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Original article

The nasomaxillary complex and the cranial base in artificial cranial deformation: relationships from a geometric morphometric study

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Summary

Introduction: It is widely accepted that there is a relationship between the cranial base and the development of the nasomaxillary complex (NMC). The objective of the present study was to investigate the morphological relationship between these two anatomical units in skulls that have intentionally been subjected to one of two types of artificial deformity of the cranial vault [artificially deformed skulls (ADS)].

Material and methods: A geometric morphometry study was performed on lateral cephalometric X-rays of three groups of crania: 32 with anteroposterior (AP) deformity, 17 with circumferential (C) deformity, and 39 with no apparent deformity.

Results: The cranial base of the ADS showed marked deformity that produced a restriction of AP growth of the NMC, alterations of the roof of the orbit as a consequence of the rotation of anterior cranial fossa, and nasal protrusion. Pronounced morphological differences were found between the three groups: increased vertical development of the maxilla occurred in both ADS groups due to growth of the alveolar process, and rotation of the maxilla and displacement of the orbital rim was observed in the C group. This confirms that the posterior facial plane is regarded as an axial structure that serves as an interface between the middle cranial base and the NMC (Enlow, D.H. and Hans, M.G. (1996) *Essential of Facial Growth*. WB Saunders Co., Philadelphia, PA).

Limitations: It is important to take into account that these results have been obtained from an archaeological sample, with all the limitations that this implies such as being a small sample and with no absolute certainty regarding the use of the same type of deforming device within each group. Furthermore, this is a lateral two-dimensional study in which transverse development has not been analysed.

Conclusions: Artificial modification of the shape of the vault has repercussions on the NMC that support the theory of an all-inclusive integration of the different cranial units in normal as well as in restricted development.

Introduction

The cranial base is a structure that has a close functional relationship with the central nervous system (CNS). Its development is subject to the specific demands of the CNS, of the vessels, of the nerve trunks and of the meningeal capsule (1, 2). This close interrelationship extends into adjacent functional matrices (1, 2), with the cranial base acting as a connection between the cranial vault and the viscerocranium. The nasomaxillary complex (NMC) is situated beneath the anterior cranial fossa, which serves as a platform for its development (3, 4). Embryologically, the anterior cranial base and the viscerocranium both arise from cells of the neural crest, but they undergo distinct ossification processes (5). The cranial base is traversed by several synchondroses and sutures that permit a certain level of morphological reorganization during development and that present a degree of plasticity with respect to environmental factors (4, 6). The spheno-ethmoidal synchondrosis (SES) plays a dominant role in the morphological development of the anterior cranial fossa (7) and it is closely associated with the NMC through the orbit and nasal septum (6, 8, 9). The spheno-occipital synchondrosis (SOS) is a fundamental structure in the organization of the cranial base and of its flexure and it defines the posterior limits of the NMC (10). Counterpart analysis shows that this synchondrosis interacts with the NMC through the posterior maxillary (PM) plane (3, 11, 12). The cranium is made up of a number of functional units that, despite maintaining their independence, interact in a hierarchical and closely integrated mosaic (3) that guarantees the correct function of this particularly complex structure (13, 14). The NMC is also made up of different functional units: orbit, nasopharynx, and stomatognathic system. These units interact together (4), as has traditionally been advocated by the functional matrix hypothesis (FMH) (1, 2).

Artificially deformed skulls (ADS) give us an excellent opportunity to investigate the degree to which restrictions of the development of the vault and cranial base affect the NMC. These skulls represent a natural experiment (15) in which the cranial growth vectors are redirected (3, 4, 16). Two main types of artificial cranial deformity can be found in skulls from pre-Columbian Peru: anteroposterior (AP) deformity, in which sagittal growth was limited by means of rigid frontal and occipital elements held in place by bandages and circumferential (C) deformity, in which bandages were employed to limit growth of the whole circumference of the vault, producing an extreme mortar-shaped deformity (17, 18). The deforming device was fitted on the newborn infant and was kept in place throughout early childhood (19). The deformity of the vault affected the cranial base and was thus propagated to the viscerocranium, with alteration of the transverse diameters of the temporo-mandibular joints and of the jaws (15, 20–22). Some authors have detected increased facial height (15, 20, 21, 23). AP alterations of the NMC (15), with morphological changes affecting the orbit and the nose (20, 21), appear to be the most relevant; there is considerable discrepancy between authors, however, regarding changes in the jaws (20, 21, 23). As the maxilla is a structure that forms part of the stomatognathic system, its morphology will also be affected by its function and by its relationship with the mandible (24) due to eruption of the teeth (25) and because its development occurs at a later stage (3).

Relatively few studies in the field of orthodontics have used geometric morphometrics (GM) as a tool for analysis of the cranial base (26) and of its relationship with the jaws (11, 12, 27). Studies of ADS using these methods are also scarce (15, 21, 28). GM analysis has a series of advantages over traditional cephalometric studies of angles and lengths: results are not affected by differences in the size of the different specimens because the technique uses standardized values; the Procrustes superimposition of landmarks creates an interrelationship between the landmarks and each one of them becomes a variable, thus making it possible to perform multivariate analysis; and the thin-plate spline (TPS) grid allows us to visualize the areas in which the variance is concentrated and the magnitude of that variance (29, 30).

The objective of the present study was to investigate the influence of deformity of the cranial base on the position of the NMC in skulls with artificial AP and C deformities. Two working hypotheses were defined: Hypothesis 1 stated that the shape and sagittal position of the units that make up the NMC were not affected by deformity of the neurocranium. Hypothesis 2 stated that there was no difference in the morphological alterations of these structures caused by the two types of deformity. To the best of the authors' knowledge, this is the first time that nasomaxillary morphology and the configuration of the cranial base have been studied in ADS using GM analysis.

Material and methods

For the study, we used 88 skulls of precontact Amerindian adults from the Central Andean coastal region. The skulls were drawn from the collections of the National Museum of Archaeology, Anthropology and History of Peru. The skulls with cranial deformity were divided into two groups, classified visually and according to their origin (18) (Figure 1). These crania came from the Middle Horizon period (600–1000 CE) (31). Thirty-two skulls from Ancon presented AP cranial deformity, 17 skulls from the burial sites at Cerro Colorado, Arena Blanca, and Cabeza Larga in Paracas had circumferential (C) cranial deformity. The remaining 39 skulls from Makatampu (Lima) presented no apparent cranial deformity and were used as the control group. The age range was determined by closure of the SOS and by the presence of the third molar and its degree of attrition (32). The following inclusion criteria were applied to the three groups:

Figure 1. Artificially deformed skulls used in the present study. Left: circumferential (C) deformity. Right: anteroposterior (AP) deformity.

1. integrity of the cranial structures, taking special care regarding the presence of upper and lower jaws and of the dental arches; 2. male skulls, with rejection of those specimens without this characteristic (33); and 3. absence of marked ex visu asymmetry of the cranial vault and of the jaws to reduce the bias in the superimposition of the bilateral landmarks and to avoid, as far as possible, the compensatory growth processes described in these crania (34).

After fixing the crania on a cephalostat, lateral teleradiography was performed using a Proline PM 2002 CC X-ray device (Planmeca Corporation, Finland). The images obtained were digitized using a Nikon D70 camera with a Nikkor 18-70 AF-S ED objective, mounted on an RS2 copy stand (Kaiser, Germany). The landmarks were digitized using the tpsUtil version 1.52 and tpsDig2 version 2.16 software (35). The landmarks used to define both the cranial base and the NMC were mainly of types 1 and 2, with some type 3 landmarks (29) (Table 1; Figure 2). The landmarks were established by one of the authors (IF) and reviewed by another author. The error of identification of the landmarks (measurement error) was determined by repeating the marking of 10 crania on two different occasions after an interval of 2 weeks. An analysis of variance study was performed and showed no significant difference between the repeated samples, indicating that the error of measurement (4%) was less than the variation between subjects. The GM analysis was performed using the MorphoJ software, version 1.05 a* (36). Principal components analysis (PCA) was used initially on the overall sample in order to determine the patterns that explained the variability of the Procrustes superimposition in the shape space. The first principal components (PCs) were studied in order to define the morphological changes that differentiated the sample. A multiple analysis of variance test (IBM SPSS 20, Chicago, Illinois, USA) was used to calculate the significance of the difference between PCA scores. The discriminant dimensions were studied using canonical variate analysis (CVA), determining the Procrustes distances. Discriminant function analysis (DFA) was employed to examine the anatomical differences and to determine the separations between the means of the different groups (30). The goodness of the initial ex visu classification was checked a posteriori using DFA. Study of the deformity in TPS and wireframe enabled us to visualize the scores and to determine those regions of the cranial base in which compression occurred and those others areas in which the result was a compensatory expansion. It was also possible to identify the areas with a more stable interface (30, 36). Significance was established as an alpha value of 0.05.

Results

The first eight PCs accounted for 66% of the total variance. The point of inflection of the eigenvalue curve occurred at PC5, with a cumulative variance of 54%. PC5 was the last PC to present a variance over 5% (6.2%); the remaining PCs could therefore be considered of low relevance for differentiation between groups (30). PC1 accounted for 20% of the variance and significantly separated the AP group from the control group and from the C group ($P < 0.001$ for both differences). This PC showed changes in the shape of the anterior and posterior poles of the cranial base, with little alteration of the clivus. It also showed rotation of the maxillary plane and of the alveolar apophysis. PC2 accounted for 12% of the variance and significantly separated the AP group from the control group ($P < 0.001$) and the C group from the control group ($P < 0.015$). PC2 the changes in the shape with anterior displacement of the clivus, changes in the anterior pole and posterior pole of the cranial base, rotation of the roof

Table 1. Cranial landmarks employed in this study, landmark numbers are represented in Figure 2.

Landmark	Cranial landmarks	Cranial landmarks definition
1	Nasion	Frontonasal suture. Midline
2	Sella	Centre of the sella turcica (pituitary fossa). Midline
3	Basion	Lowermost and anteriormost point on the anterior margin of the foramen magnum. Midline
4	Bolton point	Highest point of the curvature between the occipital condyle and the lower border of the occipital bone. Midline
5	Squama	Point of the maximum convexity of the outer contour of the occipital squama. Midline
6	Crista temporalis	Most posterior point of the middle cranial fossa, at the temporo-parietal junction. Lateral
7	Foramen coecum	Most anterior point of the cribriform plate in the junction with the frontal tabula interna. Midline
8	Glabella	Most prominent point of the supraorbital ridge. Midline
9	Orbitale superior	Uppermost point of the superior border of the orbital ridge. Lateral
10	Orbitale posterior	Most posterior point of the lateral orbital ridge. Lateral
11	Pterygopalatine fossa	Most postero-superior point of the pterygopalatine fossa. Lateral
12	Pterygomaxillary fissure	Most inferior point of the pterygomaxillary fissure. Lateral
13	Zygoma	Most inferior point in the outer contour of the zygomatic process. Lateral
14	Infraorbitale	Most inferior point of the lower border of the orbital cavity. Lateral
15	Anterior nasal spine (ANS)	Most anterior bony projection of the floor of nasal cavity. Midline
16	Posterior nasal spine (PNS)	Most posterior point of the hard palate. Midline
17	Incisal	Most occlusal point of the palatal alveolar ridge. Midline
18	Prosthion	Most occlusal point of the buccal alveolar ridge. Midline
19	Subspinale (A)	Deepest point on the concavity between ANS and prosthion. Midline
20	Glenoid	Deepest point on the contour of the glenoid fossa. Lateral
21	Wing	Junction between the jugum sphenoidale and the ala major. Lateral
22	Nasal inferior	Most anterior and inferior point on the nasal bones. Midline
23	Nasal medium	Mid-point between nasion and nasale inferior. Midline
24	Pyriformis	Most posterior point of the pyriformis border in the maxilla. Lateral

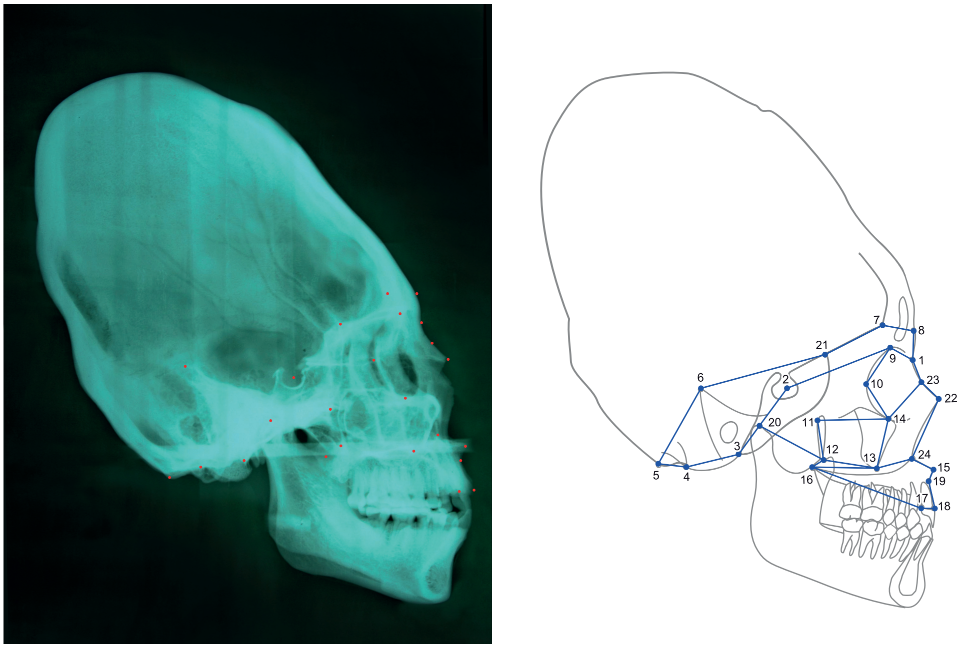

Figure 2. Left: X-ray of a circumferentially deformed skull with the landmarks. Right: wire frame and landmarks used in the analyses. See Table 1 for a definition of the landmark positions.

of the orbit, and variations in the vertical maxillary dimension. The combination of PC1 and PC2 separated the three groups morphologically (Figure 3). PC3 was associated with maxillary protrusion and frontonasal and orbital retrusion. It separated the C group from the control group ($P < 0.001$) and accounted for 9% of the variance. PC4 separated the two deformed groups (C and AP) from the control group ($P < 0.001$), though it only accounted for 7.8% of the total variance; the most relevant changes were in the middle cranial base, posterior cranial base, and in the nasal area.

The CVA study (Figure 4) defined two axes that separated the morphological variation of the sample. CV1 (with 56.2% of the variance) showed that the anterior and posterior poles of the cranial base and the anterior and posterior extremes of the maxilla were the elements that best discriminated the deformity. The negative loading was found in the C deformity and control groups and the positive loading in the AP deformity group. Positive loading reflected changes in the posterior cranial fossa and frontonasal retrusion with maxillary protrusion. CV2, which give the 43.7% of the variance, separating the C group from the other two groups. The positive loading of the C group referred to rotation of the maxilla (ante-rotation), to the upward and backward displacement of the anterior cranial fossa and to the forward and downward displacement of the clivus. The permutation test (10000 permutations) (36) for the Procrustes distances between the groups produced a significant difference ($P < 0.0001$) between all groups (Table 2).

The DFA also showed that no cranium was misclassified on visual examination, with a confidence level of $P < 0.0001$. The specific characteristics of each deformity are highly discriminant.

The morphological patterns can be seen graphically on the superimposed wireframes between the DFA means (36) (Figures 5–7).

Morphological alterations common to both deformities:

NMC

1. Increased anterior vertical dimension, more marked in the C group.
2. Antero-inferior growth of the alveolar process that provoked protrusion of the prosthion.
3. Point A practically unchanged, with minimal protrusion in the C group.
4. Downward and forward displacement of the nasal bones.
5. Maintenance of the PM plane with slight forward displacement.

Cranial base

1. Backward and upward displacement and rotation of the cribriform plate, more significant in the C group; this causes backward displacement of the roof of the orbit.
2. Forward and downward displacement of the clivus.
3. Closure of the clivo-foraminal angle.
4. Increased sagittal diameter of the foramen magnum and elevation of the occipital squama.

Group-specific changes:

1. AP deformity group

NMC

- Backward displacement of the nasion
- Protrusion of the anterior nasal spine
- Reduced posterior vertical dimension of the pterygomaxillary fissure

Cranial base

- Closure of the angle of the cranial base
- Backward displacement of the occipital squama

2. Circumferential deformity group

NMC

- Backward and upward displacement of the orbit
- Ante-rotation of the maxilla
- Backward displacement of the posterior nasal spine

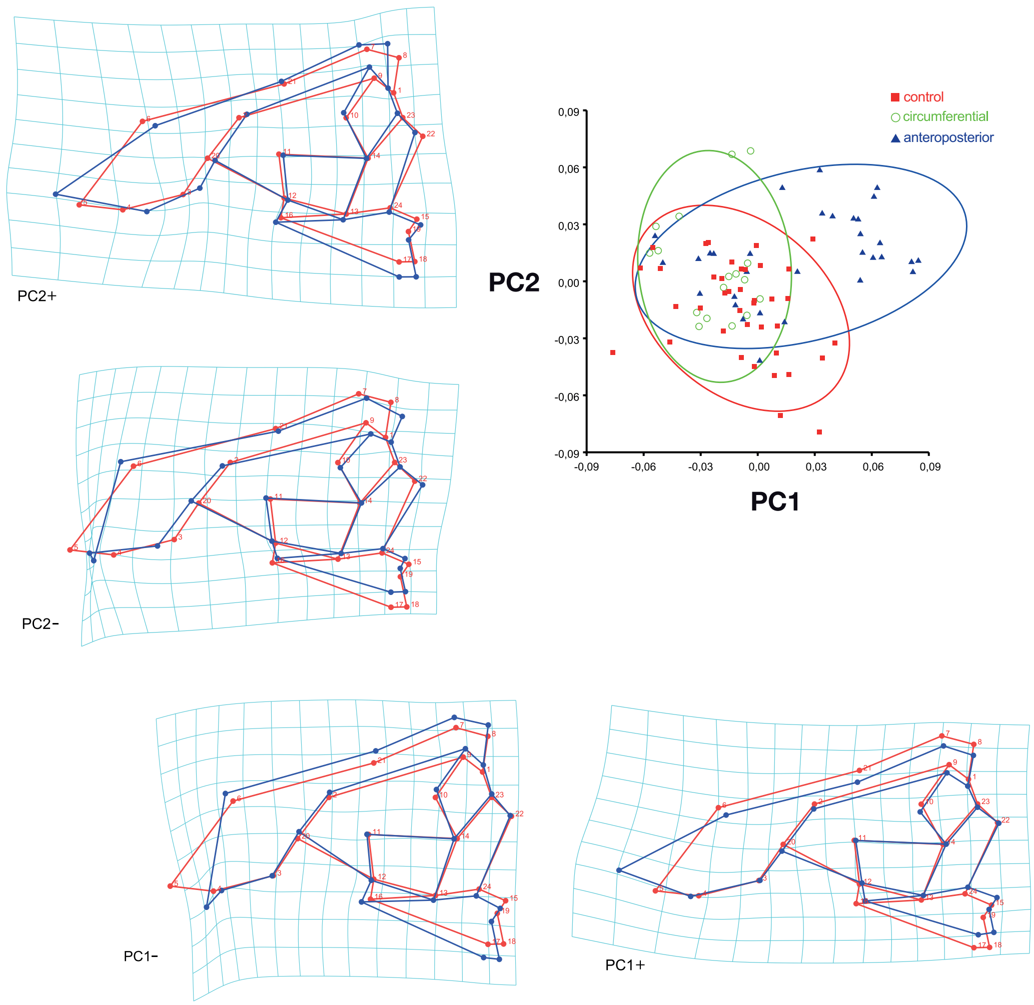

Figure 3. Scatter plot (with 80% confidence ellipses) of the first and second principal components (PC1 and PC2) [anteroposterior deformity (AP), blue triangles; circumferential deformity (C), green circles; Control, red squares] and thin-plate spline transformation grids with shape change vectors for the positive and negative values of the corresponding PCs. Observe PC wire frames and transformation grids with the tendencies of morphological changes. Red frame: neutral value; blue frame: ±maximum tendency. See Table 1 for a definition of the landmark positions.

- Counter clock wise rotation of the anterior profile of the zygomatic bone

Cranial base

- Opening of the angle of the cranial base
- Elevation of the crista temporalis.

On the basis of these results, the working hypotheses were rejected.

Discussion

Summary of key findings

The results of this study show that artificial AP and circumferential cranial deformities induced morphological changes in the cranial base and that these alterations were propagated to the NMC. Even anatomical units as distant from the original deformity as the maxilla are affected. The two types of vault deformity provoke different morphological alterations of the base of the cranium and of the NMC.

Strengths and limitations

This method of analysis gives us an overall picture of the morphological changes of the complete anatomical structure and makes it easier to locate the subunits or areas of those subunits that have undergone greatest change (30, 36). The PC analysis shows us the variance both between the different groups and within the individual groups and enables us to see where the morphological changes are most intense and the predominant patterns in each type of cranium. It is important to realize that this study is limited by the specific characteristics of an archaeological sample and that part of the morphological variability is not included in the PCs studied. In this study, the C group was small, which could have reduced the strength of the statistical signal; however, this was outweighed by the high level of coherence and the homogeneity of the group in the plots of the PCA (Figure 3) and of the CVA (Figure 4). It can thus be stated that this was a small but homogeneous group that seems representative.

Changes affecting the NMC

The two ADS groups used in this study showed two types of response to two distinct deforming actions. According to the balloon model hypothesis (3), the AP deformity is characterized by AP growth restriction with medial-lateral compensation (15, 22), whereas the C deformity presents a medial-lateral and supero-inferior restriction, producing an AP compensation (21). Because of this, it has been reported in the literature that the AP deformity leads to

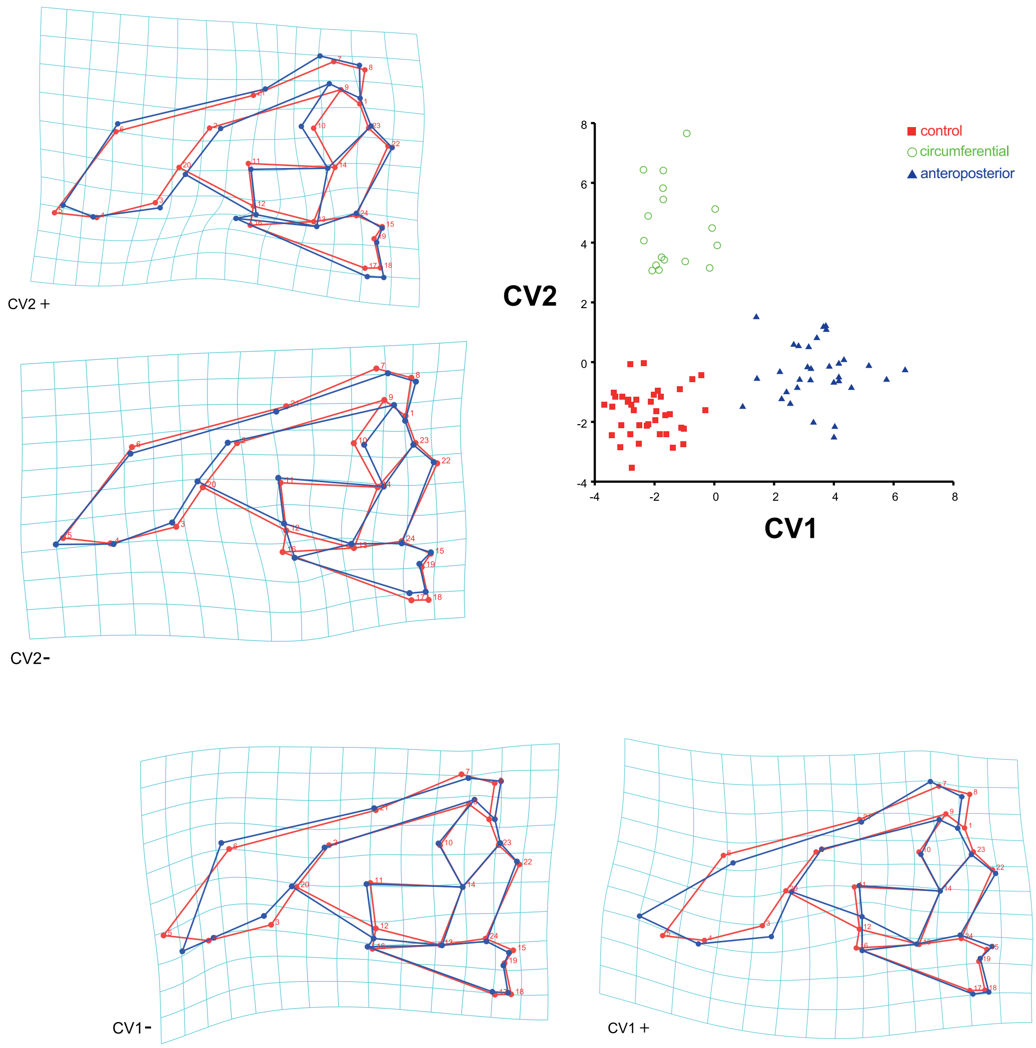

Figure 4. Scatter plot of canonical variate analysis (CVA) [anteroposterior deformity (AP), blue triangles; circumferential deformity (C), green circles; Control, red squares]. The three groups are clearly differentiated. Shape variation along the corresponding axis is shown by the thin-plate spline transformations (red wire: neutral value; blue frame: ±maximum tendency). Useful traits for discriminating between groups are revealed. See Table 1 for a definition of the landmark positions.

Table 2. Procrustes distances and *P* values for permutation tests for Procrustes among groups.

	Control	Circumference
Circumference	0.0625 ($P < 0.0001$)	
Anterior–posterior	0.0600 ($P < 0.0001$)	0.0651 ($P < 0.0001$)

shortening of the NMC in the AP plane, whereas the C deformity produces lengthening of the NMC in the AP plane (15, 21). The results obtained in our study clarify and contradict these statements. In the AP group, protrusion of the nasal bones and of the anterior nasal spine does occur, but point A is not affected and the nasion and glabella undergo backward displacement (Figure 5); this could be an effect of propagation of the compression of the cranial base through the nasal septum (6). In the C group, protrusion of the anterior nasal spine was not observed but slight protrusion was detected in the nasal bones, and there was retrusion of the glabella (Figure 6). The protrusion affecting the prosthion in both the AP and the C deformities was related to alveolar compensation, which was clearly visible (particularly in the C group) and has been reported previously (20, 22). This alveolar compensation, responsible for a large part of the intergroup variance, was probably caused mainly by the processes of tooth eruption, to migration of the tooth germs through the maxilla (25) and to occlusal factors, which will have had a compensatory effect to preserve the function of the stomatognathic system (24). There is no net forward displacement of the maxilla, as has been suggested after closure of the cranial base angle (8) or when the anterior cranial floor rotates upwards and backwards (6). In fact, there is AP compression of the NMC in both groups, particularly in the space between the pyriform aperture and nasion anteriorly and the PM plane posteriorly. In this area, there is backward and upward displacement of the orbital rim in the C group (4, 20), but these changes in the orbit are minimal in the AP group. Compression of this space also affected the zygomatic-malar region, which presented compression and ante-rotation in the C group and only compression and posterior vertical restriction in the AP group.

Role of the PM plane

Compression in the area of the tuberosity, an area responsible for pushing the NMC forward and downward (3), was detected in both deformities. This compression occurred due to the forward

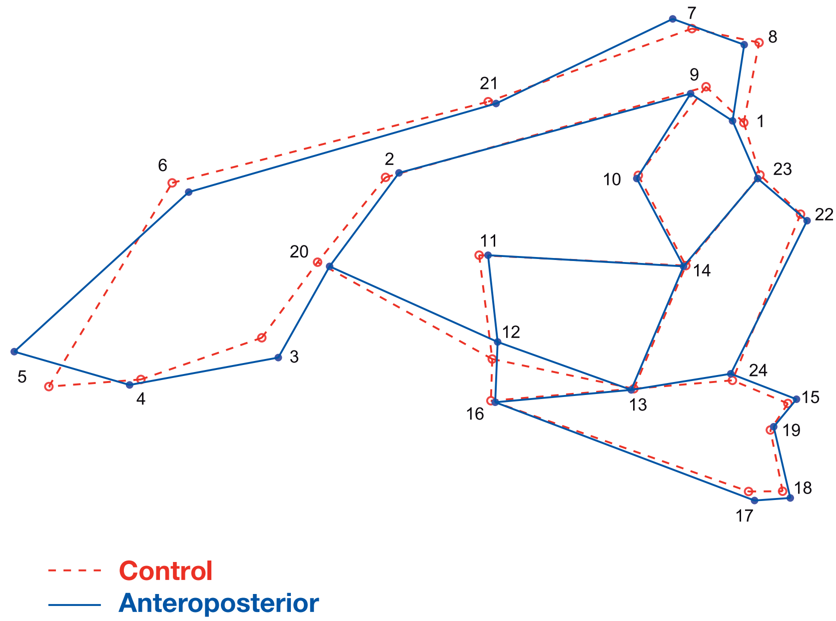

Figure 5. Morphological mean differences revealed by discriminant function analysis (DFA); wire frame representation of the control group and the anteroposterior group. Differences are increased 1.5 times. See Table 1 for a definition of the landmark positions.

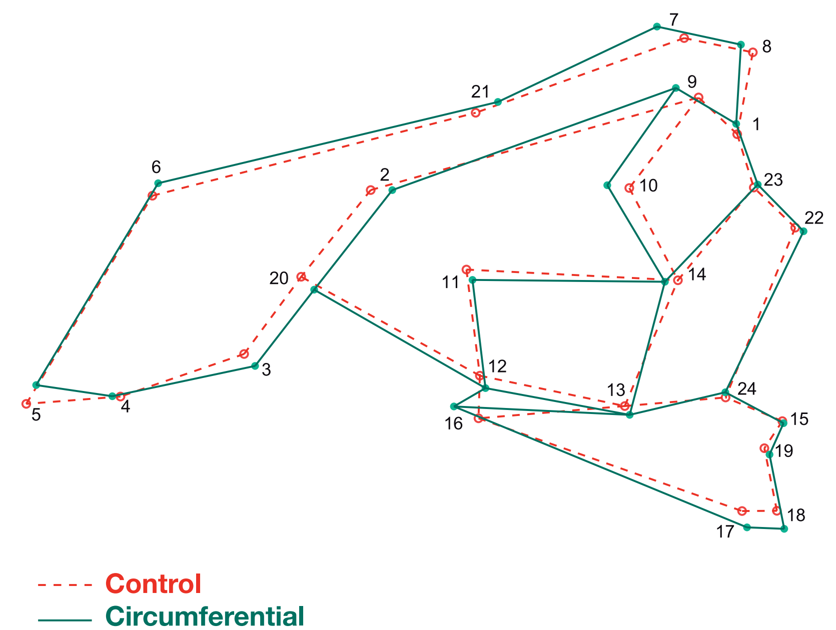

Figure 6. Morphological mean differences revealed by discriminant function analysis (DFA); wire frame representation of the control group and the circumferential group. Differences are increased 1.5 times. See Table 1 for a definition of the landmark positions.

displacement of the PM plane. In the C group, this displacement of the PM plane did not affect the posterior nasal spine, which was involved in the post-rotation of the maxilla and in its antero-posterior elongation (20). In the AP group, in contrast to what has been reported in another study (23), we detected an increase in the AP dimension of the maxilla, produced by changes in the premaxilla. The PM plane is a vertical plane that acts as an interface between the middle cranial fossa and the NMC. Its definition as an axis that separates two vertical modules (3, 11, 12) is supported by the results of our study; the large compensatory displacements occurred on either side of this axis, but the plane defined by the landmarks of the sphenoid wing and pterygomaxillary fissure only underwent slight forward displacement. Through the pterygoid apophysis, the PM plane acts as an element that transmits the plasticity of the cranial base (7).

Changes affecting the cranial base

It is very possible that a large part of the pressure exerted by the growth of the encephalon is redirected (16) through rotation of the cribriform plate (20). This upward and backward rotation of the anterior pole of the anterior cranial fossa occurs around the fulcrum of the SES (wing landmark), and it is particularly noticeable that a structure traditionally considered to be very stable (7) undergoes such marked changes in both types of deformity. Despite its endochondral origin (5), this structure has great plasticity, satisfying the principles of the FMH that no

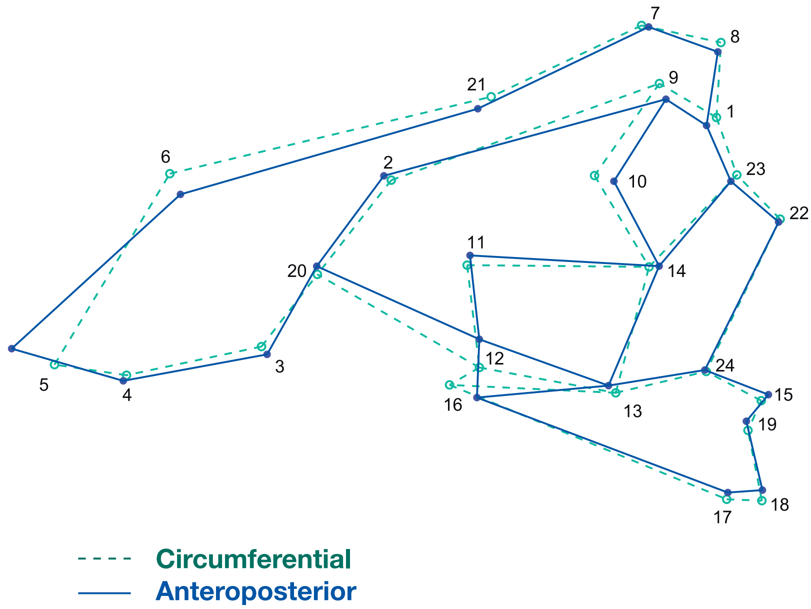

Figure 7. Morphological mean differences revealed by discriminant function analysis (DFA); wire frame representation of the anteroposterior group and the circumferential group. Differences are increased 1.5 times. See Table 1 for a definition of the landmark positions. Note the morphological variation in the orbital and nasal region, the occipital squama, and the nasal posterior spine (NPS) region. Note also the similarities in the clivus.

bone has a predetermined topographic position (16). Shortening of the anterior cranial fossa in the ADS led to antero-posterior constriction of the NMC, which has been noted previously in other situations (9). This rotation of the anterior cranial fossa and the development of the maxilla below the fossa produce an increase in facial height (15, 20, 21, 23).

In the middle cranial fossa, the late closure of the SOS (10) implies that the pressure of the encephalon (16) displaced the clivus forward and downward; in the C group, this displacement did not provoke closure of the angle of the cranial base; in fact, the marked rotation of the cribriform plate produced platybasia (20). In the AP group, there was less compensation in the cribriform plate and closure of the angle did occur. There was a clear displacement of the occipital squama in the posterior cranial fossa and marked changes around the foramen magnum that accounted for a large part of the variance (Figures 3 and 4). The increase in the sagittal dimension of the posterior cranial fossa and its ventral rotation, together with closure of the clivo-foraminal angle, can be explained by the pressure produced by growth of the infratentorial part of the encephalon (16, 20).

Integration

The results obtained in our study show that there is a degree of integration between the cranial base and the NMC. There is integration between neighbouring structures within the same functional unit, but there is also some degree of integration between more distant structures that do not share functional characteristics. The cranium has a high degree of plasticity, and even structures with endochondral ossification, such as the cranial base, can be modified by environmental factors acting during the development phase of those structures (16, 34). The morphological development and final configuration of the cranial structures is the result of a combination of factors (13): genetic determinants, functional requirements, and environmental factors. The strict hierarchical integration of all the different functional units guarantees the function and development of such a complex structure (3, 11), even when subjected to environmental aggression as limiting as the intentional deformity of the vault. It is very likely that the deforming elements were only kept in place until 4 or 5 years of age (19) but, as we have noted, this has a marked effect on synchondroses that close years later, and these structural alterations of the cranial base cause the growth of the viscerocranium to follow a pre-established pattern, in a compensatory manner, with the aim of maintaining function. In conclusion, there is a pervasive integration of the different functional units (28) that confirms that the cranium itself is much more than the sum of the development of a series of different, independent parts (1, 2).

Conclusions

The cranial base of the ADS showed marked deformity that produced an antero-posterior constriction of the NMC. Morphological changes common to both deformities include increased growth of the alveolar process of the maxilla, anterior displacement of the pterygomaxillary plane, alterations of the roof of the orbit, and forward and downward displacement of the clivus. In addition, there are changes specific to each type of deformity. In the C group, rotation and antero-posterior elongation of the maxilla were observed. In the AP group, there was naso-orbital retrusion. The artificial modification of the shape of the vault has consequences on the NMC that support the theory of an all-inclusive integration of the different cranial units and that indicate that this is the basis for development not only under normal conditions but also in situations of extreme restriction.

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