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Effects of Artificial Deformation on Cranial Morphogenesis in the South Central Andes

J. A. COCILOVO,[a]* **H. H. VARELA**[a] AND **T. G. O'BRIEN**[b]

[a] *Facultad de Ciencias Exactas, Departamento de Ciencias Naturales, Físico-Química y Naturales, Universidad Nacional de Río Cuarto, 5800 Río Cuarto, Argentina*
[b] *Department of Sociology, Anthropology and Criminology, University of Northern Iowa, Cedar Falls, Iowa, USA*

ABSTRACT One of the most interesting issues of the interface between biology and culture is the artificial deformation of the skull. This modification is produced during early morphogenesis through the use of devices that alter the normal growth and development, to obtain a culturally established model. This paper, using a large cranial sample from the South Central Andes (1586 individuals), describes and documents a detailed morphometric study of the changes affecting the vault, cranial base, face, orbits and nasal region resulting from the tabular erect (TE), tabular oblique (TO), circular erect (CE) and circular oblique (CO) deformations with respect to the model without deformation. Data from 17 metric variables were processed by a one-way ANOVA and LSD test for paired comparisons. All of the deformation types produce significant morphometric divergence in most of the anatomical structures of the skull. The TE exhibits: a restriction of antero-posterior growth producing expansion in cranial width and height, frontal flattening, shortening of the face and cranial base, widening of the face, increased nasal and orbit height (ORH) and a foramen magnum size increase. The TO exhibits: most change reflected in the widening of the cranial vault, shortening of the cranial base and face, frontal flattening, increased nasal and ORH and foramen magnum size decrease. The CE style exhibits: a decrease in cranial width and strong increase in the cranial height, a reduction in frontal width, expansion of the cranial base and face, increased nasal and ORH, orbital widening and a foramen magnum size increase. The CO style exhibits: a decrease of the cranial vault's width and height, expansion along its length, stretching of the cranial base and face, reduced frontal width, fronto-malar and biorbitary elongation of the face and further development of foramen magnum. Copyright © 2010 John Wiley & Sons, Ltd.

Key words: biology and culture; artificial cranial deformation effects

Introduction

The study of artificial cranial deformation has a long history in physical anthropology, with recorded contributions of different quality and importance. It is one of the most relevant factors representing the interface between biology and culture. Nevertheless, with the information available today, it seems not an easy task to realise a synthesis on the effects of this practice (O'Brien & Sensor, 2004). In the first place, the definitions of the deformation types are not consistent, which produces such a degree of uncertainty that we should be careful with regards to the results of the various studies, such as the ones following the Neumann (1942) nomenclature, updated in Buikstra & Ubelaker (1994), and those directed by Dembo & Imbelloni (1938). In the second place, due to the nature of subjective observation, the quality of the diagnosis depends on the experience of the person. In the third place, there are remarkable differences in the consulted works, depending on the material, the variables and the type of experimental design supporting the tests of the hypothesis. In the fourth place, it is extremely difficult to understand the changes that have taken place when there is no availability of a complete sample including normal and deformed individuals of all types, both sexes, of adult age and from local and regional zones.

Below is a description of a few of the main contributions on the subject. Until the 1950s,

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* Correspondence to: Facultad de Ciencias Exactas, Departamento de Ciencias Naturales, Físico-Química y Naturales, Universidad Nacional de Río Cuarto, 5800 Río Cuarto, Argentina.
e-mail: jcocilovo@exa.unrc.edu.ar

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studies generally emphasised the morphological aspect as a result of the application of a specific deformation device, where the key diagnosis was focused on the relationship derived from a specific anatomy correlated with a specific type of device. Nevertheless, these observations were performed by a simple comparison of mean values, without considering the evaluation of the differences through some statistical procedure. In spite of this, it should be recognised that such studies are an unexhausted source of hypothesis testing for the future.

In 1912, an outline of the various forms of this cultural practice was introduced (Hrdliçka, 1912), which was later used by Oettking (1922) in order to provide the first explanations on the changes produced in the morphogenesis of the skull. In 1931 one of the most complete studies on the subject on a global level was realised (Dingwall, 1931). In Argentina, from 1920 to 1950, the main descriptive and classifying data are provided in a series of studies that are still valid today (Imbelloni, 1925, 1932, 1933; Dembo & Imbelloni, 1938). In 1938, the metric and angular characterisation of different deformation types was published, recognised in the materials obtained by Crequí Monfort and Senechal de la Grange in Bolivia, the North of Chile and Argentina (Falkenburger, 1938).

In 1942 a classifying system was proposed based on six deformation types based on their description, most probable chronological location and relationship with certain archeological entities (Neumann, 1942). This idea of association between deformation and culture reaches its maximum expression in Peru where the existence of approximately 12 deformation types was established (Weiss, 1961, 1962, 1972). Unfortunately, beyond the veracity of these models, the descriptions performed by the latter author are insufficient in such a degree that their application for comparative goals remains difficult.

From the 1950s the subject enters a new phase, supported by the development of the functional anatomy and the statistical evaluation of changes in the skull under the effects of artificial deformation. The complexity of interpreting this process is demonstrated in various publications, based on different experimental designs, and different samples and techniques for data collection (e.g. Moss, 1958; McNeill & Newton, 1965). In 1964, two studies were published, one on the effect of the artificial asymmetrical deformation (Björk & Björk, 1964) in materials of Peru, and another on a northern Chile population (Munizaga, 1964), describing some links between turbans and deformation practices as well as a chronological distribution of the deformation types, aspects which were revised later (Cocilovo, 1995).

A more detailed knowledge of the effects of the tabular erect (TE) deformation was obtained by an analysis of the data published by Marelli (1914) of the remains found in antique cemeteries of Patagonia near Trelew, Argentina. Indeed, it was proven that the skull capacity did not change whereas the variations of the main indices reflected modifications of shape. There is a decrease of the length with an increase of the vault heights and widths. At the base, modifications of width but not of length were observed. There are some effects on the visceral skull, but no sufficient proof regarding the modifications of the roof and supra-orbital margin was obtained. The normal development of the segments of the sagittal curve reinforced the idea of a reorientation of the normal growth vectors, such as was indicated by Moss (1958). Also, in agreement with Ossenberg (1970), the lateral expansion should be interpreted as a major bone growth and development in this region as a consequence of the restriction experienced in the antero-posterior growth (Cocilovo, 1978).

The analysis of the materials from Peru presenting antero-posterior (possibly tabular oblique (TO)) deformation, circular deformation and no deformation, showed a significant development in the width of the facial portion, the base and of the cranial vault; whereas the fronto-occipital compression is compensated by the lateral increase at the level of the parietals, the widening of the anterior cranial base and the minor deepening of the posterior cranial base (Anton, 1989). Incidentally, while the facial size does not change, there is an increase in its width (Cheverud *et al.*, 1992).

The influence of circular deformation was investigated with no significant results in another Peruvian collection from Paucarcancha published by Mac Curdy (1923) due to the few differences between deformed individuals of the circular erect (CE) type and non-deformed (ND) individuals (Cocilovo, 1975). But its effect on the growth and development of the skull may be better understood in the series of Morro de Arica (Chinchorro, North of Chile). Observations revealed a shortening of the inion length, a decrease in maximum width and increase of the biasteric width, although no sufficient proof for any modifications of height was obtained. The cranial capacity remained constant and various cephalic indices were modified confirming the previous results regarding the changes of cranial shape. Also alterations of the normal growth of the visceral cranium were observed, fundamentally at the level of the lengths and heights, so that the face, orbit and the nose are higher in the deformed specimens, whereas the longitudinal development of the palate and the maxilla-alveolar portion is less significant (Cocilovo *et al.*, 1982). Similar results with other materials were obtained by Anton (1989), Kohn *et al.* (1993) and Frieβ & Baylac (2003). Posterior studies in the Chinchorro series allowed the splitting up of the group of circular crania into the erect and oblique variations, in order to analyse their effects within the same cultural tradition (Mendonça & Di Rienzo, 1981; Mendonça *et al.*, 1983, 1986). Unfortunately, the facts shown in the previous studies with regards to materials from Arica were not considered by Sutter & Mertz (2004) or by Rhode & Arriaza (2006).

The morphometrical differences between the TE and TO types were more difficult to obtain due to the reduced size of the available samples. Nevertheless, in materials from the North-West of Argentina, higher mean values in the oblique types were observed for the maximum length, the spheno-basion alveolar diameter and the horizontal curve, with a reduction of the glabela-inion length, the cranial base length (CRNBSL), nasiobasilar diameter and the bregma–lambda curve, as well as the expansion of the transversal curve (Cocilovo & Baffi, 1985; Baffi, 1992). In materials from Puna, the effect of the TO and oblique circular deformation in individuals of both sexes showed significant changes at the level of the cranial vault and facial portion (Mendonça *et al.*, 1994). A more precise analysis was performed at various locations in the North of Chile: in San Pedro de Atacama (Cocilovo *et al.*, 1995; Varela, 1997), and Coyo Oriental (Cocilovo & Zavattieri, 1994) and in Pisagua (Cocilovo, 1995; Cocilovo *et al.*, 1999), establishing the differences existing among normal, TE and TO, CE and circular oblique (CO) deformed individuals.

A new and promising analysis of the artificial deformation considering the geometrical morphometry, although with only a small sample of radiographic profiles, was developed in materials of Arica from the Archaic, Middle and Late periods, by Manriquez *et al.* (2006: 29) concluding: '(1) the variation of the components of the skull shape depends on the magnitude and direction originally applied and oriented with the deforming devices on the major anatomical axes of the skull and (2) the intentional deformation involves the anatomical milestones of the neuroskull and the face.' A study with a broader continental scope was performed by Perez (2007), who discusses the usefulness of the traditional typological approach by proposing a new and efficient approach for the analysis of the cranial vault generated by cultural factors using techniques of geometrical morphometry and multivariate analysis. This author comes to the conclusion that the morphologies found in the analysed area (western and southern South America) correspond to the antero-posterior, lambda and antero-posterior compression plus superior expansion (Perez, 2007).

Although most of the mentioned antecedents for the south central Andes contributed to understanding the local level impact of artificial cranial deformation, thus constituting a necessary methodological stage, sample sizes available were reduced, such that due to a lack of degrees of freedom in the statistical tests many effects might have been unnoticed. This is valid for whatever the data measurement, recording and analysis might have been. Neither is there an updated study at the regional level to provide a more general view with better fundamentals in order to evaluate the impact of this specific cultural phenomenon. For this reason, the objective of the present work is to analyse the modifications during the morphogenesis of the cranium through the influence of the different cranial deformation models which are currently recognised, such as those by Dembo & Imbelloni (1938) and the works mentioned above in the north of Chile and northwest Argentina.

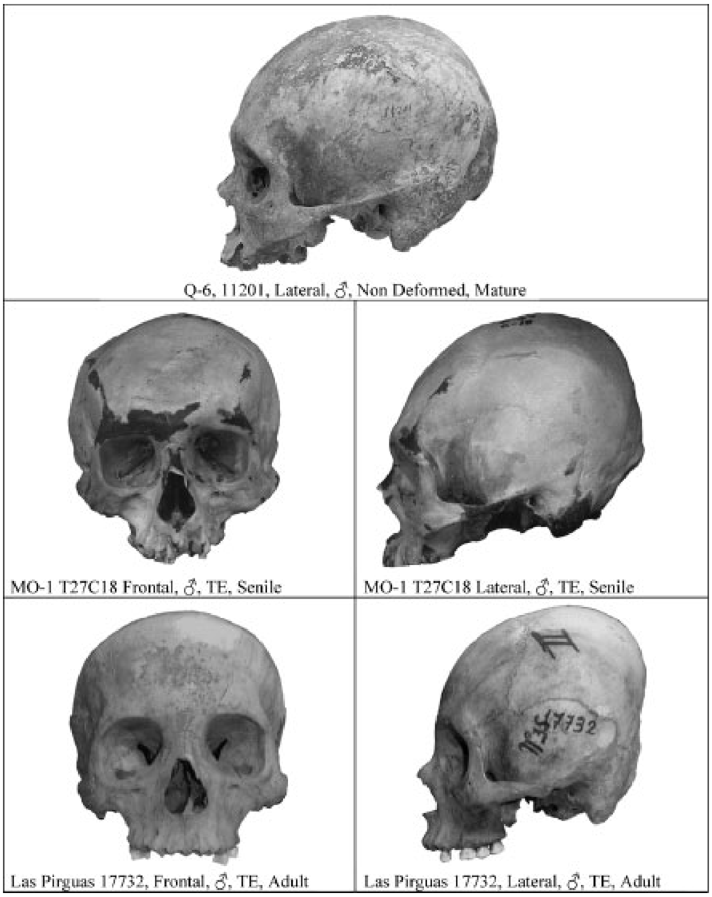
Therefore, it is expected that the different deformation types are characterised by the following modifications with regards to the normal cranium (Figure 1).

Tabular erect deformation

Specimens of this type tend to have a net vertical plane in the occipital's lambda region, which is often parallel to the basion-bregma height (BABH). The frontal bone may be flattened or weakly modified. A strong increase in cranial width and height is observed, produced from antero-posterior compression by firm and rigid elements (e.g. cradle board, pads or tablets). The modifications are most evident in the neurocranium, although the splanchnocranium is also affected. The general shape axis is approximately orthogonal with regards to the Frankfort horizontal plane.

Tabular oblique deformation

Specimens of this type tend to exhibit a net oblique plane in the iniac region, which is parallel to the also flattened and strongly inclined frontal. There is a


Q-6, 11201, Lateral, ♂, Non Deformed, Mature

MO-1 T27C18 Frontal, ♂, TE, Senile

MO-1 T27C18 Lateral, ♂, TE, Senile

Las Pirguas 17732, Frontal, ♂, TE, Adult

Las Pirguas 17732, Lateral, ♂, TE, Adult

Figure 1. South Central Andes. Types of artificial deformation. For each case the site, specimen, view, gender, deformation and age are mentioned.

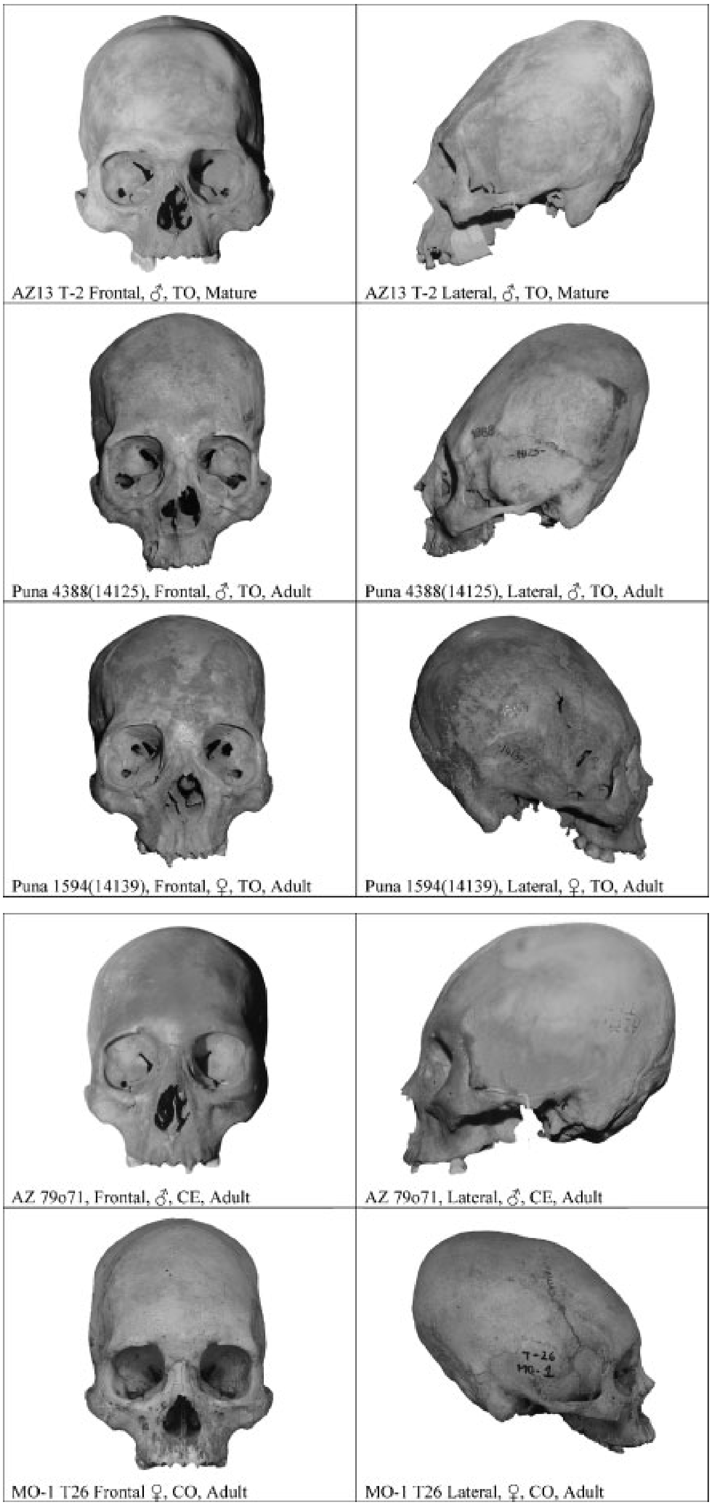
marked increase in cranial width and length. These modifications are produced by antero-posterior compression by firm and rigid elements (e.g. pads or tablets). The general shape axis is displaced posteriorly, above the Frankfort horizontal plane.

Circular erect deformation

Specimens of this type tend to demonstrate either a slight or pronounced flattening of the frontal. Additionally, a transverse, curved groove is often noted on the frontal that continues along the temporal walls of the vault, terminating around lambda on the occipital bone. The growth in length and width is restricted, with consequential growth expressed in height increase and expansion in the area of obelion. The general shape axis may be vertical or slightly inclined backwards with regards to the Frankfort horizontal plane. This form is a result of the application of more flexible elements like bandages, bands, tapes or cross-strands combined with other non-plastic materials in the posterior part (e.g. llautú or turban-like headdress). This category includes the deformation subtype previously defined as pseudocircular by Dembo & Imbelloni (1938) and also diagnosed in the same manner by Munizaga (1964).

Circular oblique deformation

Specimens of this type tend to have cranial vaults with slight or pronounced flattening of the frontal and occipital (at the iniac or infra-iniac level). In the zones of higher intensity deformation one often finds a transverse groove running perpendicular to the general shape axis. Incidentally, there is a more



AZ13 T-2 Frontal, ♂, TO, Mature

AZ13 T-2 Lateral, ♂, TO, Mature

Puna 4388(14125), Frontal, ♂, TO, Adult

Puna 4388(14125), Lateral, ♂, TO, Adult

Puna 1594(14139), Frontal, ♀, TO, Adult

Puna 1594(14139), Lateral, ♀, TO, Adult

AZ 79o71, Frontal, ♂, CE, Adult

AZ 79o71, Lateral, ♂, CE, Adult

MO-1 T26 Frontal ♀, CO, Adult

MO-1 T26 Lateral, ♀, CO, Adult

Figure 1. (Continued).

pronounced backwards inclination with regards to the Frankfort horizontal plane. The normal development of height and width is restricted with compensatory growth most noted in longitudinal vault expansion. The same elements employed in CE deformation have been used (e.g. llautú or turban-like headdress), but of an exclusively flexible nature, such as tapes or strands.

Without deformation

This category includes those specimens apparently free from the morphological features produced by the action of the before-mentioned specific deformation practices. The aspect of the total and specific morphology of the frontal, parietal and occipital regions is normal.

Materials and methods

The analysed sample comprises 1586 adult individuals of both sexes, without artificial deformation and those deformed in the types of tabular (erect and oblique) and circular (erect and oblique) according to Dembo & Imbelloni (1938). The materials correspond to three regions of the south central Andes (Figure 2): eastern Bolivia, northwest Argentina and northern Chile (Table 1) including materials from the following subregions: Cochabamba valleys in Bolivia (CCBB); Arica (ARI), Pisagua (PISA), San Pedro de Atacama (SPA) in northern Chile; and Puna (PUNA), Quebrada de Humahuaca (QUE), Valliserrana (VAL) and Selvas Occidentales (SELV) in northwest Argentina. The determination of the sex and age was performed according to Acsádi & Nemeskéri (1970), Molnar (1971), Bass (1981), Lovejoy (1985), Buikstra & Ubelaker (1994). The data file has been previously prepared (see Varela *et al.*, 2008).

The crania from Bolivia come from different sites of the valleys of Cochabamba and surroundings and corresponds to the Formative, Tiwanaku and Historical periods of the region (O'Brien, 2003). The crania from northern Chile were exhumated in Arica, Pisagua and San Pedro de Atacama and have a broad chronological distribution including the Archaic, Late, Formative, Tiwanaku, Regional Development and Inca periods. The crania from northwest Argentina archaeological sites assigned to the Early farmers, Middle and Late periods (see references in Varela *et al.*, 2008) (Figure 2).

Seventeen metric characters of the cranium were used: maximum cranial length (MAXCL), Maximum Cranial Breadth (MAXCB), BABH, minimum frontal breadth (MINFB), maximum frontal breadth (MAXFB), upper facial breadth (UPFB), bizygomatic breadth (BIZYGB), upper facial height (UPFH), nasal height (NZH), nasal breadth (NZBR), orbit height (ORH), orbit breadth (ORB), biorbital breadth (BIORB), basion prosthion length (BAPRL), CRNBSL, foramen magnum length (FORML) and foramen magnum breadth (FORMB).

This paper assumes that endocranial volume is constant, an assertion supported so far by cases from Trelew (TE deformation) and in Morro de Arica (CE and CO deformation) (Cocilovo, 1978; Cocilovo *et al.*, 1982).

This experimental design includes four deformation types: TE, TO, CE and CO and the ND category. The craniometrical differences are analysed through a one-way ANOVA for each variable separately and in a global manner by the Wilks' lambda. The individual variations are evaluated according to pairs with the LSD test *a posteriori*. Due to reasons of space, the alterations are graphically shown for those variables expressing the main changes at the level of the cranial vault.

Results

The statistical analysis sufficiently illustrates the cranial changes effected by different deformation types such that the efficiency of the performed classification can be measured simultaneously. Table 2 shows the mean values, the standard error and the amount of observations for each category according to the artificial deformation. Generally the differences are significant (Wilks' Lambda of $= 0.22316$, $\approx F = 31.823$ with 68 and 4648.7 df and $p = 0.000$). From a univariate point of view, the different categories express different mean values in most of the variables; only for two features was it not possible to obtain sufficient proof: the NZBR and ORB. For each variable in Table 3 probability values higher than 5% from the LSD tests of the deformed and ND types are displayed.

Figures 3–7 illustrate the most representative variables according to the modifications produced by the different deformation models and in regards to the ND type. In these graphics the distribution of the mean values and the corresponding standard errors are observed. Figure 3 shows the shortening of the MAXCL produced by the tabular deformation and the most significant development in the CO, whereas an intermediate position is taken by the CE type, which is not differentiated from the ND (Table 3). In Figure 4, the two tabular types exhibit considerable expansion of the MAXCB and their development is restricted in the circulars likewise for both subgroups (Table 3). Additionally, in the tabulars, less change is observed in BABH (Figure 5); and TO shows no difference from the ND crania. In

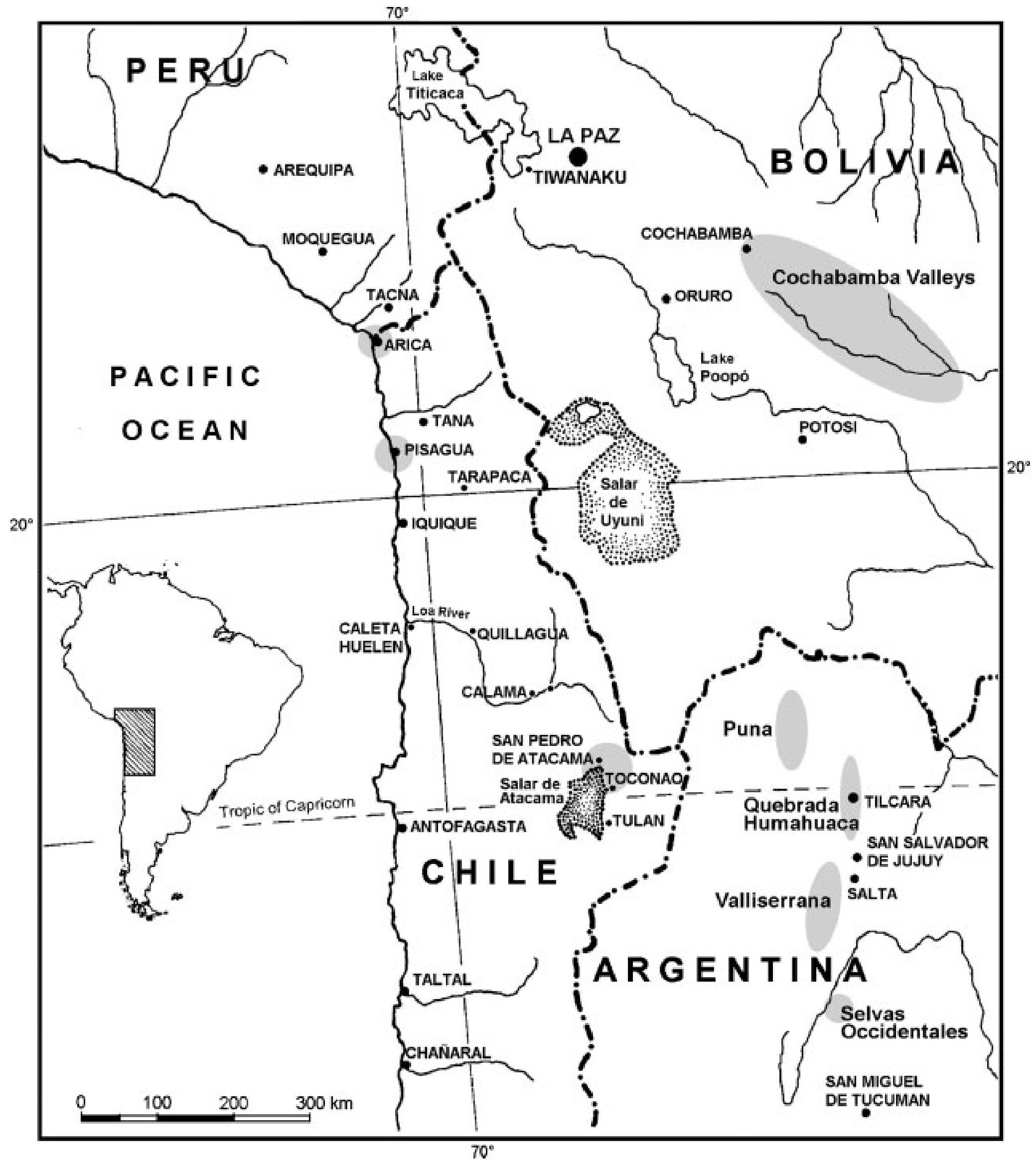


Figure 2. South Central Andes. Locations where the materials originate are shaded.

Table 1. Sample distribution

Region (code)	Subregion (code)	Total
South of Bolivia (CCBB)	Valles de Cochabamba (CCBB)	202
North Chile (NCH)	Arica (ARI)	292
	Pisagua (PISA)	67
	San Pedro Atacama (SPA)	120
NW Argentina (NOA)	Puna Jujeña (PUNA)	331
	Quebrada Humahuaca (QUE)	350
	Valliserrana (VALL)	184
	Selva (SELV)	40
Total		1586

the circulars, large average values are observed, especially those of the CE type. The maximum frontal diameter (Figure 6) exhibits becomes greater in the tabulars yet shows more restricted growth in the circulars (Table 3). Finally, the CRNBSL (Figure 7) displays much less growth in the tabulars than the greater development in the circulars. These changes are significantly different from those in ND skulls (Table 3).

The remaining variables express the modifications due to the deformation effect according to models more or less consistent among themselves. For example, the BAPRL is similar to the CRNBSL with

Table 2. Distribution of the cranial metric variables

Variables	Deformation									
	Tabular erect		Tabular oblique		Circular erect		Circular oblique		Non-deformed	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
MAXCL	161.93	0.457	164.24	0.382	172.16	0.877	178.42	0.738	170.76	0.464
MAXCB	145.91	0.392	146.28	0.328	130.13	0.752	129.68	0.633	137.61	0.398
BABH	132.99	0.356	131.55	0.298	138.33	0.683	134.25	0.575	131.91	0.361
MINFB	90.69	0.289	88.15	0.241	88.67	0.554	88.69	0.466	89.81	0.293
MAXFB	117.41	0.396	113.70	0.331	106.64	0.760	107.21	0.639	111.63	0.402
UPFB	103.16	0.250	102.64	0.209	101.60	0.479	101.29	0.403	101.91	0.253
UPFH	68.92	0.285	70.37	0.238	70.20	0.546	69.38	0.459	68.66	0.289
BIZYGB	134.12	0.377	133.13	0.315	131.61	0.723	131.17	0.608	132.05	0.382
NZH	50.47	0.189	50.90	0.158	50.61	0.363	49.74	0.305	49.56	0.192
NZBR	24.80	0.114	24.73	0.095	24.27	0.218	24.71	0.183	24.83	0.115
ORH	35.53	0.131	36.99	0.110	35.47	0.251	35.16	0.211	35.01	0.133
ORB	37.82	0.108	37.72	0.090	38.21	0.208	37.67	0.175	37.57	0.110
BIORB	96.21	0.231	95.69	0.193	95.92	0.442	95.83	0.372	94.84	0.234
BAPRL	92.10	0.323	91.86	0.270	97.56	0.619	96.96	0.521	93.27	0.328
CRNBSL	93.57	0.279	91.87	0.233	97.81	0.536	96.27	0.451	94.38	0.283
FORML	35.15	0.149	34.01	0.124	35.67	0.285	35.52	0.240	34.76	0.151
FORMB	30.83	0.156	29.71	0.131	32.92	0.300	31.99	0.252	30.32	0.159
N	276		395		75		106		268	

Note: ANOVA test, Wilks' lambda = 0.22316, $F(68, 4648.7) = 31.823$, $p = 0.0000$. Variables in bold do not show any significant differences in the univariate analysis.

minor mean values in the tabular types and most notable mean values in the circular types; although within each group mean values are similar (Table 3). The UPFB and the BIZYGB show a more significant development in the tabular types. The UPFH shows changes affected by the TO, CE and CO deformations. The NZH shows a more significant growth in the deformed TE, TO and CE types. The FORMB has

Table 3. Comparisons of pairs, LSD test among deformed types

Variables	Comparisons									
	TE	TE	TE	TE	TO	TO	TO	CE	CE	CO
	TO	CE	CO	ND	CE	CO	ND	CO	ND	ND
MAXCL									0.238	
MAXCB	0.857							0.740		
BABH							0.859			
MINFB					0.432	0.291		0.917		
MAXFB								0.452		
UPFB	0.107							0.700	0.431	
UPFH			0.109	0.493	0.848	0.136		0.360		
BIZYGB	0.052				0.053			0.838	0.499	0.292
NZH	0.051	0.689	0.080		0.432			0.096		0.426
NZBR	0.958		0.472	0.387		0.476	0.320	0.185		0.174
ORH		0.763	0.139					0.393	0.245	0.851
ORB	0.610	0.089	0.509	0.145		0.744	0.288			0.691
BIORB	0.140	0.514	0.394		0.815	0.872		0.937		
BAPRL	0.971							0.467		
CRNBSL										
FORML		0.066	0.079	0.196				0.791		
FORMB										

Note: In all cases degrees of freedom for the SME are = 1200.0. Non-significant probability values are shown at the level of 0.05. Deformation code: TE, tabular erect; TO, tabular oblique; CE, circular erect; CO, circular oblique; ND, non-deformed.

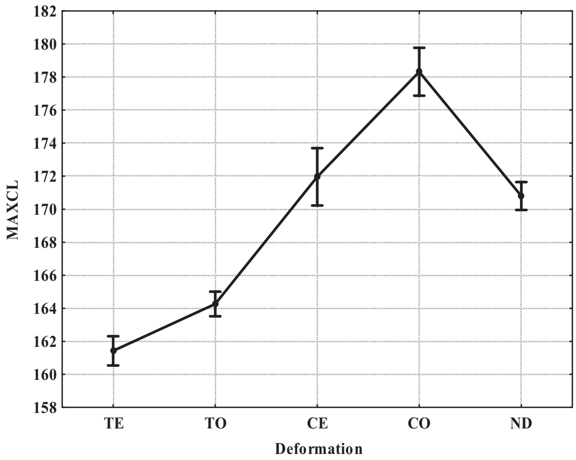


Figure 3. Effect of artificial deformation on the MAXCL. Vertical bars indicate a 95% interval for the mean value. Deformation code: TE, tabular erect; TO, tabular oblique; CE, circular erect; CO, circular oblique; ND, no deformation.

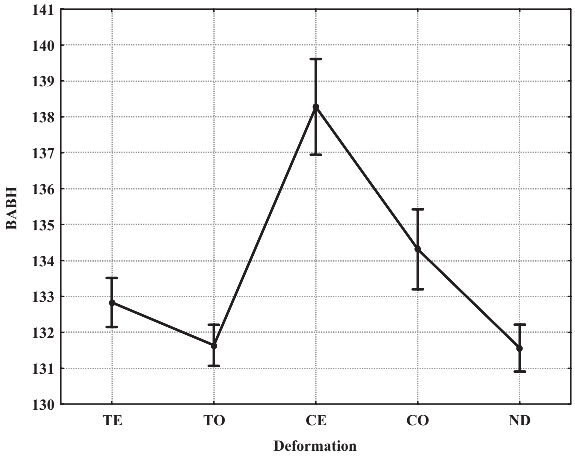


Figure 5. Effect of artificial deformation on the maximum cranial height. Vertical bars indicate a 95% interval for the mean value. Deformation code: TE, tabular erect; TO, tabular oblique; CE, circular erect; CO, circular oblique; ND, no deformation.

lesser dimensions in the TO and greater dimensions in the other types; whereas the FORML follows the same model but of a lesser degree.

Discussion

The categories used in this study do not exhaust the diversity of shapes which may have been observed and stated by other authors, including the same classifying system proposed by Dembo & Imbelloni (1938) for types, shapes and variety. The model of four main types plus the ND type was adopted in order to avoid the excessive subdivision of the sample and loss of degrees of freedom in the evaluation of the distribution of the frequencies. Certainly in many cases it is difficult to discern between ND and deformed individuals, and even within the latter category, to assign a skull to a specific type. Too many times this has been tried based on the distinction of particular subtypes (see Dembo & Imbelloni, 1938) by traits that many times overlap or are confusing to

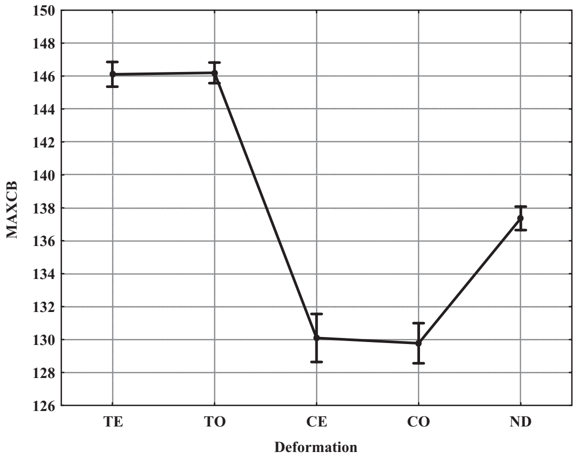


Figure 4. Effect of artificial deformation on the MAXCB. Vertical bars indicate a 95% interval for the mean value. Deformation code: TE, tabular erect; TO, tabular oblique; CE, circular erect; CO, circular oblique; ND, no deformation.

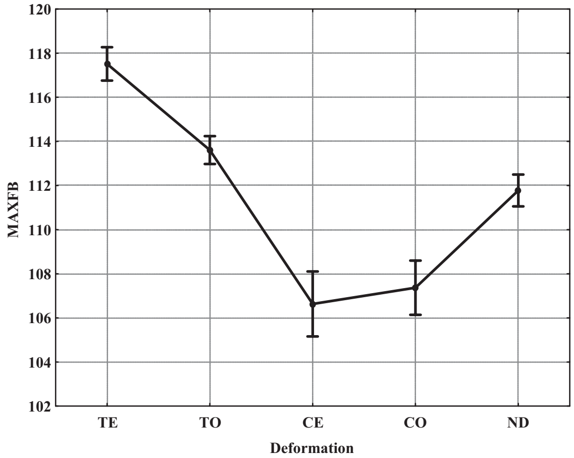


Figure 6. Effect of artificial deformation on the MAXFB. Vertical bars indicate a 95% interval for the mean value. Deformation code: TE, tabular erect; TO, tabular oblique; CE, circular erect; CO, circular oblique; ND, no deformation.

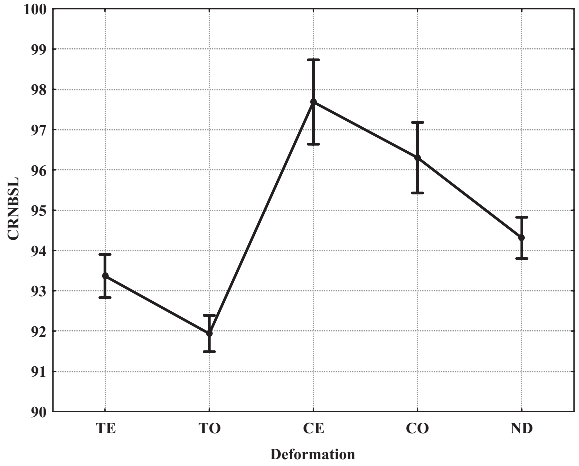


Figure 7. Effect of artificial deformation on the CRNBSL. Vertical bars indicate a 95% interval for the mean value. Deformation code: TE, tabular erect; TO, tabular oblique; CE, circular erect; CO, circular oblique; ND, no deformation.

interpret. It was also considered unnecessary to distinguish between intentional and non-intentional deformation, because the latter is also considered as a cultural effect.

The analysis of the artificial deformation from the biometric point of view offers interesting aspects so that the expected normal shape can be associated with the different models under practice in order to obtain the desired final product according to cultural conditions. The obtained results confirm the definitions shown above and provide greater details on general and specific effects of the changes produced as a consequence of the alteration of the normal growth and development, considered as a dynamic modelling process starting in childhood. It is evident that the main changes involve the dimensions of the cranial vault (length, breadth and height), as well as those of the frontal and occipital bones and cranial base. The secondary effects are produced in the facial bone structure, nasal, orbits and dimensions of the foramen magnum. The test results shown in Table 3 contribute to the explanation of the regional effects with regards to the non-deformation model and specifically for the modifications seen in each type.

The TE and TO deformation types share the restricted cranial length which is more pronounced in TE, the expansion of the MAXCB and the maximum cranial height, although the mean value of the TO is similar to the normal. In both there is a flattening of the front which is higher in TE and a reduction of the length of the cranial base which is more pronounced in TO. The effect of the antero-posterior compression in both types also produced the greatest development of the UPFB, BIZYGB and of the ORH whereas higher values were obtained in TO. The ORB values approximate the normal values, except in CE where a greater development is observed. The dimensions of the foramen magnum are lesser in TO and greater in the circular types.

In all the deformation types there is also an expansion of the BIORB with common modifications among the tabular and circular types, for example: greater NZH in tabular types and CE, the UPFH with most notable values in TO and CE, a decrease of the MINFB in TO and circular types.

The deformed CO crania, different from the erect ones, show a considerable expansion of the MAXCL. In both models, the MAXCB is also reduced and there is a considerable development of the height, whereas most notable mean values are obtained in CE. These changes are associated with the decrease of the MAXFB whereas the elongation of the basion-prosthion length and CRNBSL is more evident in CE. Also minor changes are produced in the MINFB, UPFH and BIZYGB, with values below normal and greater development of the height of the face and the nose. The dimensions of the foramen magnum are most notable in the circular types. The NZBR reaches mean values that are significantly lesser in CE.

Generally spoken, similar facts are demonstrated by data obtained from Anton (1989) and Cheverud *et al.* (1992), although there is a higher resolution in the design shown here. For example in the first case (Anton, 1989), the comparison of the radiographic profiles of the fronto-occipital (TO?), circular and ND groups, in materials from Peru, provides evidence of angular changes in correlation with the effect of the deformation device and the expected distribution of forces, which is associated with modifications at the level of the nose, upper face, orbits, biorbital and bimaxillary breadth, minimum and MAXFBs, breadth of the cranial base and dimensions of the foramen magnum. Although this experiment was observed by Cheverud *et al.* (1992) hinting at the geographic extension of the sample, their results are quite acceptable and consistent with those obtained in this study. In the second case (Cheverud *et al.*, 1992), the study is exclusively aimed at the comparison of anterior–posterior deformed and normal individuals using materials from the cemetery of Ancón (Perú) and a sample of Songish (British Columbia) with the same cradle board deformation type. The main conclusion indicates that the fronto-occipital deformation of the cranial vault is produced by the shortening and widening of the cranial base and facial portion (Cheverud *et al.*, 1992). A more complete view is provided by Kohn *et al.* (1993) through a three-dimensional analysis of the changes produced by the circular deformation, involving restrictions of the growth in the media-lateral and superior–inferior growth as well as the antero-posterior increase of the cranial vault and base, whereas the facial region is longer and narrower than the normal.

An important consequence of the studies performed, in order to demonstrate the effects of the artificial deformation of the cranium, is their influence on the calculation of the morphological distances used to establish biological relationships among populations. Unfortunately, magical solutions to solve this relevant problem do not exist. Meanwhile this effect should be considered jointly with sexual dimorphism and variation of age, as sources affecting the objective estimation of the statistics (mean values, variances and covariances) with reference to a specific locality, region or period. This is also valid both for metric variables and non-metric features. An evaluation of this problem and a solution for the D^2 value calculation of Mahalanobis was presented by Varela *et al.* (1993). The proposed solution is based on a numerical technique to obtain the data free from one or more variation factors, whereas every original observation is transformed by subtracting the corresponding difference from the factor that is to be eliminated. The obtained results were acceptable and allowed the improvement of the evaluation of the different effects in reduced samples (e.g. Cocilovo *et al.*, 1995; Varela *et al.*, 1995), as well as a more reliable estimation of the biological distances (Cocilovo *et al.*, 1999; Varela & Cocilovo, 2000, 2002).

In the end, a critical evaluation on the analysis of the artificial deformation and its effects during the morphogenesis of the adult cranium is presented here. Without any doubt, the diagnosis based on a majority of cranial features is the key for an objective analysis, which is also valid for the study of the sexual dimorphism and age variation. The differences between the categories are not exact, as there are overlapping zones between one and the other, making it difficult to come to a conclusion. Although the decisions realised in the used collections strictly follow Dembo & Imbelloni's model (1938), assignment errors cannot be excluded, nor any type of omission or variant for certain locations or subareas. Although the present work, by the extension of the sample, partly offsets the lack of knowledge on this subject in the South Central Andes, a new project would strengthen or modify the results of this experience.

Conclusions

Cranial dimensions are changed, altered and modified during early childhood, if the infant is subjected to the agency of externally applied forces to the head. This paper has explored the cultural restrictions imposed on the normal growth and development of the skull, through artificial deformation. Furthermore, it demonstrates quite clearly the compensatory effects of cranial morphogenesis. The conclusions below, confirm just how much and where on the cranium any changes are most apparent.

In TE deformation antero-posterior compression is applied on the frontal and occipital bones at lambda, with the following consequences: expansion of the breadth and height of the cranial vault, frontal flattening, decrease of the CRNBSL and facial pyramid, narrowing of the face, greater nasal and orbital heights and an increase in the dimensions of the foramen magnum, yet no change in facial height, nasal and orbital breadths.

In TO deformation compression between the frontal and the iniac region of the occipital produces the following: expansion of the breadth and decrease of the CRNBSL with normal height values, frontal flattening, decrease of the antero-posterior growth of the face and expansion of its height and breadth, stretching of the orbits and nasal aperture without any changes to their respective breadths, and a significant decrease of the foramen magnum dimensions.

Deformation in the CE style produces a decrease in cranial breadth, a significant expansion of vault height, a decrease in the frontal breadth and longitudinal expansion of the cranial base, despite a normal range for maximum length. The face is stretched with regards to height with no changes in width, however nasal width dimensions are increased while its height remains unchanged, and finally an expansion of the foramen magnum dimensions.

Deformation in the CO style produces a decrease of cranial breadth, greater height and the maximum expansion of the cranial length, an important stretching of the cranial and visceral base, decrease in breadth of the frontal, biorbital and malar dimensions, elongation of the face with a normal development of the breadth, nasal and orbit dimensions, with an increase of the foramen magnum dimensions.

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