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Nasal septal and craniofacial form in European- and African-derived populations

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Abstract

As a component of the chondrocranium, the nasal septum influences the anteroposterior dimensions of the facial skeleton. The role of the septum as a facial growth center, however, has been studied primarily in long-snouted mammals, and its precise influence on human facial growth is not as well understood. Whereas the nasal septum may be important in the anterior growth of the human facial skeleton early in ontogeny, the high incidence of nasal septal deviation in humans suggests the septum's influence on human facial length is limited to the early phases of facial growth. Nevertheless, the nasal septum follows a growth trajectory similar to the facial skeleton and, as such, its prolonged period of growth may influence other aspects of facial development. Using computed tomography scans of living human subjects ($n = 70$), the goal of the present study is to assess the morphological relationship between the nasal septum and facial skeleton in European- and African-derived populations, which have been shown to exhibit early developmental differences in the nasal septal–premaxillary complex. First we assessed whether there is population variation in the size of the nasal septum in European- and African-derived samples. This included an evaluation of septal deviation and the spatial constraints that influence variation in this condition. Next, we assessed the relationship between nasal septal size and craniofacial shape using multivariate regression techniques. Our results indicate that there is significant population variation in septal size and magnitude of septal deviation, both of which are greater in the European-derived sample. While septal deviation suggests a disjunction between the nasal septum and other components of the facial skeleton, we nevertheless found a significant relationship between the size of the nasal septum and craniofacial shape, which appears to largely be a response to the need to accommodate variation in nasal septal size.

Key words: chondrocranium; computed tomography; human variation; septal deviation.

Introduction

The morphology of the facial skeleton is the product of a complex, integrated process involving a combination of factors both intrinsic and extrinsic to the facial skeleton proper. Among the various causal mechanisms that influence the development and evolution of the facial skeleton, considerable emphasis has been placed on the role of the chondrocranium. In particular, the angulation and orientation of the cranial base, the relative sizes of cranial fossae, and differential growth cessation have been suggested to influence aspects of the adult facial skeletal phenotype, most notably facial size and facial projection (Moss & Young, 1960; Enlow, 1990; Ross & Ravosa, 1993; Lieberman et al. 2000; McCarthy & Lieberman, 2001; Kuroe et al. 2004; Bastir & Rosas, 2005, 2006; Bastir et al. 2006; Rosas et al. 2008; Lieberman et al. 2008). The nasal septum, as one component of the chondrocranium,[1] also plays an important role in normal mammalian facial development. According to the nasal septal traction model, the nasal septal cartilage acts as a growth plate (Scott, 1953; Baume, 1961; Catala & Johnston, 1980; Copray, 1986; Wealthall & Herring, 2006) placing tension on the premaxillary suture via the septopremaxillary ligament, thus inducing an osteogenic response

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[1] Anatomically, the nasal septum is composed of the nasal septal cartilage, the perpendicular plate of the ethmoid and the vomer. While the first two structures are chondrocranial and thus grow via endochondral ossification, the vomer grows intramembranously.

(Latham, 1970; Gange & Johnston, 1974; Mooney & Siegel, 1986, 1991; Mooney et al. 1989; Siegel et al. 1990). The importance of the nasal septal cartilage as a growth center intrinsic to the facial skeleton is well established, as surgical resection of all or part of the nasal septum in a variety of animal models results in a deficiency in the anteroposterior dimensions of maxilla and premaxilla (Wexler & Sarnat, 1961; Sarnat & Wexler, 1966, 1967; Ohyama, 1969; Riesenfeld, 1970; Latham et al. 1975; Friede & Morgan, 1976; Friede, 1978; Wada et al. 1980; Rhys-Evans & Brain, 1981; Siegel & Sadler, 1981; Squier et al. 1985). Similarly, experimentally induced maxillary growth reduction results in both normal nasal septal growth and compensatory elongation of the premaxilla (Holton et al. 2011a).

The majority of experimental research on the developmental influence of the nasal septum, however, has been conducted using long-snouted animal models. As such, the degree to which these results can be extended to facial growth dynamics in the relatively orthognathous genus *Homo* is not well understood. Surgical resection of the septal cartilage in shorter-faced animal models has a minimal effect on the anterior growth of the facial skeleton (Freng, 1981; Siegel & Sadler, 1981; Cuparo et al. 2001), suggesting that the nasal septum may only act as a key growth center in long-snouted animals. Nevertheless, there is evidence that an integrated nasal septal–premaxillary complex may be important in human facial development during early ontogeny. Indeed, the contribution of the nasal septum to the anterior growth of the human facial skeleton has factored into discussions of normal and pathological craniofacial development, including facial retrusion associated with cleft lip and palate (e.g. Delaire & Precious, 1986; Mooney et al. 1989; Siegel et al. 1991), and in the development of sagittal occlusal disharmonies (e.g. Singh, 1999). Moreover, the nasal septal cartilage likely plays a key role in the morphogenesis and regulation of facial sutures (Adab et al. 2002, 2003). Additionally, as evidenced by various congenital abnormalities that affect the size or presence/absence of the nasal septum, variation in septal growth has significant effects on the projection of the external nose and nasal bridge elevation during craniofacial development (e.g. Moss et al. 1968; Moss & Salentijn, 1969; Kremble, 1973). For example, in cases of holoprosencephaly, which affects the growth of midline craniofacial structures, individuals can exhibit nasal septal reduction or agenesis associated with a flattened nasal bridge (Fitz, 1983; Kjær et al. 2002; Ribeiro et al. 2006). Moreover, nasal hypoplasia is common in cases of warfarin embryopathy (Zakzouk, 1986), resulting in reduced nasal projection. This condition is associated with a reduction in nasal septal size resulting from the ectopic ossification of the septal cartilage early in development (Howe & Webster, 1992; Howe et al. 1997).

The influence of the nasal septum on early ontogenetic development of the human facial skeleton is further evident based on population variation in facial prognathism and premaxillary suture fusion in European- and African-derived populations. Mooney & Siegel (1986) documented that African-derived subadults are characterized by a prolonged period of premaxillary suture patency when compared with European-derived subadults. Interestingly, early premaxillary suture fusion corresponds to an increase in anterior nasal spine development, presumably due to the septal cartilage's inability to tense the synostosed premaxillary suture. A similar pattern of premaxillary suture fusion and anterior nasal tubercle development has also been documented in *Pan* (Mooney & Siegel, 1991). Moreover, given the prolonged period of premaxillary suture patency in Neandertals compared with recent humans (Maureille & Bar, 1999), developmental alteration in an integrated nasal septal–premaxillary complex may contribute to variation in facial projection between archaic and modern *Homo*.

Whereas the nasal septum may act as a midfacial growth center during the early phases of ontogeny, its possible influence on human facial morphology later in development is unclear. Indeed, the nasal septal traction model emphasizes the morphogenetic influence of the nasal septum on the anterior growth of the facial skeleton; however, the occurrence of deviated nasal septa suggests that the growth of the nasal septum and other components of the facial skeleton are not isomorphic. As such, there is a disconnect between the facial skeleton and nasal septum resulting in deformation of the nasal septum, particularly in more orthognathous taxa. Comparative mammalian studies, for example, have documented that facial length is inversely correlated with the frequency of nasal septal deviation, such that shorter-faced mammals have an increased incidence of septal deviation (Gray, 1978; Takahashi, 1987). The increased presence of nasal septal deviation in shorter-faced mammals suggests that across broader taxonomic ranges there is a degree of independence between the size of the nasal septum and other components of the facial skeleton. Similarly, facial length reduction via experimental synostosis of the premaxillary sutures in rats also results in deviation of the nasal septum (Rönning & Kantomaa, 1985), suggesting that the patterns observed across taxa are also relevant to ontogenetic development within taxa. Taken together, the results of these comparative and experimental studies suggest that reduction in facial size can impose spatial constraints on the nasal septum resulting in aberrant septal growth.

Based on the nasal septal traction model, one would predict that nasal septal size, in humans, is positively correlated with the anterior growth of the facial skeleton. However, an increased incidence of septal deviation in orthagnathous humans (Gray, 1978; Takahashi, 1987) suggests that the nasal septum, as a facial growth center, may have a limited influence on later periods of facial development. This limited influence, however, does not preclude the nasal septum from affecting other aspects of craniofacial form.

While the majority of chondrocranial growth in humans is completed during childhood (e.g. Lieberman et al. 2000; Bastir et al. 2006), the nasal septal cartilage and perpendicular plate of the ethmoid continue to grow through adulthood, and thus follow a growth trajectory similar to the facial skeleton (Van Loosen et al. 1996). As such, the continued influence of the nasal septum on later periods of facial growth cannot be ruled out. Thus, while the septum may be restricted by factors such as premaxillary suture fusion, its continued growth may be expressed in other areas of the facial skeleton (e.g. nasal projection).

To determine if there is a continued developmental relationship between the nasal septum and facial form in later phases of growth, regardless of the precise nature of causality, it is necessary to establish morphological covariation between these variables in the adult facial skeleton. The goal of the present study, therefore, is to assess the degree of morphological interaction between the nasal septum and other components of the facial skeleton in adult human populations that exhibit early developmental differences in the nasal septal–premaxillary complex. To accomplish this we first examine whether there is variation in the absolute and relative size of the nasal septum in European- and African-derived samples. This includes an evaluation of nasal septal deviation and the underlying spatial and morphological constraints that influence variation in this condition. While it can be difficult to establish spatial constraints based solely on a static adult sample, the results of pan-mammalian comparative studies (Gray, 1978; Takahashi, 1987) and experimental research (Rönning & Kantomaa, 1985) indicate that nasal septal deviation results from constraints placed on the septum by the facial skeleton. However, it is unclear if variation in facial form, vs. variation in nasal septal size, explains septal deviation in narrower human comparisons. If nasal septal deviation in humans results from the same dynamic documented across mammals, we would predict that measures of nasal septal deviation would be largely independent of nasal septal size. As such, the size of the nasal septum should be relatively constant across deviated and non-deviated individuals. Alternatively, nasal septal deviation may result largely from variation in the size of the nasal septum. Thus, individuals with increased septal deviation would be characterized by an increase in the size of the septum relative to the available nasal capsular midsagittal space.

Next, we will assess the morphological relationship between the nasal septum and craniofacial form. Given the disjunction between the nasal septum and other components of the facial skeleton, as evidenced by nasal septal deviation, we test the null hypothesis that there is no correlation between nasal septal size and multivariate descriptors of variation in craniofacial anatomy across European- and African-derived populations.

Materials and methods

To assess nasal septal morphology and covariation between the nasal septum and other aspects of the facial skeleton, we used computed tomography scans of a sample composed of European- and African-derived living human subjects ($n = 70$). Our European-derived subsample ($n = 51$) consisted of $n = 29$ male and $n = 22$ female European-Americans ranging in age from 19 to 70 years (mean = 39.2 years). Our African-derived subsample ($n = 19$) was composed of $n = 6$ male and $n = 13$ female African-Americans and native South Africans ranging in age from 20 to 67 years (mean = 43.3 years). The subjects included in this analysis were originally recruited for other studies related to the assessment of *in vivo* masticatory function (Holton, 2009) and internal nasal morphology (Yokley, 2006, 2009, 2010). Despite uneven population sampling, our sample is enhanced through the use of living human subjects, which allows us to assess anatomical structures that normally do not preserve in dry skulls. As such, we are able to include the fragile, and often unpreserved, bony aspects of the nasal septum (i.e. the vomer and perpendicular plate of the ethmoid) as well as the nasal septal cartilage. Moreover, we are able to include in our analysis other non-osseous aspects of the external nose that would otherwise be unavailable (see below).

The composition of our sample is particularly well suited to assess the morphological association between the nasal septum and facial form. Previous research has established that population-specific morphological features that manifest early in development in European- and African-derived populations are associated with differential growth of an integrated nasal septal–premaxillary complex (Mooney & Siegel, 1986). Furthermore, European- and African-derived populations are characterized by highly distinctive differences in craniomandibular morphology including nasal form (Charles, 1930; De Villiers, 1968; Glanville, 1969; Franciscus, 1995; Yokley, 2006, 2009; Holton & Franciscus, 2008). Thus, if there is a relationship between the nasal septum and population variation in craniofacial form, it is likely to be evident in our samples.

To assess the relationship between the nasal septum and facial morphology, we first measured nasal septal size as a volume that included the septal cartilage, the perpendicular plate of the ethmoid and the vomer. While a component of the nasal septum, the vomer is not part of the chondrocranium. Nevertheless, there is evidence that the vomer may play an important role in septal influence on facial growth (e.g. Latham et al. 1975). Moreover, there are distinct morphological differences in vomer shape in European- and African-derived individuals that manifest early in development (Weinberg et al. 2005). As such we included this intramembranous aspect of the septum in our analysis. Using Osirix (Rosset et al. 2004), we manually segmented the nasal septum from the anterior-most aspect of the cartilage in the external nose to the posterior aspect of the vomer (i.e. hormion) while maintaining a constant septal thickness of 1.0 mm (Fig. 1a,b). This method allowed us to quantify the overall size of the septum, while mitigating the effects of variation in the thickness of the cartilage and overlying mucosa (e.g. Elwany et al. 2009). To measure relative nasal septal size, we scaled nasal septal volume to the centroid size of the coordinate landmarks (excluding pronasale) used to assess craniofacial form (see below). We tested for significant population differences

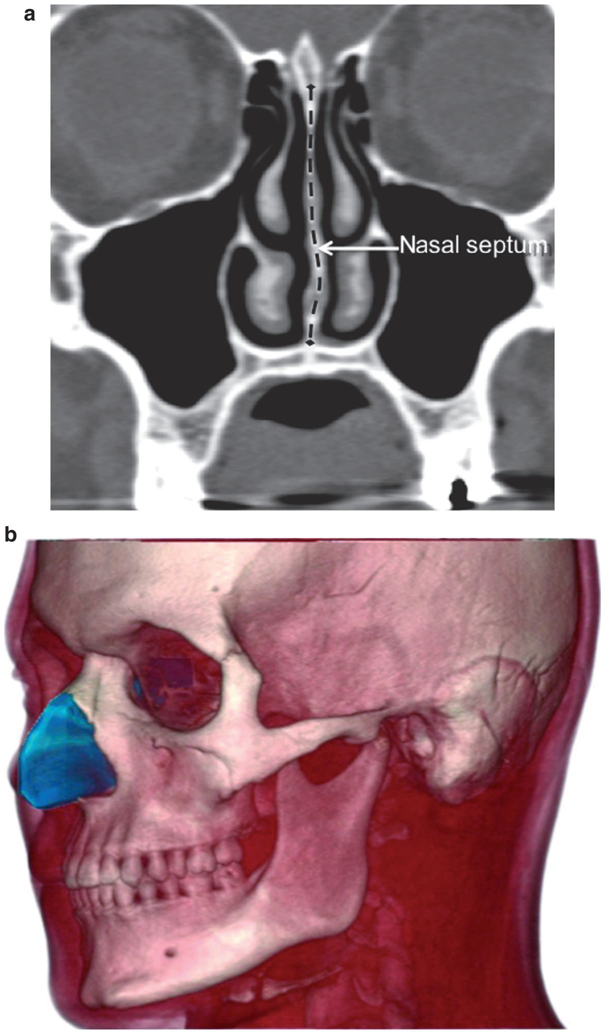

Fig. 1 (a) Volumetric measurements of the nasal septum were calculated by manually segmenting the nasal septum using coronal computed tomography slices through the external nose and internal nasal capsule. (b) The segmented nasal septum was then reconstructed to calculate septal volume while maintaining a constant thickness.

in absolute and relative nasal septal volume using a non-parametric Mann–Whitney *U*-test.

To assess the potential spatial and morphological factors that contribute to nasal septal deviation, we segmented a 1.0-mm-thick midsagittal nasal volume that extended along the borders of the nasal septum. This volume served as a model for a 'non-deviated' nasal septum, or the minimum amount of space available in the midline nasal capsule. Nasal septal deviation was calculated for each individual as a percentage of nasal septal volume relative to their modeled 'non-deviated' septal volume [(nasal septal volume/midsagittal volume) × 100)]. A value of 100% indicates a straight, non-deviated, nasal septum, while values > 100% indicate some level of septal deviation. As with nasal septal size, we tested for significant differences in nasal septal deviation between our samples using a non-parametric Mann–Whitney *U*-test.

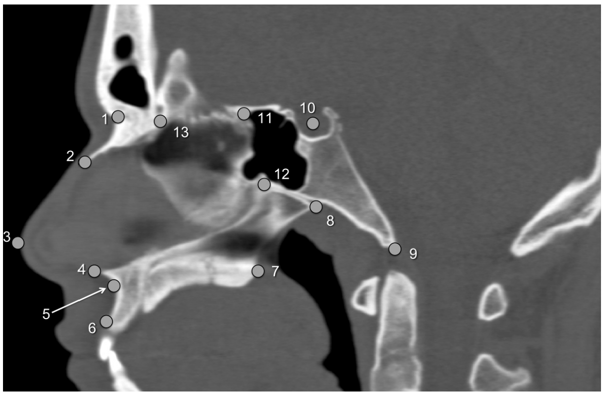

Fig. 2 Landmarks used in our geometric morphometric assessment of craniofacial shape: 1, nasion; 2, rhinion; 3, pronasale; 4, anterior nasal spine; 5, subspinale; 6, prosthion; 7, staphylion; 8, hormion; 9, basion; 10, sella; 11, posterior ethmoid/superior sphenoethmoidal synchondrosis; 12, inferior sphenoethmoidal synchondrosis; 13, anterior ethmoid.

Next, we assessed the morphological and spatial factors that contribute to nasal septal deviation by examining the components of the septal deviation ratio in bivariate space to further assess the underlying determinants of septal deviation. This included using general linear modeling to test for significant differences in nasal septal scaling relationships between our samples.

We assessed the relationship between nasal septal size and facial morphology using a series of two-dimensional coordinate landmarks (Fig. 2) that included both soft-tissue and osseous components of the midfacial skeleton and cranial base. Given that previous researchers have emphasized the relationship between nasal septal growth and the antero-inferior components of facial growth (Scott, 1953; Baume, 1961; Wexler & Sarnat, 1961; Sarnat & Wexler, 1966, 1967; Ohyama, 1969; Riesenfeld, 1970; Catala & Johnston, 1980; Copray, 1986; Mooney & Siegel, 1986, 1991; Wealthall & Herring, 2006; Holton et al. 2011a), we restricted our assessment of facial form to the midsagittal plane. In a subset of our total sample ($n = 4$), the anterior-most aspect of the external nose (pronasale) was not included in the scan field. We therefore estimated this landmark as the intersection between two vectors that defined the trajectory of the nasal bridge and the columella. This estimated landmark was also used in the calculation of the anterior-most aspect of the volume of the nasal septum in these individuals.

To quantitatively examine the relationship between nasal septal size and facial form, we first aligned and scaled the coordinate landmarks using generalized Procrustes analysis. Next, we used the Procrustes coordinates in a multivariate regression with facial shape data as dependent variables and the log-transformed absolute nasal septal volume as the independent variable. To control for between-group variation and the potential confounding effects of morphological covariance due to factors such as shared population history, we used a pooled within-group regression in MorphoJ (Klingenberg, 2008–2010). The morphological relationship between the independent and dependent variables was assessed visually using wireframe models.

Results

Descriptive statistics for absolute septal volume and scaled septal volume are presented in Table 1. There is a significant difference in nasal septal volume, with the European-derived sample characterized by a larger nasal septum than the African-derived sample ($P < 0.001$). On average, the European-derived sample exhibited a nasal septal volume of 4.35 cm^3 in contrast to an average septal volume of 3.04 cm^3 for the African-derived sample. As evidenced by the box plot in Fig. 3, there is little overlap in the distributions of nasal septal volume in the two samples, with no overlap between the interquartile ranges. Similarly, when scaled to centroid size, the significant difference in septal volume between our samples was retained ($P < 0.001$; Fig. 4). As with absolute nasal septal volume, there is little overlap in the distributions between the two samples. It is of note that a comparison between the native South African and African-American groups that compose the African-derived subsample exhibited no significant differences in absolute nasal septal volume ($P = 0.370$) or scaled septal volume ($P = 0.650$).

Our results indicate that there are significant population differences in septal deviation, with our European-derived sample exhibiting a significantly greater magnitude of deviation compared with our African-derived sample ($P < 0.001$; Fig. 5; Table 1). Nasal septal deviation averaged 149.00% in the European-derived sample, and reached a maximum value of 176.00%. This is in contrast to the African-derived sample, which exhibited a mean deviation value of 125.00% and reached a maximum of 156.00%.

With respect to the bivariate assessment of the components of the septal deviation ratio (Fig. 6; Table 2), there is a clear separation of the European- and African-derived samples, indicating differences in the scaling of the nasal

Table 1 Descriptive statistics for nasal septal volume and deviation variables. Scaled septal volume was calculated as the log-transformed cube-root of septal volume divided by log-transformed centroid size. Centroid size used in this standardization excluded pronasale, as variation in this landmark is potentially influenced by variation in nasal septal size. All mean comparisons were significantly different ($P < 0.001$).

Measurement	European-derived	African-derived
Absolute septal volume (cm^3)		
Mean	4.35	3.04
SD	0.48	0.39
Minimum	3.05	2.07
Maximum	5.26	3.79
Scaled septal volume (%)		
Mean	32.96	29.52
SD	1.06	1.27
Minimum	29.72	25.99
Maximum	34.92	31.93
Midsagittal volume (cm^3)		
Mean	2.91	2.44
SD	0.34	0.30
Minimum	2.36	1.89
Maximum	3.72	2.84
Nasal septal deviation (%)		
Mean	149.00	125.00
SD	11.70	15.00
Minimum	125.00	100.00
Maximum	176.00	156.00

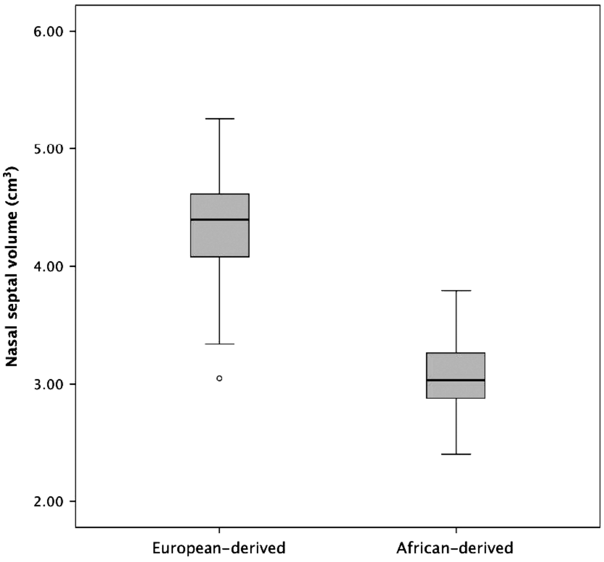

Fig. 3 Box plot comparison of absolute septal volume (cm^3) in our European- and African-derived samples. The difference between the samples was statistically significant ($P < 0.001$).

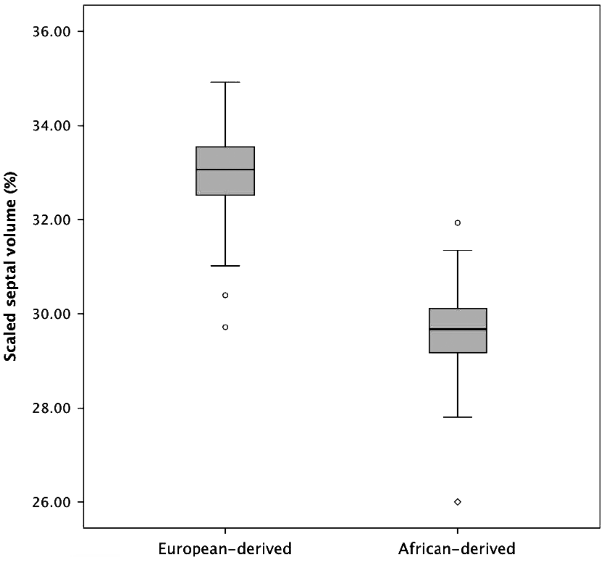

Fig. 4 Box plot comparisons of scaled septal volume (%) in our European- and African-derived samples. The difference between the samples was statistically significant ($P < 0.001$).

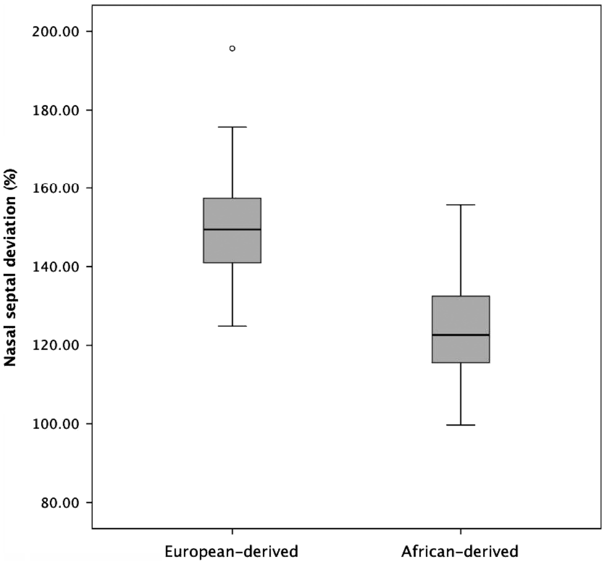

Fig. 5 Box plot comparisons of nasal septal deviation (%) in our European- and African-derived samples. The difference between the samples was statistically significant ($P < 0.001$).

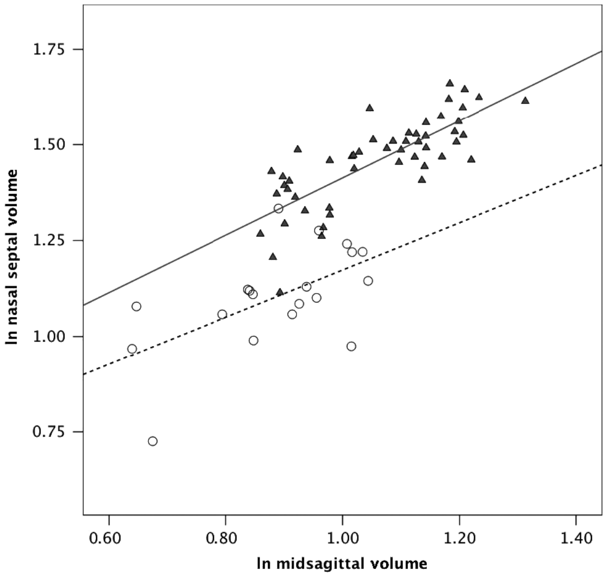

Fig. 6 Scatter plot of ln nasal septal volume on ln midsagittal volume. European-derived individuals are represented by triangles, while African-derived individuals are represented by circles. As is evidenced by the regression lines, there are different scaling relationships between the European- and African-derived samples. While there is no significant difference in the regression line slopes ($F = 0.493$; $P = 0.485$), there is a significant difference in the Y-intercepts ($F = 73.469$; $P < 0.001$). Thus, for a given midsagittal volume, the European-derived sample is characterized by a larger nasal septal volume while the African-derived sample exhibits a relatively smaller nasal septal volume.

septum. For a given midsagittal volume, the European-derived sample is characterized by a relatively larger nasal septum when compared with the relatively smaller nasal septa of the African-derived sample. Moreover, in addition to exhibiting a significantly larger nasal septal volume, the European-derived sample was also characterized by a significantly larger midsagittal volume ($P < 0.001$; Fig. 7; Table 1). Thus, while the European-derived sample has a larger midsagittal space available for the septum, they are characterized by a disproportionally larger septum relative to the African-derived sample. Using ANCOVA to test for significant differences in scaling, we found that while there was no significant differences in the slopes of the regression lines ($F = 0.493$; $P = 0.485$), the Y-intercepts were significantly different ($F = 73.469$; $P < 0.001$).

Table 2 Regression statistics for the bivariate analysis of ln nasal septal volume and ln midsagittal volume.

Sample	*r*	Slope	*Y*-intercept	SE	*P*
European-derived	0.78	0.74	0.67	0.07	< 0.001
African-derived	0.58	0.61	0.56	0.11	0.009

The result of our multivariate regression indicates that there is a significant relationship between nasal septal volume and facial shape ($P < 0.001$). With respect to the facial skeleton, there is a clear association between septal volume and the nasal and subnasal alveolar regions. Nasal septal size was inversely correlated with variation in subnasal alveolar prognathism (subspinale-prosthion, landmarks 5 and 6), such that individuals with a larger nasal septum were characterized by a reduction in subnasal prognathism (i.e. posterior displacement of prosthion), whereas individuals with a smaller septum exhibited a greater degree of subnasal prognathism.

With respect to external nasal morphology, there is a relationship between nasal septal size and the shape of the nasal septal cartilage as reflected by variation in external nasal projection (Fig. 8). Individuals with a larger nasal septum are characterized by an anterior displacement of pronasale (landmark 3). Additionally, there are associated changes in the skeletal components of the external nose, such as greater elevation of the nasal bridge (nasion-rhinion, landmarks 1 and 2) and a more projecting anterior nasal spine (landmark 4). Conversely, a smaller nasal septum is associated with reduced nasal projection, a flattened nasal bridge and a reduced anterior nasal spine.

Nasal septal volume was also correlated with shape variation in the superior and posterior borders of the nasal septum (and associated articulation with the sphenoid). With respect to the anterior cranial base (posterior ethmoid–anterior ethmoid, landmarks 11 and 13), a larger nasal septal volume is associated with a superior reorientation of the anterior ethmoid relative to the posterior ethmoid at the sphenoethmoidal synchondrosis. Conversely, individuals with a smaller nasal septum are characterized by a more inferior displacement of the anterior ethmoid relative to

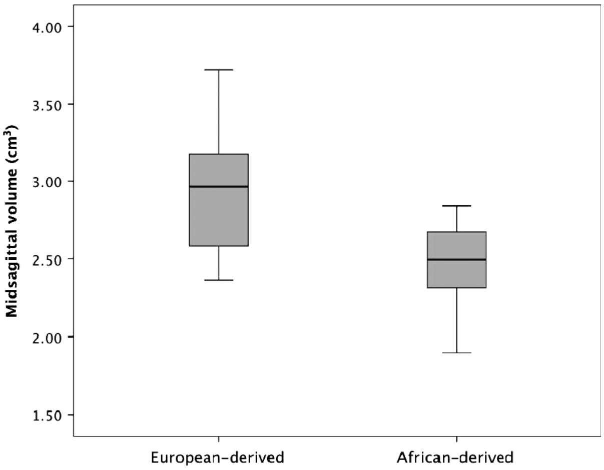

Fig. 7 Box plot comparisons of midsagittal volume (cm^3) in our European- and African-derived samples. The difference between the samples was statistically significant ($P < 0.001$).

the sphenoethmoidal synchondrosis. Additionally, the relative size and position of sphenoethmoidal synchondrosis itself covaries with nasal septal volume. Individuals with a larger nasal septal volume are characterized by relative reduction in the synchondrosis height as evidenced by the superior displacement of the inferior aspect of the synchondrosis (inferior synchondrosis, landmark 13). Finally, individuals with a larger nasal septal volume are characterized by a posterior displacement of staphylion (landmark 7) relative to the sphenoethmoidal synchondrosis.

Discussion

The nasal septal traction model underscores the morphogenetic capacity of the nasal septum on the anterior growth of the face (Scott, 1953; Baume, 1961; Latham, 1970; Catala & Johnston, 1980; Copray, 1986; Mooney & Siegel, 1986, 1991; Mooney et al. 1989; Siegel et al. 1990; Wealthall & Herring, 2006; Holton et al. 2011a). This is particularly evident in long-snouted animal models, but the influence of the nasal septum as a facial growth center in humans is less clear. While the nasal septum potentially plays a key role in anterior facial growth during prenatal and early postnatal development, the nature of this relationship and the precise influence of the nasal septum on adult facial form are not well understood.

The results of our analysis show that there is a significant difference in the absolute and relative size of the nasal septum between European- and African-derived populations. Indeed, the European-derived sample used in our analysis was characterized by nasal septa that were, on average, $\sim$ 30% larger in volume compared with the African-derived sample (controlling for the effects of nasal septal thickness). In addition to having a larger nasal septum, our European-derived sample was also characterized by a greater magnitude of septal deviation when compared with our African-derived sample. This result is broadly consistent with Post (1966), who documented high frequencies of septal deviation in Europeans compared with a geographically diverse skeletal sample. The majority of the Europeans in Post's (1966) sample exhibited some form of deviation, with 19% of his European sample exhibiting 'very marked' deviation. While Post did not include African populations in his analysis, the high frequency of septal deviation in Europeans contrasts starkly with other groups, such as Native Americans who were characterized by low levels of septal deviation. A study by Gray (1978) interestingly found little difference in septal deviation among different human populations. Frequencies of straight nasal septa ranged from 13% in Indians to 27% in Australian Aborigines, and comparisons between Europeans and Africans showed minor differences in frequencies of straight nasal septa (17% and 20%, respectively).

The general disparity in results among these studies (including the present study) may speak to: i) the differences in and the subjectivity of categorical systems for coding severity of septal deviation; and ii) comparing results from studies that use categorical systems for assessing septal deviation to studies that employ quantitative techniques. With respect to the latter point, we should note that, as is

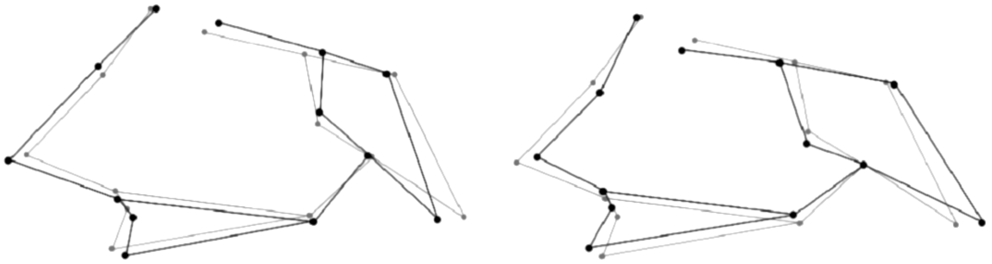

Fig. 8 Wireframe renderings of craniofacial shape variation significantly correlated ($P < 0.001$) with nasal septal volume (gray = mean shape; black = deviations from mean shape). The renderings are oriented with the anterior aspect of the facial skeleton pointing to the left (see Fig. 2 for description of landmarks). Individuals with a larger nasal septum (left) are characterized by a general reduction in subnasal alveolar prognathism, a more pronounced external nose and a posteriorly-superiorly rotated anterior cranial base. Individuals with a smaller nasal septum (right) are characterized by a greater degree of subnasal alveolar prognathism, a reduction in external nasal projection including a flatter nasal bridge and reduced anterior nasal spine. A smaller nasal septum is further associated with a downward rotation of the midline anterior cranial base.

evident from Fig. 5, nearly all individuals in our sample exhibit some level of septal deviation (i.e. septal deviation > 100%). Thus, the argument could be made that there is little difference between Europeans and Africans when septal deviation is treated as a qualitative character state (e.g. Gray, 1978). However, the use of a quantitative (vs. categorical) measure gives us finer resolution for assessing the differences in the degree of septal deviation, as is evident in the non-overlap of interquartile ranges in the European- and African-derived septal deviation sample distributions.

Population variation in nasal septal deviation was largely driven by variation in the size of the nasal septum rather than solely by spatial constraints imposed on the nasal septum by the facial skeleton. This is evidenced by the univariate assessment of the components of the nasal septal deviation ratio and the bivariate relationship between nasal septal and midsagittal volumes. While the European-derived sample exhibited a disproportionately larger nasal septum, it was also characterized by an increased midsagittal volume. This pattern largely contrasts with broader mammalian comparisons in which there is an inverse correlation between the relative length of the facial skeleton and occurrence of nasal septal deviation, suggesting that septal deviation is caused primarily by spatial constraints rather than variation in relative septal size. Among long-snouted animals, the frequency of septal deviation approaches 0.0% (Gray, 1978), whereas the frequency of septal deviation increases in anthropoid primates, with the greatest occurrence found in humans (Gray, 1978; Takahashi, 1987). Thus, across larger taxonomic comparisons, the relationship between nasal septal and facial size is not isomorphic. The near ubiquitous occurrence of septal deviation in our samples suggests that facial length is an underlying causal factor when viewed in light of this broader mammalian trend. However, within narrower taxonomic comparisons (e.g. intraspecies comparisons), nasal septal size is a potentially more important contributing factor in determining the presence/absence and magnitude of septal deviation.

Nevertheless, the results of our multivariate regression analysis indicate that there is an inverse correlation between nasal septal volume and subnasal alveolar prognathism. Thus, individuals with larger nasal septa are characterized by a relative decrease in lower facial prognathism, while individuals with smaller nasal septa were associated with an increase in lower facial prognathism. This inverse relationship is likely due, in part, to population variation in the growth of the nasal septal–premaxillary complex. As documented by previous studies, the growth of the nasal septum has a significant morphogenetic influence on the anterior growth of the premaxilla (Latham, 1970; Gange & Johnston, 1974; Mooney & Siegel, 1986, 1991; Mooney et al. 1989; Siegel et al. 1990; Holton et al. 2011a). Mooney & Siegel (1986) documented that there is population variation in the timing of premaxillary–maxillary suture fusion during facial development in European- and African-derived populations. Thus, while there appears to be increased growth of the nasal septum in European-derived populations relative to African-derived populations (as evidenced by variation in nasal septal size), early synostosis of the premaxillary–maxillary suture in European-derived populations restricts anterior premaxillary growth that is likely driven by the nasal septum. As such, variation in the potential for anterior growth of the premaxilla during the early phase of facial development may also factor into population differences in nasal septal deviation in our samples. This suggests that while population differences in septal deviation are influenced largely by nasal septal size, we cannot rule out the influence of spatial constraints resulting from variation in the anterior growth of the facial skeleton (as in pan-mammalian comparisons; Gray, 1978; Rönning & Kantomaa, 1985; Takahashi, 1987).

Nevertheless, while our European-derived sample exhibited both a disproportionally large nasal septum and a higher incidence of nasal septal deviation, it was also characterized by a significantly larger midsagittal volume, indicating a greater availability of midsagittal space for the nasal septum. Thus, while anterior growth of the septum is potentially constrained by variation in lower facial prognathism, as evidence by the experimental reduction of facial length in animal models (e.g. Rönning & Kantomaa, 1985), relative changes in aspects of internal nasal capsular shape appear to accommodate population variation in nasal septal size. Nasal septal volume was correlated with aspects of midline cranial base morphology that are reflective of both nasal septal shape as well as shape changes in corresponding cranial base elements. This was particularly evident in the orientation of the ethmoidal contribution to the midline anterior cranial base (which is composed partly of the superior border of the nasal septum) and the sphenoethmoidal synchondrosis. These variables were associated with nasal septal size such that the larger septum in the European-derived sample exhibited a more dorsally rotated midline anterior cranial base with a concomitant anterior rotation of the inferior sphenoethmoidal synchondrosis. In contrast, the small septum characterizing the African-derived sample exhibited a more ventrally rotated midline anterior cranial base with associated posteriorly oriented sphenoethmoidal synchondrosis. The population differences in anterior cranial base orientation shown here are consistent with previous studies that have also documented population variation in the orientation of the ethmoidal component of the midline anterior cranial base (e.g. Kuroe et al. 2004; Rosas et al. 2008). Experimental studies have also shown that cranial base morphology is affected by disproportionate increases in nasal septal size. This is evidenced by the effects of experimentally induced synostosis of the facial sutures in various animal models resulting in a disjunction between facial and septal growth. The increase in nasal septal size relative to the facial skeleton in these animal models produced alterations in cranial base form, including changes in anterior cranial base length (Ruan et al. 2008), alterations in cranial base angle (Rönning & Kantomaa, 1985), as well as changes in the orientation of the facial skeleton relative to the cranial base and neurocranium (Rönning & Kantomaa, 1985; Mooney et al. 1992; Holton et al. 2010). Thus, variation in midline anterior cranial base morphology may be tied to the need to accommodate the spatial demands of the nasal septum.

The results of our analysis further indicated that nasal septal volume is correlated with both the anterior and posterior projection of the nasal septum. With respect to anterior projection, a larger nasal septum in our European-derived sample was associated with previously documented increases in the anterior projection of the external nose, nasal bridge elevation and prominence of the anterior nasal spine (Charles, 1930; Franciscus, 1995; Yokley & Franciscus, 2005; Yokley, 2006, 2009; Noback et al. 2011). Additionally, a larger nasal septum was associated with a greater posterior positioning of the vomer relative to the sphenoethmoidal synchondrosis.

Population variation in internal and external nasal morphology, including nasal projection and nasal bridge elevation, has been explained largely within the context of climatic adaptation (Thomson & Buxton, 1923; Davies, 1932; Weiner, 1954; Wolpoff, 1968; Hiernaux & Froment, 1976; Carey & Steegmann, 1981; Crognier, 1981a,b; Franciscus & Long, 1991; Franciscus, 1995; Roseman, 2004; Yokley, 2006, 2009; Holton & Franciscus, 2008; Hubbe et al. 2009; Holton et al. 2011b). While our results cannot speak directly to developmental causality, or the ultimate causal mechanisms influencing population variation in nasal septal size, they do suggest that climatically associated variation in nasal projection and nasal bridge elevation are likely driven by morphological differences in the nasal septum.

Previous studies assessing the air-conditioning capacity of the nasal capsule have documented that, along with other aspects of the nasofacial skeleton, the nasal septum is key to properly heating and humidifying air during respiration (e.g. Lindemann et al. 2001a,b). Indeed, the nasal septum transfers a greater proportion of heat to inspired air than any other individual anatomical element within the nasal passages such as the lateral nasal wall or individual turbinates (Naftali et al. 2005). An increase in nasal capsule length, via increased external nasal projection and posterior displacement of the vomer, increases the amount of time that respired air is in contact with the nasal mucosa (i.e. residence time) affecting heat and moisture transfer during respiration (Schroter & Watkins, 1989; Keck et al. 2000a,b; Inthavong et al. 2007). As such, variation in skeletal features such as nasal bridge elevation may be a secondary response to adaptive changes in the size of the nasal septum associated with the demands of conditioning respired air in colder climates. Thus, the relationship between skeletal nasal projection and climate (Carey & Steegmann, 1981; Hubbe et al. 2009), as well as the deviation of nasal projection from the expectations of neutral evolution (Hubbe et al. 2009), may actually explain variation in the nasal septum rather than external nasal projection *per se*. This, however, may not account for the 'disproportionate' increase in nasal septal volume that results in an increase in septal deviation. While a deviated nasal septum ultimately has the effect of increasing total mucosal surface area and thus increasing the ability to condition respired air (Schmidt-Nielsen et al. 1970; Collins et al. 1971; Hanna & Scherer, 1986; Schroter & Watkins, 1989; Yokley, 2006, 2009; Lindemann et al. 2009), it also increases the propensity for mouth breathing (D'Ascanio et al. 2010) potentially due in increased airflow resistance in the nasal passages.

Conclusion

The interaction between the chondrocranium and facial skeleton is complex and incompletely understood (e.g. Lieberman et al. 2000). The complex nature of this relationship is further underscored by the results of the present study. The presence of nasal septal deviation suggests a level of disjunction between the nasal septum and other aspects of the craniofacial skeleton; nevertheless, our results indicate that there is significant correlation between nasal septal volume and craniofacial shape that may stem from the need to spatially accommodate variation in nasal septal volume. It is important to emphasize, however, that our results cannot speak directly to the causal nature of this relationship. As such, future research should be geared toward assessing the ontogenetic growth of the nasal septum and its longitudinal interaction with other components of the facial skeleton, as well as the functional influences of nasal septal variation in respiratory air conditioning. This is key to developing a better understanding of the proximate and ultimate causal mechanisms that explain variation in nasal septal form and its potential influence on facial growth and development.

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