid; paranasal sinuses

Introduction

Accurate and reliable methods of personal identification are crucial in medicolegal scenarios. Correct identifications provide family members with closure and facilitate forensic investigations; thus, medical examiners and coroners strive to obtain a positive identification as quickly as possible. Incorrect identifications can have dire consequences, including an emotional burden on families, the possible hindrance of investigations, and a high likelihood of legal ramifications. In lieu of or in addition to more familiar methods of identification (e.g., DNA, fingerprints, dental records), identifications can be based on radiographic and computed tomographic (CT) comparisons using the frontal sinus (for reviews see Christensen & Hatch 2018; Pereira et al. 2021). The frontal sinus is an air-filled, mucus-lined space between the external and internal cortical layers of the frontal bone located just above the orbits. Typically, this structure consists of paired (right/left) lobes separated by an inter-sinus septum. Each of the air-filled lobes expand superiorly and laterally as a series of septa (bony walls) and arcades (or scallops), which vary in size, shape, and number. While most individuals have some presence of the frontal sinus, others may exhibit bilateral aplasia. Bilateral aplasia (i.e., complete absence of a frontal sinus in adults) frequencies are reported to range between 2% and 24%, although this may be higher in Arctic and Oceanic populations (Aydinlioglu et al. 2003; Buck et al. 2019; Butaric et al. 2020; Fatu et al. 2006; Hansen & Owsley 1980). When the frontal sinus is present, there is a high degree of variation in the frontal sinus, with lobal presence/absence, positioning relative to the orbits, overall size, and morphology varying across individuals. Left and right lobal asymmetry is also common, further increasing possible levels of variation (Fatu et al. 2006); even monozygotic twins express visually different frontal sinuses (see Asherson 1965; Kjaer et al. 2012; Schuller 1943).

The individualistic nature of the frontal sinus makes this structure valuable in terms of personal identification. The

[a]Des Moines University, Anatomy, West Des Moines, IA, USA
*Correspondence to: Lauren Nicole Butaric, Des Moines University, Anatomy, 8025 Grand Avenue, West Des Moines, IA 50266, USA
E-mail: lauren.butaric@dmu.edu.

Lauren Nicole Butaric (ORCid: 0000-0003-3743-2408)
Heather Marie Garvin (ORCid: 0000-0002-9787-4366)

This research was funded by National Institute of Justice, grant number 2020-75-CX-0013.

Received 26 June 2023; Revised 18 August 2023; Accepted 11 September 2023

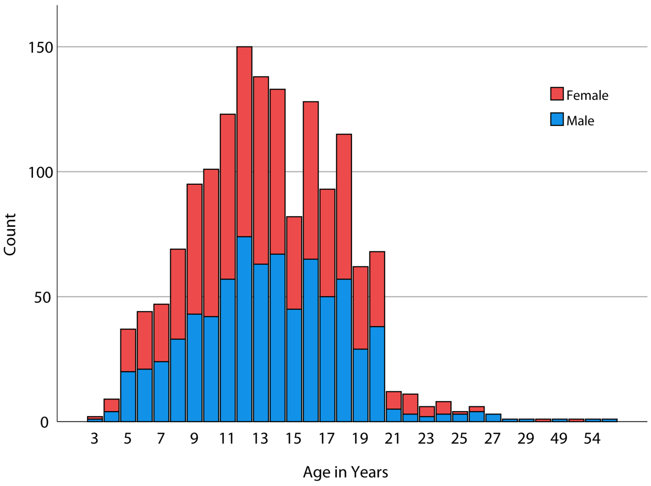

FIGURE 1—*Histogram illustrating number of radiographs distributed across age in years for males and females.*

most commonly utilized and earliest proposed method for sinus identification is visual assessment, where investigators visually compare antemortem and postmortem radiographic images of frontal sinuses and determine whether they morphologically match either with side-by-side comparisons or via superimposition (e.g., Atkins & Potsaid 1978; Culbert & Law 1927; Hashim et al. 2015; Jablonski & Shum 1989; Kullman et al. 1990; Marlin et al. 1991; Murphy & Gantner 1982; Nambiar et al. 1999; Owsley 1993; Quatrehomme et al. 1996; Schuller 1921; Ubelaker 1984). However, due to increasing concerns for more statistically validated and rigorous techniques (Christensen 2004; National Research Council 2009), individuals have questioned whether visual assessment is too subjective (see Christensen 2005; Christensen & Hatch 2018). Because of this, more statistically objective and quantitative methods of radiographic frontal sinus comparisons have been developed utilizing metrics, coding of qualitative traits, and/or sinus outline analyses (e.g., Cameriere et al. 2005; Christensen 2004, 2005; Cox et al. 2009; Reichs & Dorion 1992; Riberio 2000; Soares et al. 2016; Tatlisumak et al. 2007; Uthman et al. 2010; also see Pereira et al. 2021 for a systematic review of methods). Regardless of method, frontal sinus identification studies are often limited to adult samples or compare duplicated postmortem radiographs thereby only simulating an antemortem-postmortem comparison. Although postmortem radiographs may be retaken in such comparisons to incorporate error from small deviations in radiographic orientation, if skeletal remains are utilized it eliminates any challenges with the superimposition of soft tissue structures. Additionally, these study methods overlook any potential temporal (i.e., age-related) changes in sinus morphology, particularly during the subadult period (see Kirk et al. 2002). Thus, one area of concern for the use of the frontal sinus in identification relates to patterns of growth and development of the frontal sinus, as well as stability of sinus morphology throughout one's life. However, little is known regarding frontal sinus growth and development in general, and studies assessing sinus ontogeny are often contradictory.

Several studies attempt to assess ages of appearance and growth cessation of the frontal sinus. During fetal development, the frontal recess (which will later become the frontal sinus) emerges as an outpouching from the nasal capsule either directly or indirectly via ethmoidal air cells (Kasper 1961; Scheffer 1916; Weiglein 1999). However, most of the growth and development of the frontal sinus occurs postnatally. Since it is not well-developed at birth, visualizing this sinus radiographically is difficult at young ages. While reported to appear radiographically as young as the age of two (Davis 1914; Kirk et al. 2002; Maresh 1940; Park et al. 2010; Quatrehomme et al. 1996; Weiglein et al. 1992; Yoshino et al. 1987), it is typically not radiographically visible until 6–8yoa (Dolan 1982; Duque & Casiano 2005; Enlow & Hans 1996; Scuderi et al. 1993; Tatlisumak et al. 2007, 2008). Around this time, the frontal sinus usually expands superiorly above the orbital borders and is more easily distinguished from the ethmoidal air cells, which tend to obscure smaller frontal sinuses in radiographs. The linear dimensions, overall shape, and complexity of the frontal sinus continues to increase with age into early adulthood, with most sinus growth occurring during puberty (Brown et al.1984; Butaric et al. 2022a; Fatu et al. 2006; Gagliardi et al. 2004; Quatrehomme et al. 1996; Sardi et al. 2018).

The age at which the frontal sinus reaches its adult size and shape is also still largely unknown. Generally, terminal development of the frontal sinuses has been suggested to occur by 18–20yoa (Brown et al. 1984; Butaric et al. 2022a; Fatu et al. 2006; Schuller 1921; Marek et al. 1983; Prossinger 2001; Rennie et al. 2017; Sardi et al. 2018; Spaeth et al. 1997; Yun et al. 2011). Studies on sinus size (e.g., sinus volume, area, or linear dimensions) indicate that while the sinuses tend to appear earlier in males (Brown et al. 1984; Gagliardi et al. 2004), females tend to reach their adult state earlier (Brown et al. 1984; Gagliardi et al. 2004; Prossinger 2001; Sardi et al. 2018). Finally, some studies suggest there may be additional changes that occur later in life, with conflicting accounts of sinuses either enlarging (Fatu et al. 2006; McLaughlin et al. 2001; Tatlismuak et al. 2017) or decreasing in size during senescence (e.g., Akhlagi et al. 2016; Emirzeoglu et al. 2007).

One of the primary issues in establishing when the frontal sinus attains adult maturity is that most ontogenetic publications are cross-sectional (e.g., Bargouth et al. 2002; Buyuk et al. 2017; Fatu et al. 2006; Mahmood et al. 2016; Moore & Ross 2017; Park et al. 2010; Patil & Revankar 2013; Prossinger 2004; Sardi et al. 2018; Spaeth et al. 1997; Tehranchi et al. 2017; Weiglein et al. 1992; Yun et al. 2011), limiting the understanding of individual growth patterns. When longitudinal studies have been conducted, they are largely focused on lateral radiographs (e.g., Brown et al. 1984; Gagliardi et al. 2004; Nathani et al. 2016; Ruf & Pancherz 1996a,1996b; Shah et al. 2003), which do not capture the full scope of sinus visible in frontal views (e.g., arcades, septa, asymmetry). More recently, Butaric et al. (2022b) analyzed a longitudinal sample of frontal radiographs to assess frontal sinus shape based on outlines. Using averaged Loess trendlines, these authors found that on average sinus shape stabilized around 14–16yoa for females, with male shape stabilizing around 18–20yoa. While informative, that study was limited to closed outline shape and could not capture certain identifiable features, such as varying presentation of intra- and inter-sinus septa or asymmetry in lobal presence. Thus, the age at which frontal sinuses reach their maximum number of arcades and septa—features that are arguably the most indicative for personal identifications—remains relatively unknown.

Purpose of current study

While visual, metric, coding, and outline identification methods vary in specific protocols and sinus traits utilized, most methods rely on consistent sinus traits in antemortem and postmortem images and any developmental changes in sinus morphology—particularly the number of arcades and septa and/or arcade/cell expansions—could affect match accuracy. However, as mentioned above, age-related changes to these traits during ontogeny and into adulthood are not well-documented, and there are no reported standards for minimum decedent ages for frontal sinus identification nor acceptable time intervals between antemortem and postmortem radiographs. As such, the current study aims to assess age-related changes in several frontal sinus traits to better understand potential method limitations in medicolegal frontal sinus identification. Unlike previous studies, this study utilizes a longitudinal (versus cross-sectional) sample of frontal (versus lateral) radiographs. The aim was to longitudinally evaluate changes in frontal sinus traits relevant to coding, outline, and visual assessments, to specifically investigate the age at which these traits stabilized during growth and development. The overall purpose is to determine the minimum ages at which traits, regardless of method utilized, can be applied reliably for radiographic identifications.

Materials and Methods

Sample

A longitudinal sample of radiographs available online as part of the American Association of Orthodontists Foundation (AAOF) Legacy Growth Collection were used in this study (https://www.aaoflegacycollection.org/aaof). The Legacy Collection includes a total of nine ontogenetic radiographic collections developed by multiple US and Canadian universities between 1930 and 1985 for growth and development studies (for reviews, see Al-Jewair et al. 2018; Baumrind & Curry 2015). Most of the growth studies attempted to collect radiographs either annually or semi-annually from study participants from around 3–5yoa into early adulthood. To maximum sample sizes, our study used radiographs from the specific Burlington, Bolton Brush, Oregon, Mathews, and Forsyth collections as they had available frontal radiographs with widest age ranges (Table 1). Radiographs in these collections of males and females were visually assessed, and images of poor quality (e.g., over exposed) that obscured sinus traits (see trait descriptions below) were excluded. Individuals who did not possess at least one image 18 years or older and/or those with less than four usable radiographs were also excluded. These inclusion parameters ensured that adult sinus morphology was captured for each individual and that age-related sinus changes could be documented over a series of radiographs for each individual, while maintaining acceptable sample sizes. These protocols resulted in 146 available individuals; however, among this sample five individuals (2M, 3F; 3.4% of the sample) exhibited bilateral aplasia and, thus, were not included in further analyses. Those displaying unilateral presence of the sinus (i.e., aplasia of either the right or left lobe) were included in the study and represented 3.4% of the total sample (right-side unilateral aplasia: 2F; left-side unilateral aplasia: 1F/2M). This final sample, counting those with unilateral aplasia, includes 1500 radiographs from 141 individuals (66F/75M) ranging from three to 56yoa (see Fig. 1 for distribution of ages). In terms of number of images per individual, the median number of radiographs per individual was 10; average number of radiographs was 10.7; minimum number of radiographs was four; and maximum number of radiographs was 24. In terms of oldest radiographic age available, 31 (13F/18M) individuals had an oldest age at 18; 30 individuals (16F/14M) at 19yoa; 51 individuals (20F/31M) at 20yoa; and 28 individuals (16F/12M) at 21yoa or older.

TABLE 1—*Sample composition of number of radiographs and individuals based on collections utilized in the current study, not including individuals with bilateral aplasia.*

AAOF Collection	Radiographs (*n*)	Individuals (*n*)
Bolton Brush	308 (136F/ 172M)	30 (14F / 16M)
Burlington	620 (300F / 320M)	63 (28F / 35M)
Forsyth Twins	60 (31F / 29M)	7 (3F / 4M)
Mathews	31 (24M / 7F)	4 (1F / 3M)
Oregon	481 (284F / 197M)	37 (20F / 17M)
TOTALS	**1500 (775F/ 725M)**	**141 (66F / 75M)**

Trait collection

The radiographs were opened in ImageJ (Schneider et al. 2012), enlarged to 3000 pixels, and brightness and contrast were manually adjusted to best visualize the frontal sinus. For each image, a total of nine traits (see Fig. 2 and Table 2) were assessed following trait definitions presented in

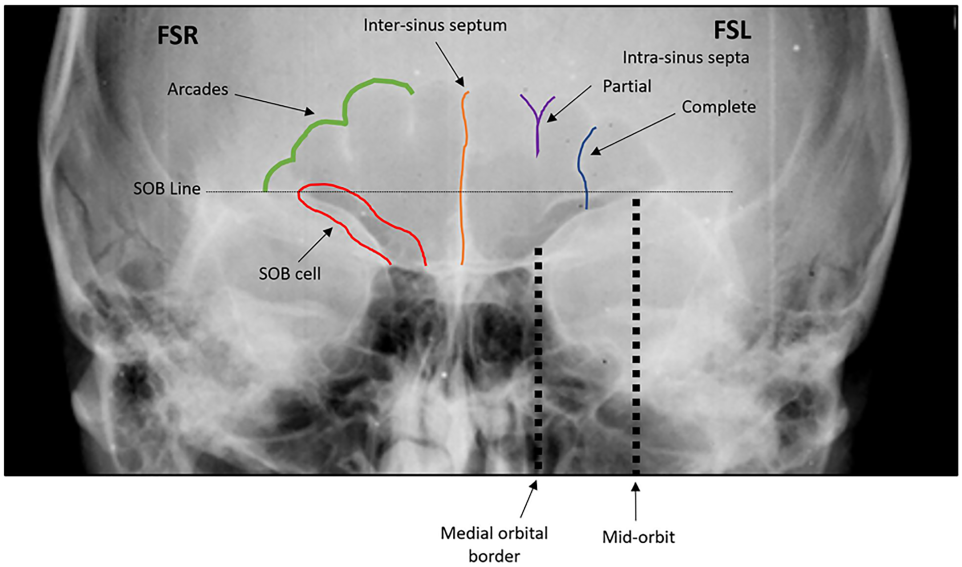

FIGURE 2—*Frontal radiograph with collected traits demarcated on the right (FSR) and left (FSL) frontal sinus lobes. Note arcades are defined along the outer margins of the sinus and do not include internal air cells. See Table 2 for additional trait definitions; SOB, supraorbital.*

TABLE 2—*Descriptions and coding for sinus traits utilized in this study. Also see Figure 2.*

Name of trait*	Description	Code Recorded
Presence (L/R)	Absolute "presence" or "absence" of lobe	Absent/Present
Presence above supraorbital line (L/R)	"presence" or "absence" of lobe extension above the supraorbital line	Absent/Present
Taller lobe	Whether the right or left lobe extends farther superiorly (or are equal)	Right/Left/Equal
Lateral extension (L/R)	Lateral extension of lobe relative to orbit	0: does not reach orbital medial border; .5: at orbit medial border; 1: past medial border, but does not reach orbit midline; 1.5: at orbit midline; 2: past orbit midline
Lobes separated	Whether right and left lobes are joined at the inter-sinus septum or are separated (i.e., discontinuous)	Separated/Joined
Arcades (L/R)	Number of arcades or scallops on the lobe	Count (e.g.,1,2,3,); if unclear a possible range was provided with minimum used in analyses
Intra-sinus complete (L/R)	Number of intra-sinus septa that continue to the lobal borders, thereby splitting the sinus into separate compartments	Count (e.g.,1,2,3)
Intra-sinus partial (L/R)	Number of partial or incomplete intra-sinus septa (do not reach lobe border)	Count (e.g.,1,2,3)
Supraorbital cells (L/R)	Number of air cells located just above the orbits; may appear darker in color	Count (e.g., 0,1,2,3)

* (L/R) indicates that the trait was scored separately for the left and right lobes.

previously published coding methods: Cameriere et al. (2005), Tatlisumak et al. (2007), and Yoshino et al. (1987). Note, while the coding methods include metric dimensions, due to the potential introduction of additional error (see Cameriere et al. 2005; Tatlisumak et al. 2007) and the radiographs not possessing an accurate scale, metric dimensions were not included in the current study. However, a new trait, "lateral extension of the sinus," was included to provide a scale-free measurement of relative sinus breadth (see Table 2)

The traits were collected without images being blinded; in other words, consecutive years of an individual could be viewed simultaneously to better ensure the accuracy of the trait identification and age progression, as well as potential effects of differential orientation, given that the aim of the paper was to assess the anatomical stabilization of these traits not to test method reliability. Frontal sinus presence/absence was collected in two ways: first considering the frontal sinus as any pneumatization regardless of whether it reached the supraorbital line, and secondly considering sinuses present only when they extended above the supraorbital line. Owing to the issue of superimposition, whereby ethmoidal air cells may obscure the frontal sinus, several studies advocate the use of the supraorbital line (Christensen, 2004, 2005; Cox et al. 2009; Hashim et al. 2015; Hanson & Owsley 1980). In such cases, the frontal sinus is only deemed present if it expands superiorly above a line drawn across the upper borders of the orbits. While this method ensures one is capturing the frontal sinus (as compared to ethmoidal cells), it is not necessarily biologically accurate (see Butaric et al. 2020). Since a potential air space could be tracked through older ages, we were able to discern ethmoidal air cells from frontal sinus lobes. As such, we opted to collect sinus presence with and without the supraorbital line so that our sinus appearance results would be comparable across a wider range of studies.

Several structures were difficult to initially assess, with vague definitions provided in the original literature; thus, more precise definitions were standardized during a trial run. For example, the inter-sinus septum presented ambiguously several times, as it seemingly branched out in multiple directions. In such cases, only one inter-sinus septum path was selected based on being closer to the midline and/or based on the origin that was displayed in earlier radiographs for that individual. Additionally, the number of arcades was also sometimes difficult to discern owing to radiographic quality, especially when utilizing the zoom feature for closer inspection. Sometimes small, subtle indentations were visible and appeared to create smaller arcades. Therefore, the range of possible interpretations of arcade number were documented; for statistical analyses, the minimum counts were used. Arcades were counted along the outer contours (i.e., outlines) of the right and left lobes separately, using the inter-sinus septum to differentiate between lobes. Any arcades that did not extend to the outer contour of the sinus or did not extend to the superior margins were not counted.

Presence/absence, count, and coded data for the traits across the 1500 radiographs were recorded. For each individual, the trait age-of-stabilization was recorded by identifying the year at which each coded trait became consistent throughout the later ages. For example, if an individual's age range was 10–20 years and they presented with two arcades at 10yoa but then increased to five arcades at 13yoa, and this number remained consistent (five) until 20yoa, it was recorded that their arcade count stabilized at 13 years. All subsequent analyses were carried out on these age-of-stabilization data. Note that in the Legacy Collection, ages are given in year and months at each radiograph; for the purpose of this study, age was recorded as the given year regardless of month (both "16 years 1 month" and "16 years 11 months" were both recorded as 16yoa), following Butaric et al. (2022b).

For most individuals, several years had occurred between available radiographs. Thus, for each stabilization year recorded, the number of years since the previous image was also collected given that the trait may have stabilized at sometime between those two images. Continuing with the previous individual example, if their arcade count stabilized at 13yoa and their immediate previous radiograph was at 10yoa, then three years was recorded as their "years since last." For individuals who had a trait stabilize within the same year (example, age of stabilization was 13 years 8 months of age, with last known radiograph 13 years 3 months), 0.5 was used for the years since last value. Finally, it is important to note that for sinus traits across several individuals no previous ages were accounted for (i.e., the trait appeared stabilized at the first available radiograph); in such cases, the years since last value was recorded as "not applicable" to prevent the assumption of that individual stabilizing at that particular age.

To account for discrepancies associated with these temporal gaps in radiographs, analyses were conducted on two separate samples: (1) the complete sample (referred to as "Full Sample"), providing larger sample sizes and greater sinus variation, regardless of the temporal gaps or missing images, and (2) a subsample that included only those individuals in which stabilization of the trait occurred within the radiographic sample with no more than two "years since last" (referred to as "2-Year Transitional Sample"). Although the 2-Year Transitional Sample presents a more limited sample size depending on the sinus traits, its use should eliminate potential bias from including individuals where the transition-year was not directly observed.

All data were collected on right and left sides separately. However, preliminary analyses indicated no significant differences in the timing of appearance and/or stabilization of right versus left sides for paired traits. Thus, to get an overall idea of trait stabilization, the maximum age-of-stabilization between the left and right sides of each individual was utilized to represent the time at which a trait fully stabilized in the overall sinus. For example, if an individual had left lobe presence stabilize at age 10 and right lobe stabilize at age 12, the final age of stabilization for lobe presence was recorded as 12yoa.

Statistical analyses

Descriptive statistics were used to analyze the age-at-stabilization data. For each trait the average, minimum, maximum, standard deviation (SD), count, and approximated 95% confidence interval (+/− 2SD) were calculated for each trait. These data were also plotted to visually assess the ages of stabilization across the two samples, as well as sex differences. Preliminary analyses suggested that the data largely followed a normal distribution, and thus parametric statistical analyses were performed. Two-tailed student t-tests with Bonferroni corrections were conducted to test for sex differences in ages of stabilization. All statistical analyses were conducted in SPSS version 28.0 (IBM Corp, 2021).

Results

Initial investigations into the data revealed similar trends for age-of-stabilization along all traits between the Full Sample and the 2-Year Transitional Sample. Owing to these similarities and to streamline the results, only the results of the Full Sample analyses are presented below. Results for the 2-Year Transitional Sample are provided in the supplementary materials (see Fig. S1 and Table S1).

Table 3 presents the Full Sample descriptive statistics for trait ages of stabilization, with sexes pooled and separated. Age-of-stabilization averages are illustrated in Figure 3. Trends for the pooled sample will be discussed first, followed by analyses of sex-based differences.

As expected, sinus presence/absence is the first trait to stabilize (pooled average: 10.03yoa), with frontal sinus presence above the supraorbital line occurring a few years later (pooled average: 12.04yoa). Arcade count was the last trait to stabilize (pooled average: 15.02yoa). For the remaining traits, stabilization occurred on average around 11–15yoa. Beyond these average values, the large range encompassed by the two standard deviations and min/max values indicate a high degree of individual variability in ages-of-stabilization. For example, the two standard deviation range for arcade count stabilization was 9–21 years, with a minimum of 6 years and maximum of 21 years.

Sex differences in ages of trait stabilization

Females reached ages of stabilization on average approximately one to two years earlier than males for most sinus traits. Similar to the trends discussed above, sinus presence among females was the first trait to stabilize with an average of 9.52 years of any presence and 11.23 years for presence above the supraorbital line. Sinus presence was also

TABLE 3—*Descriptive statistics for the ages of stabilization (in years) of frontal sinus traits for the Full Sample by pooled-sex, males, and females. Minimum (min), maximum (max), average (avg) ages, as well as standard deviations (SD) are provided. The p-values for the student t-tests of sex differences also provided. See Table 2 for definitions.*

Variable	Sex	*n*	Min Age	Max Age	Avg Age	SD	Neg 2SD	Pos 2SD	Test Stat	*p*-value
Presence	Pooled	141	4	16	10.028	3.207	3.614	16.442		
	F	66	4	16	9.515	3.034	3.446	15.584	–1.797	.075
	M	75	4	16	10.480	3.306	3.868	17.092		
Presence above supraorbital line	Pooled	136	5	20	12.044	3.466	5.112	18.976		
	F	64	5	20	11.234	3.250	4.734	17.735	–2.624	**.010**
	M	72	5	20	12.764	3.515	5.735	19.793		
Taller lobe	Pooled	131	4	20	11.053	3.617	3.820	18.287		
	F	63	5	19	10.429	3.495	3.438	17.419	–1.923	**.028**
	M	68	4	20	11.632	3.657	4.319	18.945		
Lateral extension	Pooled	140	4	24	13.836	3.351	7.133	20.539		
	F	65	4	19	12.769	3.111	6.547	18.992	–3.658	**<.001***
	M	75	6	24	14.760	3.296	8.169	21.351		
Lobes separated	Pooled	127	4	20	10.827	3.434	3.958	17.696		
	F	58	4	19	10.086	3.363	3.361	16.812	–2.264	**.025**
	M	69	5	20	11.449	3.394	4.662	18.236		
Arcades	Pooled	129	6	21	15.0155	3.0413	8.9328	21.0982		
	F	61	6	21	14.377	3.302	7.772	20.982	–2.27	**.025**
	M	68	6	20	15.588	2.684	10.221	20.955		
Intra-sinus septum: complete	Pooled	64	4	20	12.703	3.201	6.302	19.104		
	F	26	4	16	11.077	3.273	4.531	17.623	–3.682	**<.001***
	M	38	9	20	13.816	2.660	8.497	19.135		
Intra-sinus septum: partial	Pooled	69	9	26	14.884	3.003	8.879	20.889		
	F	30	9	21	13.933	2.900	8.134	19.733	–2.385	**.020**
	M	39	9	26	15.615	2.908	9.800	21.430		
	Pooled	57	5	19	11.561	2.994	5.573	17.550		
Supraorbital cells	F	26	5	16	10.692	2.768	5.156	16.228	–2.065	**.044**
	M	31	5	19	12.290	3.024	6.242	18.339		

Bold *p*-values indicate significance at .05; * indicates significance for Bonferroni-corrected *p*-values at .005.

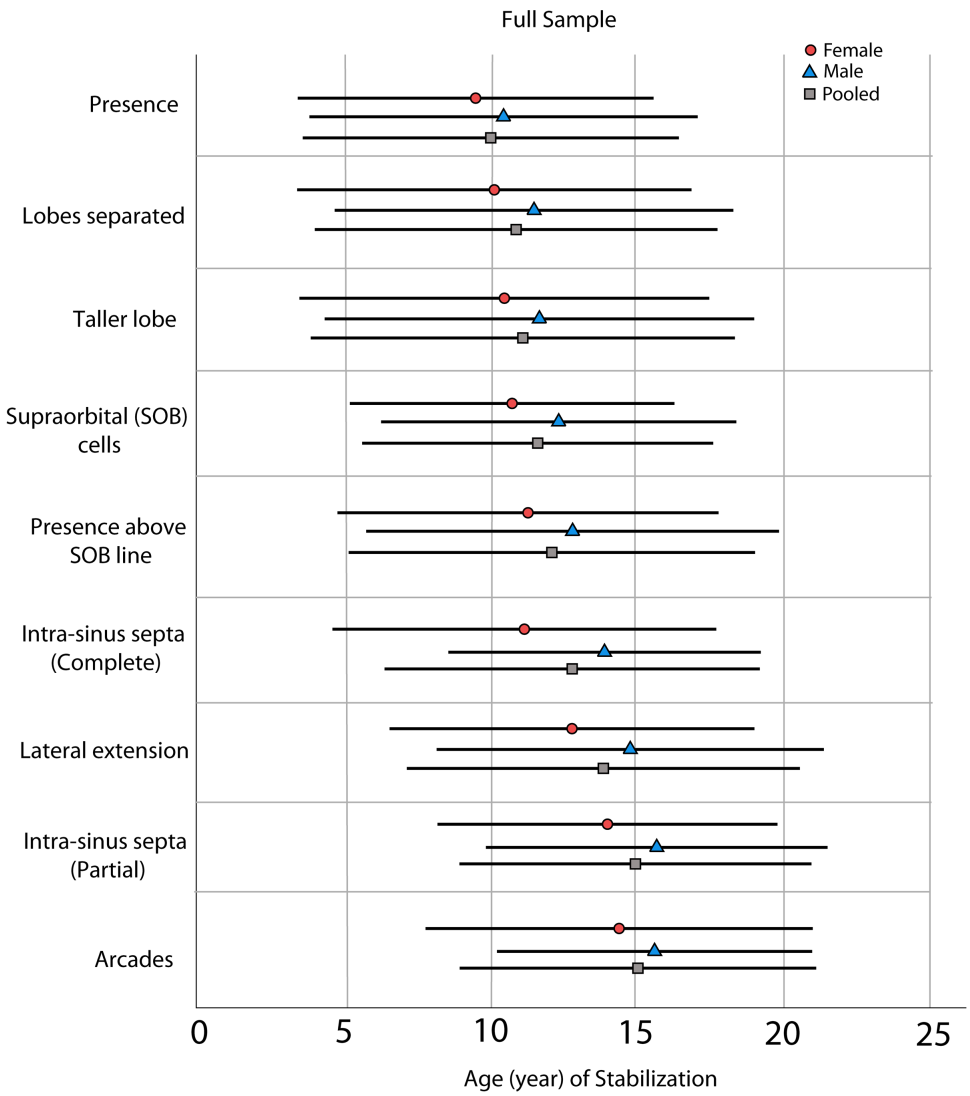

FIGURE 3—*Distributions of the ages of stabilization of frontal sinus traits from the full sample for averages and +/– two standard deviations among the male (blue triangles), female (red circles), and pooled (grey squares) sub-samples. Traits organized by age of appearance. See Table 2 for trait definitions. SOB, supraorbital.*

the first to stabilize in males, at an average of 10.48 years and 12.76 years above the supraorbital line. Among males and females, the *minimum* age of appearance for the frontal sinus was the same: 4yoa without the supraorbital line, and 5yoa when considering the supraorbital line.

Similar to the pooled sample, arcade count was also the last sinus trait to stabilize for each sex. On average, female arcades stabilized around 14.38 years, with males around 15.59 years. Both sexes displayed minimum ages of stabilization as low as 6 years, with maximum ages of arcade stabilization being 20 and 21 for males and females, respectively. Student t-tests revealed significant differences between the sexes in the age of stabilization when considering unadjusted p-values (i.e., $p < .05$). However, when considering Bonferroni corrections ($p < .005$), significant sex-based differences were only found for two traits: complete intra-sinus septa count ($p < .001$) and lateral extension of the sinus relative to the orbit ($p < .001$).

Discussion

Overall, our results demonstrate that frontal sinus traits stabilize on average between 10 and 15yoa (among pooled sexes), with sinus presence being the first to stabilize and arcade counts the last to stabilize (regardless of sex). Although not directly measured in the current study, this finding may suggest that frontal sinus growth in size is closely integrated with arcade count; in effect, as the frontal sinus grows, arcade numbers increase as well. This trend can be visualized in the exemplar individuals provided in Figures 4 and 5, which showcase an individual with large/complex sinuses and small/simpler sinuses, respectively. The later timing of arcade count stabilization could potentially suggest a correlation with sinus size, where larger sinuses are more likely to be more complex compared to smaller sinuses (also see Smith et al. 2010). Size traits, however, were unable to be included in the present study and thus the relationship was not directly tested. With the lack of sinus size data, it is also important to highlight that the stabilization of the sinus traits included in this study does not mean that sinus *size* stabilized at those times. An individual may have stabilized in all the traits tested, but then still have sinus expansion without altering number of arcades and septa (also see Butaric et al. 2022a).

Overall, the finding of sinus stabilization occurring between 10 and 15yoa, on average, aligns well with previous studies reporting full maturation of the frontal sinus being attained by mid-to-late teenage years (Brown et al. 1984; Butaric et al. 2022a; Gagliardi et al. 2004; Sardi et al. 2018; Spaeth et al. 1997). This age of stabilization for traits also corresponds with the general age of puberty, during which many other skeletal elements reach maturity (Buyuk et al. 2018; Mahmood et al. 2016). Similarly, 95% of cranial growth and development is reported to cease around 14–18yoa (Björk 2007; Farkas et al. 1992; Humphrey 1998). Along these lines, previous studies also suggest pneumatization of the frontal sinus may correlate with cranial growth and development, particularly with anterior brain expansion (Enlow 1975:120; Shapiro & Chorr 1980; Takahashi 1984; but see Sardi et al. 2018).

The current study also found sex differences in stabilization trends, with females generally stabilizing approximately one-to-two years prior to males for individual sinus traits (see Table 3, Fig. 3). Overall, female traits stabilized at 9–14yoa on average compared to 10–15yoa for males. The earlier presence of female sinuses contradicts two previous studies (Brown et al.1984; Gagliardi et al. 2004), which, while also longitudinal, utilized lateral radiographs. Theoretically, the difference in orientation should not affect sinus presence; however, lateral radiographs would capture the first appearance of *either* the left or right lobe (with an inability to distinguish which one or the age at which both lobes became present). Our study assessed sinus presence age-of-stabilization across *both* lobes, which would be of more forensic relevance as it represents the final, stabilized state of sinus presence for that individual (i.e., the age at which you would not expect any further changes in sinus presence). If we were to instead look at the first appearance of either sinus lobe, we still see that females (on average) first present any indication of a sinus at 8.77yoa, again earlier than males at 9.48yoa. However, the sex differences in the stabilization of sinus presence did not maintain statistical

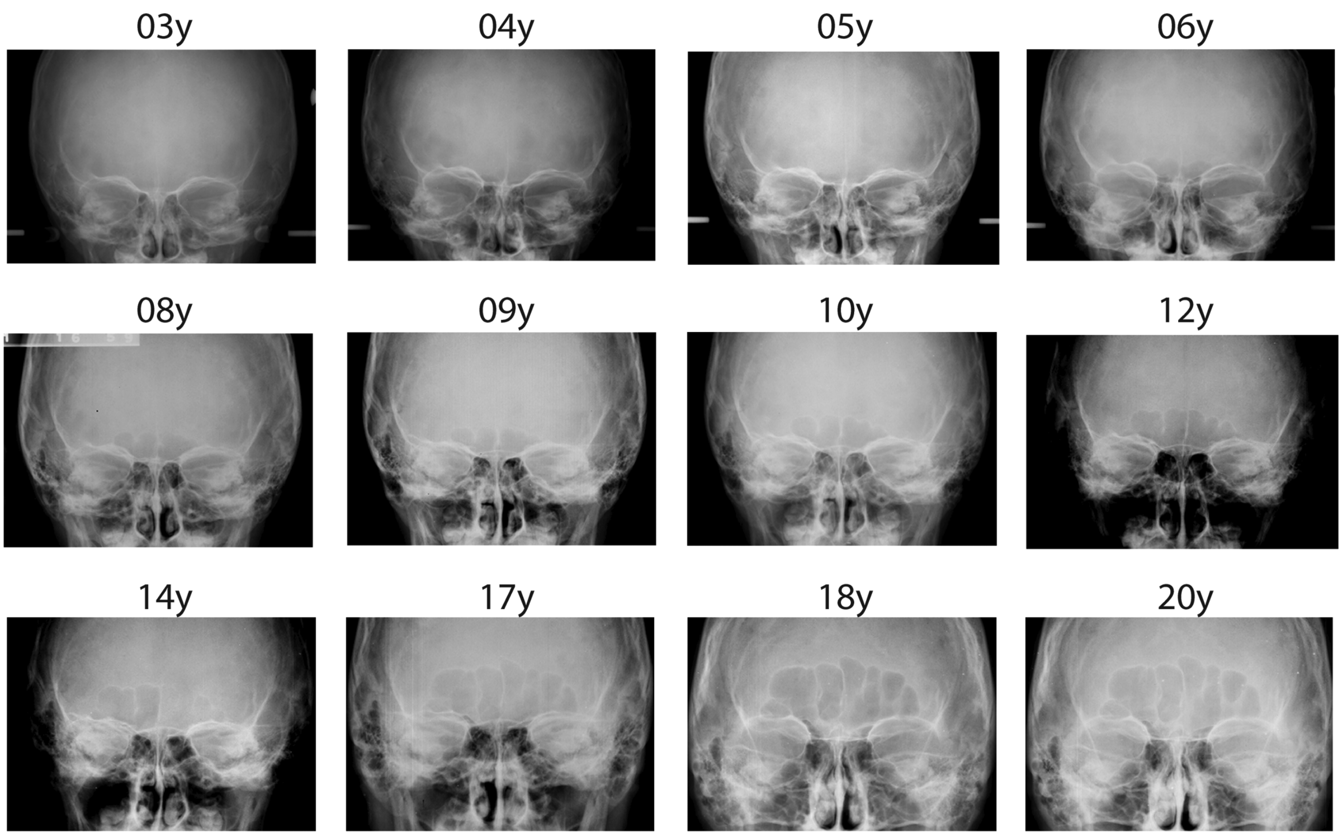

FIGURE 4—*Visual representation of sinus growth of a relatively large and complex sinus (Burlington 152M).*

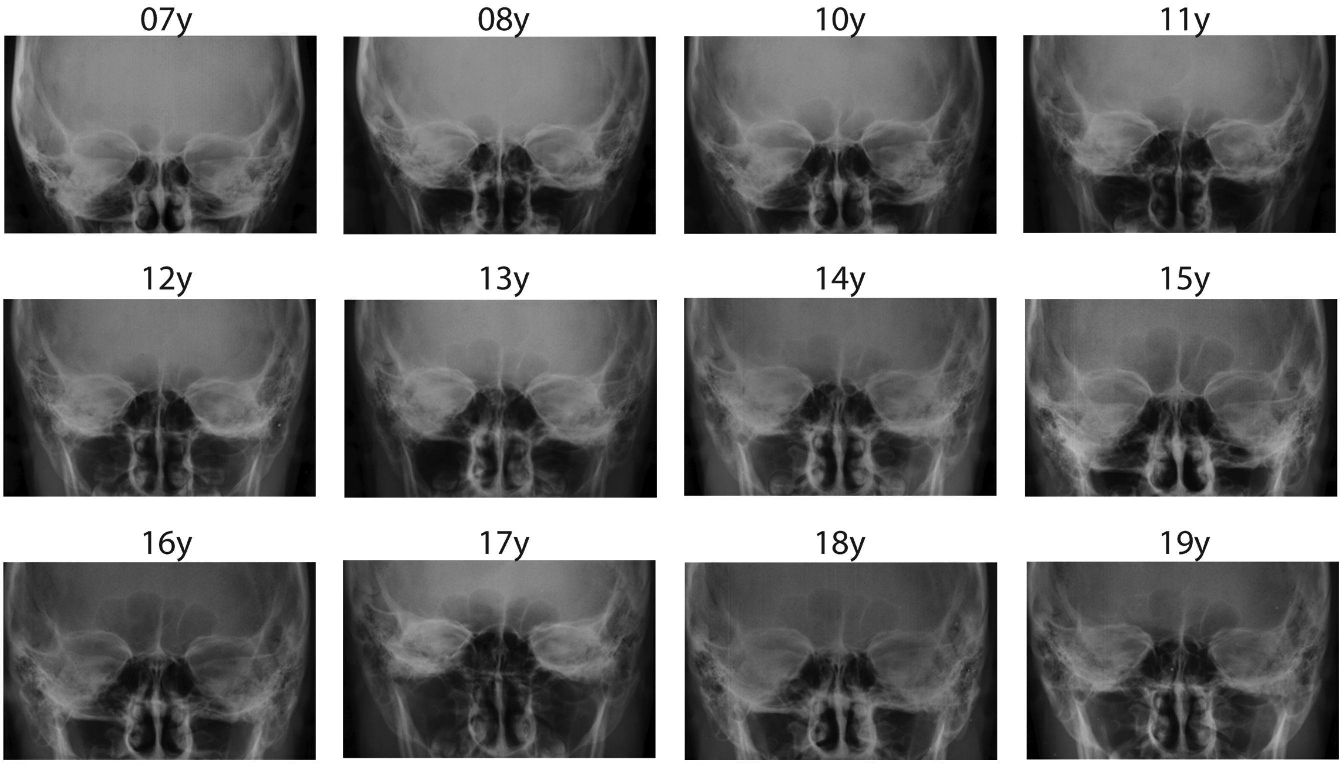

FIGURE 5—*Visual representation of sinus growth of smaller, simpler sinus (Burlington 865M).*

significance once a Bonferroni correction was applied; thus, these literature discrepancies in sinus presence between males and females may be a consequence of random sampling and/or the specific individuals included within each study. Each study also utilized different population groups, and it is unclear whether there would be population differences in sinus trait stabilization.

The remaining sinus traits captured in the current study follow similar patterns presented in previous studies focusing on linear dimensions and overall size/shape. Brown et al. (1984) found vertical height of adult sinus was obtained at 14.95yoa for females and 17.51yoa for males (on average). When examining linear dimensions, Spaeth et al. (1997) reported that sinus growth ceases at 15–16yoa for females and 18yoa for males. Sardi et al. (2018) identified sinus stabilization for volumetric and linear data at 14.6yoa for females and 20yoa for males. Most recently, Butaric et al. (2022b) indicated frontal sinus shape (as determined by outlines) established around 14–16yoa for females versus 18–20yoa in males. Thus, the results of the current study and previous studies follow well-established trends in skeletal maturity throughout the skeleton, with females tending to reach maturity (in this case frontal sinus stabilization) earlier than males (Bulygina et al. 2006; Eveleth & Tanner 1990; Roche 1968; Nikitovic & Bogin 2014; Wells 2007). Despite these observable trends, Bonferroni adjusted p-values, however, did not find statistical sex-based differences in ages-of-stabilization for most traits.

The lack of statistical significance may in part be due to the high degree of individual variation observed in ages of stabilization throughout the sample. This was true for all traits as demonstrated by the large min/max ranges and 95% confidence intervals. The minimum-to-maximum range spanned most of the sample age range for many of the traits (e.g., stabilization of lateral sinus extension ranged from 4 to 24 years in the pooled-sex sample; see Table 3). It is unclear what individual-specific traits may influence the ages of stabilization. Future studies could assess relationships with cranial size, sinus size, and sinus complexity or direct relationships with other skeletal maturation traits. Overall, however, the results of this study do suggest that most sinus traits stabilize by the age of 21 years, with the two outliers being male partial intra-sinus septa (26 years maximum) and male sinus lateral extension (24 years maximum). Although the 95% confidence intervals indicate that sinus traits stabilize by 21yoa, it should be noted that the study sample only had 28 individuals with radiographs at 21yoa or older. Future studies could confirm this age limit with older individuals.

Forensic Implications

Given the amount of variation observed in frontal sinus trait stabilization and overall growth and development of the sinus, forensic practitioners should be cautious using frontal sinus identification in subadults, especially when years may have elapsed between images. Although the average ages of stabilization spanned 9–15yoa depending on the sinus trait that is being observed, the two standard deviation ranges extended to 21yoa for some traits. Based on these results and previous literature, medicolegal practitioners can expect sinus traits to likely remain constant after 21yoa. If a sinus radiographic comparison involves an antemortem radiograph from an individual's late teens, it is possible that some traits may not have reached final stabilization and these explainable differences must be considered. With an antemortem radiographic image from an individual 15yoa or earlier, changes in trait presence and counts should almost be expected, with the amount of change likely related to the time between that antemortem radiograph and postmortem radiograph. The data presented in this paper may be used as a guide to assess which specific traits would be expected to be stabilized at a given age range.

With this in mind, caution is particularly warranted for arcade counts, as well as complete and partial intra-sinus septa. During data collection, while only a few instances were noted, these structures did exhibit reversals (i.e., decreases in counts). For example, in six individuals arcade count was noted to increase during growth and development, and then decrease before increasing again as the sinus continued to pneumatize into the frontal bone. It is likely that most of these reversals are not biologically accurate, but instead are artifacts of poor radiographic quality or varying radiographic orientation. While individuals with true reversals were few, they were observed (e.g., number of septa may have decreased as the sinus enlarged and arcades became joined). Forensic practitioners should be aware of this possibility when working with subadult radiographs and also understand that radiographic quality and/or orientation could also cause "false" reversals or differences in lobe, septa, and arcade presence (see further discussion below).

Along with radiographic quality, scoring subjectivity can also introduce artificial variation. Sinus traits, such as supraorbital cells, are not well-defined in the literature and little guidance is given for scoring ambiguous traits. Previous literature suggests that arcades are defined when one arc changes direction (i.e., creates an indent in the sinus outline; Besana & Rogers 2010), which seems straight forward in theory. However, while some arcades exhibited visible indentations, there were multiple occurrences where only faint indentations were observed, and it was unclear whether it should be counted as a separate arcade. Lower radiographic quality and/or presence of soft tissue structures can further exacerbate this issue by obscuring clear borders/septa. For example, difficulty in assessing arcade counts could have biased results and possibly contribute to the later ages of stabilization of arcades. A post hoc assessment of radiographic images with late arcade count stabilization, however, supports a biological basis to the older timeline in arcade count stabilization. Thus, while subjectivity may play a role, the variation in ages of stabilization observed is likely not the result of a few outliers. This is further supported by the similarity between minimum/maximum ages and two standard deviations.

Some traits are also interrelated; a misinterpretation of a complete septum as a partial septum affects both the partial and complete septa counts. There were also multiple instances where the inter-sinus septum would branch off in several directions, questioning what constituted an inter-sinus septum versus a complete septum within a lobe. A misidentification of a complete septum as the inter-sinus septum would affect left and right lobe traits.

While many of these issues were mitigated in the present study by assessing consecutive ages to confirm traits, they could have an impact on forensic radiographic comparisons that have limited number of images. The greatest impact would be on sinus coding methods (e.g., Cameriere et al. 2005; Tatlisumak et al. 2007; Yoshino et al. 1987). These methods score the various traits and then concatenate them into a chain code. A single difference in arcade counts or complete/partial septa results in a completely different chain code, which theoretically could result in either a misidentification or more likely erroneous exclusion of an identity if there was strict use of the coding method. Likewise, age-related changes would result in different chain codes and identification issues.

Outline-based frontal sinus identification methods (e.g., Christensen 2004, 2005; Cox et al. 2009) may be more protected against quality- and subjectivity-related trait identification issues; although, interpretations of arcades and indentations could result in slight differences in outline tracings between antemortem and postmortem images. Age-related changes in arcade numbers, lateral and vertical sinus extensions, however, would also impact sinus outlines. Thus, outline methods have to be cognizant of potential growth and development changes in these traits. Furthermore, given that outline methods typically use a supraorbital line, placement of that line along with head orientation during radiography, could potentially include/exclude features near the line, thereby changing the outline contours (see Butaric et al. 2022b). Indeed, slight differences in orientation are not necessarily limited to outline-based methods. Slight variations in orientation may affect whether more inferiorly located sinus traits fall above or below the supraorbital line placement, and consequently whether they are included in counts. The ability to view consecutive radiographs of an individual allowed informed decisions about whether presence/absence of traits was an anatomical change or due to cranial orientations. Furthermore, only those radiographs in which cranial position appeared consistent were included in this study and the supraorbital boundary was only utilized for trait presence/absence, not for counts or other variables. Still, forensic practitioners should be aware that slight variations in orientations may be another source of discrepancy when considering a potential match or non-match—particularly among smaller sinuses or arcades nearer the supraorbital borders (also see Butaric et al. 2022b).

None of the more objective frontal sinus coding or outline methods can adequately account for or interpret potential age-related changes (or ambiguous trait scores), as these methods provide binary results (match or no match). Given these concerns, visual assessment of frontal sinus radiographic comparisons may be the most accurate, particularly when subadult antemortem radiographs are involved. The subjectivity of the visual assessment, a characteristic typically avoided in methods, can be a major benefit when radiographic assessments require interpretations of whether the observed differences in the antemortem and postmortem radiographs may be explained by age or radiographic quality. The frontal sinus age-related results presented in this study will be a useful tool in these interpretations, assisting practitioners in differentiating what changes should and should not be expected during growth and development.

Limitations inherent to the current study

While the present study is the first to assess the growth and development of specific forensically-relevant frontal sinus traits in longitudinal frontal radiographs, and thus contributes novel information, the study does have several limitations. First, radiographs were not available at every age for every individual in this study, causing temporal gaps in the data. Thus, ages of stabilization recorded may not be precise. However, this was partially accounted for by generating a 2-Year Transitional Sample, which returned results similar to the Full Sample data set (see supplementary materials). Further, as discussed above, this study had a limited sample of radiographs beyond 21yoa. Owing to this, we have limited insight into potential age-related changes past this age. Additional longitudinal sinus studies are necessary to assess any changes in adult sinus morphology. However, given modern-day radiation and ethical concerns, obtaining longitudinal samples may be challenging.

The current study was also limited in terms of population diversity. Individuals part of the AAOF Legacy Collection are overwhelming of European ancestry (Al-Jewair et al. 2018). As global variation in frontal sinus size and shape is widely reported (Balzeau et al. 2022; Buck et al. 2019; Hanson & Owsley 1980; Noback et al. 2016; Rennie et al. 2017; Yoshino et al. 1987), the results of this study may not be directly applicable to other populations. However, it is encouraging that the current results align with previous subadult studies from diverse regions, including Aboriginal Australian (First National Australians) measured by Gagliardi et al. (2004) and Argentinians measured by Sardi et al. (2018). Still, future studies should strive to feature diverse groups to understand population differences in frontal sinus development. Although, larger and more diverse samples are always beneficial, for similar reasons discussed above, longitudinal radiographic samples, particularly those including subadults without pathological conditions or trauma, will be difficult to obtain.

Conclusion

Despite the limitations discussed above, the current study is one of the first to investigate frontal sinus trait ages of stabilization utilizing a longitudinal sample of subadult frontal (i.e., AP/PA) radiographs. Our results indicate that, on average, the ages of stabilization for frontal sinus traits occur between the ages of 10 and 15 years, with frontal sinus presence being the earliest (around 10 years) and arcade count being the latest at 15yoa. While females generally reached stabilization ages one to two years earlier than males, sex differences were generally not statistically significant. Age-of-stabilization standard deviations were around three years, indicating that that there is an approximate 12-year range during which trait stabilization occurs, depending on the individual. This high degree of variation in trait stabilization makes predicting age-related changes difficult. By 21yoa, however, most individuals displayed stabilization in sinus traits, suggesting that little developmental change should be expected with later-aged postmortem radiographs. Given that the age-of-stabilization 95% confidence intervals extend to 19, 20, or 21yoa for various sinus variables, it appears that some individuals may continue to undergo slight sinus changes during this timeframe. The majority of these changes were limited to visually minor changes, such as addition of a small arcade, appearance of a full septum to replace a partial septum, extension of one sinus to just above the supraorbital line, etc. Although minor, such changes still need to be considered during radiographic identifications and could propose problems for coding methods. When conducting a radiographic comparison that involves a subadult antemortem image (e.g., <18yoa), the practitioner must interpret whether the differences between antemortem and postmortem radiographs can be explained by age and time between radiographs. This article presents the data to support such interpretations. Care must be taken in such cases to not use age to erroneously explain inter-individual differences in sinus morphology. False positive or false negative identifications can have dire consequences to the family of the deceased, as well as potentially severe legal implications. Owing to these consequences, visual identification methods are recommended over more objective sinus comparison methods, as even the slightest variation in a single trait (such as that due to growth/development, poor quality radiographs, varying orientations, and/or placement of a supraorbital line) could affect match versus no-match results reached by outline and coding methods. The practitioner, on the other hand, can critically assess possible explanations for discrepancies.

Acknowledgements

The authors would like to thank the AAOF Legacy collection's curators and supporters for providing collections online, as well as the reviewers whose comments greatly enhanced this manuscript. This research was supported in part by Award No. 2020-75-CX-0013 granted by the National Institute of Justice, Office of Justice Programs, U.S. Department of Justice. The opinions, findings, and conclusions or recommendations expressed in this publication/program/exhibition are those of the author(s) and do not necessarily reflect those of the Department of Justice.

References

Akhlaghi M, Bakhtavar K, Moarefdoost J, Kamali A, Rafeifar S. Frontal sinus parameters in computed tomography and sex determination. *Legal Medicine* 2016;19:22–27. doi:10.1016/j.legalmed.2016.01.008

Al-Jewair T, Stellrecht E, Lewandowski L, Chakaki R. American Association of Orthodontists Foundation Craniofacial Growth Legacy Collection in the orthodontic literature-use and trends: A systematic review. *American Journal of Orthodontics Dentofacial Orthopedics* 2018;153(1):15–25.e10. doi:10.1016/j.ajodo.2017.07.015

American Association of Orthodontists. https://www.aaoinfo.org/. Accessed March 30, 2022.

Asherson N. *Identification by Frontal Sinus Prints; A Forensic Medical Pilot Survey*. London: H.K. Lewis; 1965.

Atkins L, Potsaid MS. Roentgenographic identification of human remains. *JAMA: The Journal of the American Medical Association* 1978;240(21):2307–2308. doi:10.1001/jama.1978.03290210089041

Aydınlıoğlu A, Kavaklıı A, Erdem S. Absence of frontal sinus in Turkish individuals. *Yonsei Medical Journal* 2003; 44(2):215–218. doi:10.3349/ymj.2003.44.2.215

Balzeau A, Albessard-Ball L, Kubicka AM, Fillippo A, Beaudet A, Santos E, et al. Frontal sinuses and human evolution. *Science Advances* 2022;8(42):eabp9767. doi:10.1126/sciadv.abp9767

Barghouth G, Prior J, Lepori D, Duvoisin B, Schnyder P, Gudinchet F. Paranasal sinuses in children: Size evaluation of maxillary, sphenoid, and frontal sinuses by magnetic resonance imaging and proposal of volume index percentile curves. *European Radiology* 2002;12(6):1451–1458. doi:10.1007/s00330-001-1218-9

Baumrind S, Curry S. American Association of Orthodontists Foundation Craniofacial Growth Legacy Collection: Overview of a powerful tool for orthodontic research and teaching. *American Journal of Orthodontics and Dentofacial Orthopedics* 2015;148(2):217–225. doi:10.1016/j.ajodo.2015.06.002

Besana JL, Rogers TL. Personal identification using the frontal sinus. *Journal of Forensic Sciences* 2010;55(3):584–589. doi:10.1111/j.1556-4029.2009.01281.x

Björk A. Sutural growth of the upper face studied by the implant method. *European Journal of Orthodontics* 2007 (orig. 1964); 29:i82–i88. doi:10.1093/ejo/cjl096

Brown WAB, Molleson TI, Chinn S. Enlargement of the frontal sinus. *Annals of Human Biology* 1984;11(3):221–226. doi:10.1080/03014468400007091

Buck LT, Stringer CB, MacLarnon AM, Rae TC. Variation in paranasal pneumatisation between mid-late Pleistocene hominins. *Bulletins Et Mémoires De La Société D'Anthropologie De Paris* 2019;31(1-2):14–33. doi:10.3166/bmsap-2019-0056

Bulygina E, Mitteroecker P, Aiello L. Ontogeny of facial dimorphism and patterns of individual development within one human population. *American Journal of Physical Anthropology* 2006;131:432–443. doi:10.1002/ajpa.20317

Butaric LN, Jones GC, Garvin HM. Revisiting global patterns of frontal sinus aplasia utilizing computed tomography. *Forensic Science International* 2020;315:110458. doi:10.1016/j.forsciint.2020.110458

Butaric LN, Campbell JL, Fischer KM, Garvin HM. Ontogenetic patterns in human frontal sinus shape: A longitudinal study using elliptical Fourier analysis. *Journal of Anatomy* 2022a; 241(2):195–210. doi:10.1111/joa.13687

Butaric LN, Richman A, Garvin HM. The effects of cranial orientation on forensic frontal sinus identification as assessed by outline analyses. *Biology* 2022b:11(1):62. doi:10.3390/biology11010062

Buyuk SK, Simsek H, Karaman A. The relationship between frontal sinus morphology and skeletal maturation. *Folia Morphologica* 2018;77(3):503–508. doi:10.5603/fm.a2017.0118

Cameriere R, Ferrante L, Mirtella D, Rollo FU, Cingolani M. Frontal sinuses for identification: Quality of classifications, possible error and potential corrections. *Journal of Forensic Sciences* 2005;50(4):770–773. doi:10.1520/jfs2004343

Christensen AM. Assessing the variation in individual frontal sinus outlines. *American Journal of Physical Anthropology* 2004;127(1):291–295. doi:10.1002/ajpa.20116

Christensen AM. Testing the reliability of frontal sinuses in positive identification. *Journal of Forensic Sciences* 2005;50(1):1–5. doi:10.1520/jfs2004145

Christensen AM, Hatch GM. Advances in the use of frontal sinuses for human identification. In: Latham K, Bartelink E, Finnegan M, eds. *New Perspectives in Forensic Human Skeletal Identification*. London: Academic Press; 2018:227–240.

Cox M, Malcolm M, Fairgrieve SI. A new digital method for the objective comparison of frontal sinuses for identification. *Journal of Forensic Sciences* 2009;54(4):761–772. doi:10.1111/j.1556-4029.2009.01075.x

Culbert WL, Law FL. Identification by comparison of roentgenograms of nasal accessory sinuses and mastoid processes. *JAMA: The Journal of the American Medical Association* 1927;88:1634–1636. doi:10.1001/JAMA.1927.02680470020009

Davis W. *The Development and Anatomy of the Accessory Sinus in Man*. Philadelphia: Saunders. 1914.

Dolan KD. Paranasal sinus radiology, Part IA: Introduction and the frontal sinuses. *Head and Neck Surgery* 1982;4:301–311. doi:10.1002/hed.2890040407

Duque CS, Casiano RR. Surgical anatomy and embryology of the frontal sinus. In: Kountakis S, Senior B, Draf W, eds. *The Frontal Sinus*, Berlin: Springer; 2005:21–32.

Emirzeoglu M, Sahin B, Bilgic S, Celebi M, Usun A. Volumetric evaluation of the paranasal sinuses in normal subjects using computer tomography images: a stereological study. *Auris Nasus Larynx* 2007;34:191–195. doi:10.1016/j.anl.2006.09.003

Enlow DH. *Handbook of Facial Growth*. London: W.B. Saunders Company; 1975.

Enlow DH, Hans MG. *Essentials of Facial Growth*. London: W.B. Saunders Company; 1996.

Eveleth PB, Tanner JM. *Worldwide Variation in Human Growth* (2nd ed.). Cambridge: Cambridge University Press; 1990.

Farkas LG, Posnick JC, Hreczko TM. Anthropometric growth study of the head. *Cleft Palate Craniofacial Journal* 1992;29:404–318. doi:10.1597/1545-1569_1992_029_0303_agsoth_2.3.co_2

Fatu C, Puisoru M, Rotaru M, Truta AM. Morphometric evaluation of the frontal sinus in relation to age. *Annals of Anatomy - Anatomischer Anzeiger* 2006;188(3):275–280. doi:10.1016/j.aanat.2005.11.012

Gagliardi A, Winning T, Kaidonis J, Hughes T, Townsend GC. Association of frontal sinus development with somatic and skeletal maturation in Aboriginal Australians: A longitudinal study. *HOMO* 2004;55(1-2):39–52. doi:10.1016/j.jchb.2004.06.001

Hanson CL, Owsley DW. Frontal sinus size in Eskimo populations. *American Journal of Physical Anthropology* 1980;53(2): 251–255. doi:10.1002/ajpa.1330530209

Hashim N, Hemalatha N, Thangaraj K, Kareem A, Ahmed A, Hassan NF, Jayaprakash PT. Practical relevance of prescribing superimposition for determining a frontal sinus pattern match. *Forensic Science International* 2015;253:137e1–7. doi:10.1016/j.forsciint.2015.05.020

Humphrey LT. Growth patterns in the modern human skeleton. *American Journal of Physical Anthropology* 1998;105:57–72. doi:10.1002/(SICI)1096-8644(199801)105:1<57::AID-AJPA6>3.0.CO;2-A

IBM Corp. IBM SPSS Statistics for Windows, Version 28.0. Armonk, NY: IBM Corp; 2021.

Jablonski NG, Shum BSF. Identification of unknown human remains by comparison of antemortem and postmortem radiographs. *Forensic Science International* 1989;42(3):221–230. doi:10.1016/0379-0738(89)90089-3

Kasper K. Nasofrontal connections: a study based on one hundred consecutive dissections. *Archives of Otolaryngology* 1936;23: 322–343. doi:10.1001/archotol.1936.00640040330006

Kirk NJ, Wood RE, Goldstein M. Skeletal identification using the frontal sinus region: A retrospective study of 39 cases. *Journal of Forensic Sciences* 2002;47(2):318–323. doi:10.1520/jfs15250j

Kjær I, Pallisgaard C, Brock-Jacobsen MT. Frontal sinus dimensions can differ significantly between individuals within a monozygotic twin pair, indicating environmental influence on sinus sizes. *Acta Oto-Laryngologica* 2012;132(9):988–994. doi:10.3109/00016489.2012.677064

Kullman L, Grundin R, Eklund B. Value of the frontal sinus in identification of unknown persons. *Journal of Forensic Odonto-Stomatology* 1990; 8(1): 3–10.

Mahmood HT, Shaikh A, Fida M. Association between frontal sinus morphology and cervical vertebral maturation for the assessment of skeletal maturity. *American Journal of Orthodontics and Dentofacial Orthopedics* 2016;150(4):637–642. doi:10.1016/j.ajodo.2016.03.022

Marek Z, Kusmiderski J, Lisowski Z. Radiogramme der Stirnholen als Grundlage fur die Identifizierung von Katastrophenopfern und von unbekannten Skeletten. *Arch Fur Kriminal* 1983;34:289–299.

Maresh MM. Paranasal sinuses from birth to late adolescence. *American Journal of Diseases of Children* 1940;60:55–78. doi:10.1001/archpedi.1940.02000010064005

Marlin DC, Clark MA, Standish SM. Identification of human remains by comparison of frontal sinus radiographs: A series of four cases. *Journal of Forensic Sciences* 1991;36(6):1765–1772. doi:10.1520/jfs13202j

McLaughlin RB, Rehl RM, Lanza DC. Clinically relevant frontal sinus anatomy and physiology. *Otolaryngologic Clinics of North America* 2001;34(1):1–22. doi:10.1016/s0030-6665(05)70291-7

Moore K, Ross A. Frontal sinus development and juvenile age estimation. *The Anatomical Record* 2017;300(9):1609–1617. doi:10.1002/ar.23614

Murphy WA, Gantner GE. Radiologic examination of anatomic parts and skeletonized remains. *Journal of Forensic Science* 1982; 27: 9–18. doi:10.1520/JFS11445J

Nambiar P, Naidu MD, Subramaniam K. Anatomical variability of the frontal sinuses and their application in forensic identification. *Journal of Clinical Forensic Medicine* 1999; 6(4): 258. doi:10.1016/s1353-1131(99)90010-x

Nathani R, Diagavane P, Shrivastav S, Kamble R, Gupta D, Korde S. Evaluation of frontal sinus as a growth predictor in horizontal, vertical, and average growth pattern in children from 8 to 11 years: A cephalometric study. *Journal of Indian Orthodontic Society* 2016;50(2):101–105. doi:10.4103/0301-5742.179944

National Research Council. *Strengthening Forensic Science in the United States: A Path Forward*. Washington, DC: The National Academies Press. 2009. http://www.nap.edu/catalog/12589.html

Nikitovic D, Bogin B. Ontogeny of sexual size dimorphism and environmental quality in Guatemalan children. *American Journal of Human Biology* 2014;26:117–123. doi:10.1002/ajhb.22492

Noback ML, Samo E, van Leeuwen CHA, Lynnerup N, Harvati K. Paranasal sinuses: A problematic proxy for climate adaptation in Neanderthals. *Journal of Human Evolution* 2016;97:176–179. doi:10.1016/j.jhevol.2016.06.003

Owsley DW. Identification of the fragmentary, burned remains of two U.S. journalists seven years after their disappearance in Guatemala. *Journal of Forensic Sciences* 1993;38(6):1372–1382. doi:10.1520/jfs13541j

Park I-H, Song JS, Choi H, Kim TH, Hoon S, Lee SH, et al. Volumetric study in the development of paranasal sinuses by CT imaging in Asians: A pilot study. *International Journal of Pediatric Otorhinolaryngology* 2010;74:1347–1350. doi:10.1016/j.ijporl.2010.08.018

Patil AA, Revankar AV. Reliability of the frontal sinus index as a maturity indicator. *Indian Journal of Dental Research* 2013;24:523. doi:10.4103/0970-9290.118372

Pereira JGD, Santos JBS, Sousa SP, Franco A, Silva RHA. Frontal sinuses as tools for human identification: a systematic review of imaging methods. *Dentomaxillofacial Radiology* 2021; Jul 1 50(5):20200599. doi:10.1259/dmfr.20200599.

Prossinger H. Sexually dimorphic ontogenetic trajectories of frontal sinus cross sections. *Collegium Anthropologicum* 2001;25:1–11.

Prossinger H. Macro- and mesomorphology of frontal sinuses in humans: Noisiness models relating to their ontogeny. *Annals of Anatomy* 2004;186:443–449.

Quatrehomme G, Fronty P, Sapanet M, Grévin G, Bailet P, OllierA. Identification by frontal sinus pattern in forensic anthropology. *Forensic Science International* 1996;83(2):147–153. doi:10.1016/s0379-0738(96)02033-6

Reichs KJ, Dorion RBJ. The use of computed tomography (CT) scans in the comparison of frontal sinus configurations. *Canadian Society of Forensic Science Journal* 1992;25(1): 1–16. doi:10.1080/00085030.1992.10756997

Rennie CO, Haffajee MR, Satyapal KS. Development of the paranasal air sinuses in a South African population utilising three dimensional (3D) reconstructed models. *European Journal of Anatomy* 2017;21(3):197–209.

Ribeiro, Fde AQ. Standardized measurements of radiographic films of the frontal sinuses: An aid to identifying unknown persons. *Ear, Nose & Throat Journal* 2000;79(1):26–33. doi:10.1177/014556130007900108

Roche AF. Sex-associated differences in skeletal maturity. *Acta Anatomica* 1968;71(3):321–340. doi:10.1159/000143194

Ruf S, Pancherz H. Development of the frontal sinus in relation to somatic and skeletal maturity. A cephalometric roentgenographic study at puberty. *European Journal of Orthodontics* 1996a;18:491–497. doi:10.1093/ejo/18.5.491

Ruf S, Pancherz H. Frontal sinus development as an indicator for somatic maturity at puberty? *American Journal of Orthodontics and Dentofacial Orthopedics* 1996b; 110:476–182. doi:10.1016/S0889-5406(96)70053-7

Sardi ML, Joosten GG, Pandiani CD, Gould MM, Anzelmo M, Ventrice F. Frontal sinus ontogeny and covariation with bone structures in a modern human population. *Journal of Morphology* 2018;279(7):871–882. doi:10.1002/jmor.20817

Schaeffer JP. The genesis, development and adult anatomy of the nasofrontal region in man. *American Journal of Anatomy* 1916;20:125–146. doi:10.1002/aja.1000200105

Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. *Nature Methods* 2012;9(7): 671–675. doi:10.1038/nmeth.2089

Schuller A. Das Rontgenogram der Stirnhohle: ein Hilfsmittel fur die Identitatsbestimmung von Schadeln. *Monatsschrift Feur Ohrenheilkunde Und Laryngo-Rhinologie* 1921;5:1617–1620.

Schuller A. A note on the identification of skulls by x-ray pictures of the frontal sinuses. *Medical Journal of Australia* 1943;1(25):554–556. doi:10.5694/j.1326-5377.1943.tb44655.x

Scuderi AJ, Harnsberger HR, Boyer RS. Pneumatization of the paranasal sinuses: normal features of importance to the accurate interpretation of CT scans and MR images. *American Journal of Radiography* 1993;160:1101–1104. doi:10.2214/ajr.160.5.84705

Shah RK, Dhingra JK, Carter BL, Rebeiz EE. Paranasal sinus development: a radiographic study. *Laryngoscope* 2003;113:205–209. doi:10.1097/00005537-200302000-00002

Shapiro R, Schorr SA. A consideration of the systemic factors that influence frontal sinus pneumatization. *Investigative Radiology* 1980;15:191–202. doi:10.1097/00004424-198005000-00004

Smith VA, Christensen AM, Myers SW. The reliability of visually comparing small frontal sinuses. *Journal of Forensic Sciences* 2010;55:1413–1415. doi:10.1111/j.1556-4029.2010.01493

Soares CB, Almeida MS, Lopes Pde M, Beltrão RV, Pontual Ados A, Ramos-Perez FM, et al. Human identification study by means of frontal sinus imaginological aspects. *Forensic Science International* 2016;262:183–189. doi:10.1016/j.forsciint.2016.03.030

Spaeth J, Krugelstein U, Schlöndorff G. The paranasal sinuses in CT-imaging: development from birth to age 25. *International Journal of Pediatric Otorhinolaryngology 1997;*39:25–40. doi:10.1016/S0165-5876(96)01458-9

Takahashi R. The formation of the human paranasal sinuses. *Acta Oto-Laryngologica* 1984;97:1–28. doi:10.3109/00016488409121162

Tatlisumak E, Asirdizer M, Bora A, Hekimoglu Y, Etli Y, Gumus O, Keskin S. The effects of gender and age on forensic personal identification from frontal sinus in a Turkish population. *Saudi Medical Journal* 2017;38(1):41–47. doi:10.15537/smj.2017.1.16218

Tatlisumak E, Ovali GY, Asirdizer M, Aslan A, Ozyurt B, Bayindir P, et al. CT study on morphometry of frontal sinus. *Clinical Anatomy* 2008;21(4):287–293. doi:10.1002/ca.20617

Tatlisumak E, Yilmaz Ovali G, Aslan A, Asirdizer M, Zeyfeoglu Y, Tarhan S. Identification of unknown bodies by using CT images of frontal sinus. *Forensic Science International* 2007; 166(1):42–48. doi:10.1016/j.forsciint.2006.03.023

Tehranchi A, Motamedian SR, Saedi S, Kabiri S, Shidfar S. Correlation between frontal sinus dimensions and cephalometric indices: a cross-sectional study. *European Journal of Dentistry* 2017;11:64–70. doi:10.4103/1305-7456.202630

Ubelaker DH. Positive identification from the radiographic comparison of frontal sinus patterns. In: Rathbun T, Buikstra JE, eds. *Human Identification*. Springfield: Charles C. Thomas; 1984:399–411.

Uthman AT, AL-Rawi NH, Al-Naaimi AS, Tawfeeq AS, Suhail EH. Evaluation of frontal sinus and skull measurements using spiral CT scanning: An aid in unknown person identification. *Forensic Science International* 2010;197(1-3):124.e1–124.e7 doi:10.1016/j.forsciint.2009.12.064

Wells JCK. Sexual dimorphism of body composition. *Best Practice & Research Clinical Endocrinology & Metabolism* 2007;21: 415–430. doi:10.1016/j.beem.2007.04.007

Weiglein AH. Development of the paranasal sinuses in humans. In: Koppe, T, Nagai H, Alt KW, eds. *The Paranasal Sinuses of Higher Primates: Development, Function, and Evolution*. Chicago: Quintessence Publishing Co., Inc; 1999:35–50.

Weiglein A, Anderhuber W, Wolf G. Radiologic anatomy of the paranasal sinuses in the child. *Surgical and Radiologic Anatomy*, 1992;14(4):335–339. doi:10.1007/bf01794761

Yoshino M, Miyasaka S, Sato H, Seta S. Classification system of frontal sinus patterns by radiography. Its application to identification of unknown skeletal remains. *Forensic Science International* 1987;34(4):289–299. doi:10.1016/0379-0738(87)90041-7

Yun IS, Kim YO, Lee S-K, Rah DK. Three-dimensional computed tomographic analysis of frontal sinus in Asians. *Journal of Craniofacial Surgery* 2011;22:462–467. doi:10.1097/SCS.0b013e3182074367

Supplemental materials

TABLE S1—*Descriptive statistics for the ages of stabilization (in years) of frontal sinus traits for the Full Sample by pooled-sex, males, and females. Minimum (min), maximum (max), average (avg) ages, as well as standard deviations (SD) are provided. The p-values for the student t-tests of sex differences also provided. See Table 2 for definitions.*

Variable	Sex	n	Min Age	Max Age	Avg Age	SD	Neg 2SD	Pos 2SD	Test Stat	P-value
Presence	Pooled	48	4	16	10.958	3.175	4.608	17.309		
	F	19	5	14	10.211	2.551	5.108	15.313	−1.42	0.163
	M	29	4	16	11.448	3.480	4.487	18.409		
Presence above supraorbital line	Pooled	89	5	20	12.236	3.195	5.847	18.625		
	F	42	6	20	11.571	2.923	5.726	17.417	−1.882	**0.032**
	M	47	5	19	12.830	3.338	6.153	19.506		
Taller lobe	Pooled	50	5	18	12.420	3.375	5.670	19.170		
	F	23	5	18	11.739	3.414	4.911	18.567	−1.327	0.191
	M	27	6	18	13.000	3.293	6.413	19.587		
Lateral extension	Pooled	99	6	20	14.131	2.867	8.398	19.865		
	F	45	6	19	13.333	2.884	7.565	19.102	−2.602	**0.011**
	M	54	9	20	14.796	2.701	9.394	20.199		
Lobes separated	Pooled	54	5	19	11.574	3.172	5.230	17.918		
	F	23	5	16	11.000	2.939	5.123	16.878	−1.149	0.256
	M	31	6	19	12.000	3.317	5.367	18.633		
Arcades	Pooled	86	6	20	14.837	2.934	8.969	20.705		
	F	45	6	20	14.022	3.258	7.507	20.538	−2.853	**0.006**
	M	41	8	20	15.732	2.248	11.237	20.227		
Intra-sinus septum: complete	Pooled	40	8	19	13.325	2.325	8.676	17.975		
	F	18	8	16	12.611	2.227	8.158	17.064	−1.807	**0.039**
	M	22	10	19	13.909	2.287	9.336	18.483		
Intra-sinus septum: partial	Pooled	53	9	20	14.528	2.350	9.828	19.229		
	F	26	9	20	13.846	2.634	8.579	19.113	−2.144	**0.037**
	M	27	11	18	15.185	1.861	11.463	18.908		
Supraorbital cells	Pooled	30	7	19	12.533	2.649	7.236	17.831		
	F	13	8	16	12.077	2.565	6.948	17.206	−0.821	0.419
	M	17	7	19	12.882	2.736	7.411	18.354		

Bold *p*-values indicate significance at .05; * indicates significance for Bonferroni corrected *p*-values at .005.

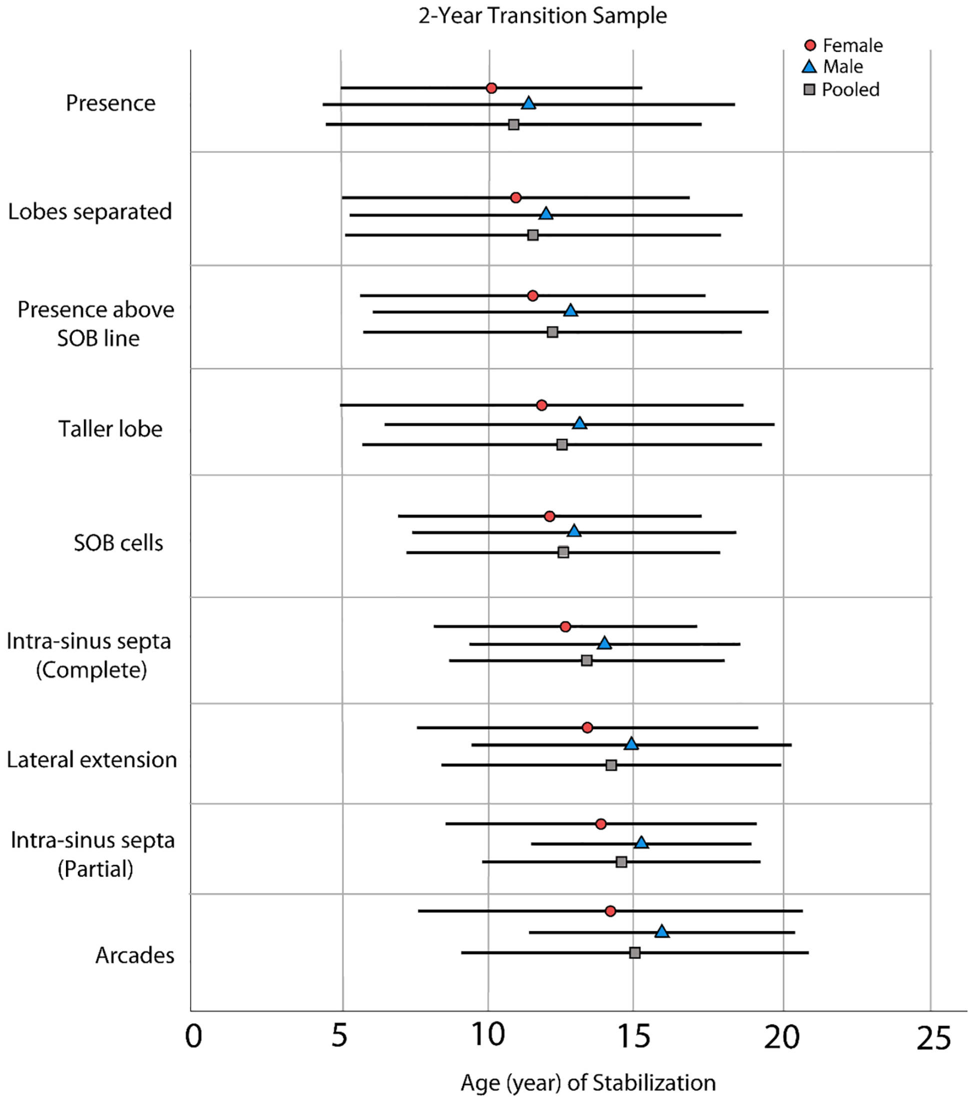

FIGURE S1—*Distributions of the ages of stabilization of frontal sinus traits from the full sample for averages and +/− two standard deviations among the male (blue triangles), female (red circles), and pooled (grey squares) sub-samples. Traits organized by age of appearance. See Table 2 for trait definitions. SOB, supraorbital.*