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MULTIPLE CORRELATIONS BETWEEN CRANIOMETRIC CHARACTERISTICS IN EARLY CHILDHOOD: AN X-RAY STUDY

ABSTRACT: The method of multiple correlations was used to assess the interrelations between the main cephalometric characteristics of the face and the cranial base in 57 normal children ranging in age from 4 to 6 years. The results showed the extent to which the variability of the characteristics studied was determined by the variability of a combination of other facial parameters. Comparison with the results of an identical analysis performed on adult males showed that the results obtained with most models were in good agreement. Yet in adults we failed to determine a combination of characteristics which would prove useful for estimating the length of the anterior and posterior parts of the cranial base. The fact that this estimation was possible in children suggests a closer correlation between the size of the cranial base and certain facial parameters during childhood. Certain of the interrelations recorded were causal in character, and thus elucidated the cause of the given condition. Interrelations which could be used for anthropological reconstructions were expressed in terms of multiple linear regression equations, which allowed estimation of the parameter investigated apart from the other cranial characteristics. The definition of general and specific principles of intracranial relations and compensatory and adaptive processes operating within the skull would provide an opportunity to apply the results obtained to the reconstruction of missing parts of the skeletal remains of our human ancestors as well.

KEY WORDS: Multiple correlations – X-ray cephalometry – Intracranial relations – Children

INTRODUCTION

In an earlier report, investigations into the relations between various cranial components in adult males were discussed (Šmahel, Škvařilová 1988a). The results obtained confirmed a varying degree of interrelation between the craniofacial characteristics of shape, size and position, and enabled a description of the main adaptive and compensatory mechanisms operating within the skull. However, the simple correlations were mostly not close enough to allow an estimate of the size of a given characteristic on the basis of a single parameter alone. Therefore, in another paper (Šmahel, Škvařilová 1988b) were assessed multiple correlations in which an adequate combination of characteristics representing independent variables provided the possibility of determining the characteristics investigated with a degree of accuracy such as could prove useful in making predictions. We succeeded in establishing a series of useful combinations which could be applied, e.g., in anthropological reconstructions or in explaining facial developmental interrelations. The aim of the present paper was to describe multiple correlations of the same characteristics in early childhood, determine the degree of intracranial relations, discover models which would prove useful in anthropological reconstructions, and compare the results obtained with the findings recorded in adults. As in our previous study, the present report is based on anthropometrical assessment of cranial X-ray films.

MATERIAL AND METHODS

For calculations of multiple correlations, cephalometric data determined on X-ray films of 57 normal children (27 boys and 30 girls) from Prague, ranging in age from 4 to 6 years, were used. All the children were native Czechs, and their mean age was 5 years and one month. Children of both sexes were pooled, as analysis of this series showed identical intracranial relations and consistent correlation coefficients in both sexes. The subjects were selected at random from kindergartens in Prague. The series included exclusively individuals with clinically acceptable occlusion, without previous orthodontic therapy or signs of facial disharmony. All of them still had deciduous incisors.

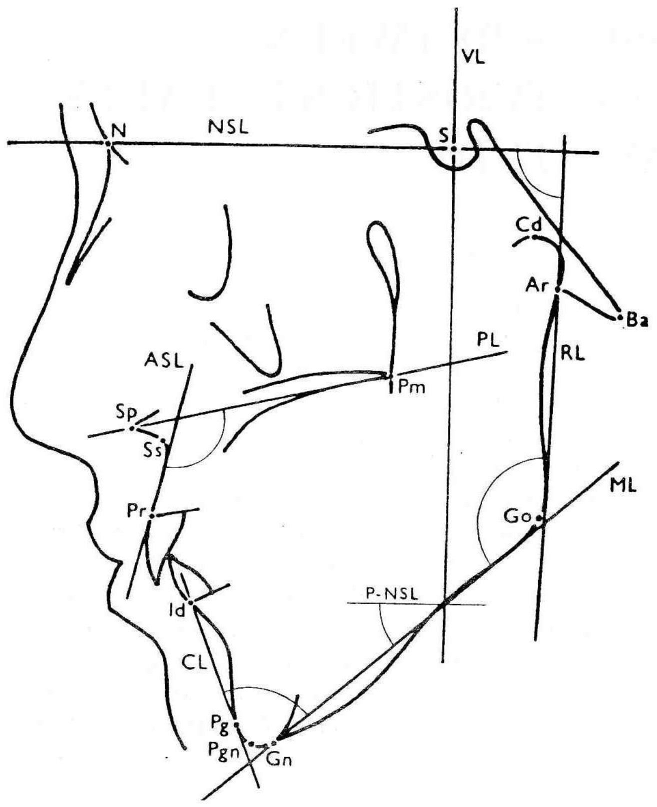

FIGURE 1. Craniometric points and reference lines used in the study: Ar – articulare = intersection of inferior contour of the cranial base and posterior contour of the ramus mandibulae, Ba – basion = most posteroinferior point on the clivus, Cd – condylion = most superior point on the condylar head, Gn – gnathion = lowest point on the mandibular symphysis, Go – gonion = point on the angle of the mandible determined by the axis of ML/RL angle, Id – infradentale = point of the gingival contact with lower central incisor, N – nasion = most anterior point on the frontonasal suture, Pg – pogonion = most anterior point on the bony chin, Pgn – prognathion = point on the mandibular symphysis farthest from Cd, Pm – pterygomaxillare = intersection of palate line PL with the fissura pterygomaxillaris, Pr – prosthion = point of gingival contact with upper central incisor, S – sella = center of sella turcica, Sp – spinale = tip of the anterior nasal spine, Ss – subspinale = deepest point of the subspinal concavity, NSL = line through N and S, VL = perpendicular to NSL through S, PL = line through anterior and posterior nasal spine, ML = tangent to the mandibular body through Gn, RL = tangent to the mandibular ramus through Ar, CL = line through Id and Pg, ASL = tangent to the maxillary alveolar process through Pr, P–NSL = line parallel to NSL. The angles measured between reference lines are marked by semicircles.

The X-ray films were made under standard conditions (focus-object distance 370 cm, object-film distance 30 cm, magnification 8.1%), with centric occlusion and with the head fixed by a cephalostat. The craniometric points and reference lines determined are given in *Figure 1*. In the case of double contours, the midpoint between both sides (lines) was marked. The perpendicular distance of the point from the reference line was marked as, e.g., Pm-NSL, and the angle either as N-S-Ba or as a fragment of the two reference lines forming a given angle (ML/RL). The accuracy of measurements was tested in the previous study, and was within acceptable limits (Šmahel, Škvařilová 1988a). The variance of error determined on the basis of two repeated measurements was mostly below 5 percent of the total variance of a given characteristic, and in no parameter exceeded 10 percent of the total variance.

Multiple correlation coefficients were calculated for the same craniometric characteristics as used in our previous study on adult males (Šmahel, Škvařilová 1988b), representing dependent variables (y). Independent variables (x_1) were used equally in the same combinations as in adult males. This allowed a comparison of the findings obtained in early childhood with those recorded in adults (*Table 1*). Further combinations of independent variables (*Table 2*), which determined the dependent variables with the highest possible accuracy, were also selected from the correlation matrix of 26 craniofacial parameters (Škvařilová *et al.*, 1997). Our strategy was to select parameters demonstrating the highest correlation to a dependent variable and the lowest mutual correlation. This procedure actually substitutes for the factor analysis, which may also serve in determining suitable predictive models. However, it is pointless to use dimensions which form part of a larger dimension, and are thus highly interrelated. Therefore, correlations were, as a rule, not evaluated in combined dimensions (e.g. total facial height), but rather were determined in individual segments of these dimensions (upper face height N-Sp and height of the upper alveolar process Pr-PL and the mandibular body Id-Gn).

For purposes of calculation, combinations of two or three independent variables were used. In general, a model is more useful when it yields higher values of multiple correlations and, as far as possible, lower numbers of independent variables. The multiple correlation coefficients were supplemented by calculations of regression coefficients for the relation $y = a + b_1x_1 + b_2x_2 + b_3x_3$ (x_1, x_2 and x_3 = independent variables; a = intercept; b_1, b_2 and b_3 = regression coefficients). They allow calculation of the investigated parameter (dependent variable) on the basis of measurements of values of other characteristics (independent variables), provided that a linear function is adequate. This prerequisite is mostly present in skeletal anthropometric characteristics, and was confirmed in our series of adult males (Šmahel, Škvařilová 1988b). Because of space limitations, we mention regression coefficients only in models which are suitable for anthropological reconstructions.

Correlation coefficients fail to show the causality of interrelations which cannot be determined by any other statistical methods. The distinction of dependent and independent variables belongs only within the scope of statistical analysis, and is by no means related to biological causality. The latter can be established only on the basis of logical considerations verified empirically by analysis of various craniographic patterns. On the basis of previous studies (Šmahel, Škvařilová 1988a,b), certain types of causalities were determined. Certain multiple correlations can show a predominantly uni-directional relationship, where a dependent variable is represented by a characteristic whose variability is actually determined by the variability of independent variables, without any clearly apparent reverse action. For example, the protrusion of the upper jaw (S-N-Ss) was definitely determined by its length (Ss-Pm) and by the flexion of the cranial base (N-S-Ba). As in our previous study on adults (Šmahel, Škvařilová 1988b), the interrelations which are considered as causal for the first two independent variables (x_1 and x_2) are marked in the tables.

RESULTS

In *Table 1* are presented the same combinations of characteristics for the calculation of multiple correlation coefficients as in the previous study on adult males (Šmahel,

TABLE 1. Single (r_{y1}) and multiple (r_{y12}, r_{y123}) correlation coefficients between dependent variable (y) and independent variables (x_1, x_2, x_3).

y	x_1	r_{y1}		x_2	r_{y12}	Ar_{y12}		x_3	r_{y123}	Ar_{y123}
N-S	: Cd-Go =	0.553	+	N-S-Pm =	0.580	(0.487)	+	Cd-NSL =	0.581?	(0.561)
S-Ba	: Pm-NSL =	0.707	+	Cd-NSL =	0.709?	(0.565)!	+	S-Go =	0.720?	(0.584)!
N-Sp	: Pgn-Go =	0.453	+	N-S-Cd =	0.479	(0.650)!	+	Id-Gn =	0.483?	(0.714)!
Pm-NSL	: mand =	0.766	+	N-S-Ba =	0.766?	(0.703)	+	S-Ba =	0.837	(0.740)
Pm-NSL	: S-Go =	0.685	+	N-S-Ba =	0.687?	(0.694)	+	S-Ba =	0.785	(0.717)
Pm-NSL	: Id-Gn =	0.330	+	N-S-Ba =	0.340?	(0.653)!	+	S-Ba =	0.725	(0.711)
Ss-Pm	: N-S =	0.537	+	S-N-Ss =	0.668	(0.618)	+	N-Sp =	0.683?	(0.678)
Pr-PL	: ASL/PL =	−0.446	+	Id-Gn =	0.602	(0.660)	+	ML/NSL =	0.643	(0.683)
S-Go	: Pm-NSL =	0.685	+	Ss-Pm =	0.735	(0.688)	+	Cd-Go =	0.897	(0.819)
S-Go	: Pm-NSL =	0.685	+	Cd-NSL =	0.798	(0.696)	+	Ss-Pm =	0.816	(0.764)
S-Go	: Id-Gn =	0.309	+	S-N-Pg =	0.380	(0.722)!	+	Ss-Pm =	0.555	(0.769)!
Cd-Go	: Pgn-Go =	0.492	+	Ss-Pm =	0.588	(0.552)	+	N-S =	0.655	(0.583)
Cd-Go	: S-Go =	0.876	+	N-S =	0.889?	(0.798)	+	N-Sp =	0.889?	(0.813)
Cd-Go	: Pm-NSL =	0.627	+	ML/RL =	0.694	(0.635)	+	N-S =	0.779	(0.714)
Pgn-Go	: Cd-Go =	0.492	+	N-Sp =	0.551	(0.571)	+	Pm-NSL =	0.697	(0.615)
Pgn-Go	: Pm-NSL =	0 692	+	ML/RL =	0.761	(0.643)	+	N-S =	0.768?	(0.674)
Pgn-Go	: ML/RL =	−0.478	+	N-Sp =	0.610	(0.590)	+	Pm-NSL =	0.761	(0.713)
Id-Gn	: Pr-PL =	0.442	+	N-Sp =	0.446?	(0.704)!	+	Pm-NSL =	0.482	(0.735)!
Cd-NSL	: S-N-Ss =	0.434	+	S-Ba =	0.541	(0.618)	+	N-S-Ba =	0.560	(0.641)
Cd-NSL	: S-N-Ss =	0.434	+	N-Sp =	0.539	(0.616)	+	S-Ba =	0.576	(0.702)!
N-S-Ba	: Cd-NSL =	−0.404	+	Pm-NSL =	0.410?	(0.640)!	+	S-N-Ss =	0.609	(0.655)
N-S-Ba	: N-S-Cd =	0.616	+	Pm-NSL =	0.617?	(0·719)	+	S-Ba =	0.638	(0.725)
N-S-Cd	: N-S-Ba =	0.616	+	N-Sp =	0.617?	(0.700)	+	Pm-NSL =	0.619?	(0.727)
N-S-Cd	: S-N-Ss =	−0.624	+	N-Sp =	0.650	(0.704)	+	Pm-NSL =	0.658?	(0.750)
N-S-Cd	: 5-N-Pg =	−0.566	+	N-Sp =	0.574?	(0.680)	+	Pm-NSL =	0.579?	(0.731)!
N-S-Pm	: N-S-Ba =	0.542	+	N-Sp =	0.595	(0.545)	+	RL/NSL =	0.683	(0.640)
S-N-Ss[1]	: N-S-Ba =	−0.583	+	Ss-Pm =	0.629	(0.694)	+	RL/NSL =	0.638?	(0.755)!
S-N-Ss	: S-N-Pg =	0.815	+	Ss-Pm =	0.816?	(0.825)	+	N-S-Ba =	0.835	(0.844)
S-N-Pg[1]	: S-N-Ss =	0.815	+	RL/NSL =	0.831	(0.820)	+	mand =	0.909	(0.875)
S-N-Pg[1]	: ML/NSL =	−0.601	+	RL/NSL =	0.618	(0.805)!	+	N-S-Cd =	0.777	(0.851)
S-N-Pg[1]	: ML/NSL =	−0.601	+	N-S-Cd =	0.765	(0.790)	+	mand =	0.777?	(0.845)
RL/NSL[1]	: N-S-Pm =	0.377	+	Cd-NSL =	0.386?	(0.588)	+	N-Gn =	0.565	(0.622)
RL/NSL	: ML/RL =	−0.558	+	S-N-Pg =	0.721	(0.821)	+	N-S-Pm =	0.753	(0.840)
RL/NSL	: N-S-Pm =	0377	+	S-N-Pg =	0.388?	(0.662)!	+	Cd-NSL =	0.393?	(0.676)!
ML/NS L[1]	: N-Gn =	0.502	+	Cd-Go =	0.882	(0.873)	+	ML/RL =	0.925	(0.904)
ML/NSL	: S-N-Pg =	−0.601	+	N-Gn =	0.685	(0.839)	+	ML/RL =	0.860	(0.952)
ML/NSL	: ML/RL =	0.658	+	S-N-Ss =	0.702	(0.838)	+	N-Gn =	0.813	(0.910)
ML/RL[1]	: Cd-Go =	−0.445	+	Sp-Pg =	0.579	(0.668)	+	RL/NSL =	0.848	(0.821)
ML/RL	: ML/NSL =	0.658	+	RL/NSL =	0.995	(0.995)				
ML/RL	: Sp-Pg =	0.282	+	CL/ML =	0.346	(0.695)!	+	Cd-Go =	0.591	(0.763)!
CL/ML[1]	: Ss-N-Pg =	0.266	+	ML/RL =	0.360	(0.692)!				

Ar_{y12} – multiple correlation coefficients for adults (Šmahel, Škvařilová 1988b)
1 – causal relation between dependent variable and the first two independent variables
0.766 – correlation coefficients of models which are suitable for reconstructions (underlined)
! – substantial differences between multiple correlation coefficients in adults and children
mand – Pgn-Go+Cd-Go
? – insignificant increase of correlation coefficient after the addition of the second (x_2) or third (x_3) independent variable

TABLE 2. Single (r_{y1}) and multiple (r_{y12}, r_{y123}) correlation coefficients between dependent variable (y) and independent variables (x_1, x_2, x_3).

y	x_1	r_{y1}	x_2	r_{y12}	x_3	r_{y123}
N-S	: Ss-Pm =	0.537 +	S-N-Ss =	0.729 +	Cd-Go =	0.787
N-S	: Cd-Go =	0.553 +	Ss-Pm =	0.636 +	N-Sp =	0.673
N-S	: Ss-Pm =	0.537 +	N-Sp =	0.635 +	S-Ba =	0.644?
S-Ba	: Pm-NSL =	0.707 +	N-S =	0.721? +	Cd-Go =	0.729?
N-Sp	: Pm-NSL =	0.643 +	S-N-Ss =	0.786 +	N-S =	0.789?
N-Sp	: Pm-NSL =	0.643 +	S-N-Ss =	0.786 +	N-S-Pm =	0.787?
N-Sp	: Pm-NSL =	0.643 +	N-S-Pm =	0.683 +	N-S =	0.768
Pm-NSL	: mand =	0.766 +	S-Ba =	0.836 +	N-Sp =	0,862
Pm-NSL	: mand =	0.766 +	S-Ba =	0.836 +	Cd-NSL =	0.840?
Pm-NSL	: S-Ba =	0.707 +	Cd-NSL =	0.722? +	N-S =	0.728?
Ss-Pm	: N-S =	0.537 +	Cd-NSL =	0.607 +	mand =	0.626
Pr-PL	: Id-Gn =	0.442 +	ASL/PL =	0.602 +	Pm-NSL =	0.633
Pr-PL	: Id-Gn =	0.442 +	ML/NSL =	0.554 +	Pm-NSL =	0.622
S-Go	: Cd-NSL =	0.622 +	S-Ba =	0.749 +	Ss-Pm =	0.777
S-Go	: Cd-NSL =	0.622 +	S-Ba =	0.749 +	N-Sp =	0.807
S-Go	: N-Sp =	0.514 +	Ss-Pm =	0.634 +	Pgn-Go =	0.689
Cd-Go	: Pm-NSL =	0.627 +	N-S =	0.719 +	ML/NSL =	0.798
Cd-Go	: S-Ba =	0.569 +	ML/RL =	0.706 +	N-S =	0.779
Cd-Go	: S-Ba =	0.569 +	N-S =	0.675 +	ML/NSL =	0.746
Cd-Go	: N-S =	0.553 +	Pgn-Go =	0.638 +	ML/NSL =	0.688
Cd-Go	: N-S =	0.553 +	Pgn-Go =	0.638 +	ML/RL =	0.695
Pgn-Go	: Pm-NSL =	0.692 +	ML/RL =	0.761 +	S-N-Pg =	0.803
Pgn-Go	: Pm-NSL =	0.692 +	S-N-Pg =	0.766 +	N-S =	0.788
Pgn-Go	: S-Ba =	0.417 +	S-N-Pg =	0.574 +	N-Sp =	0.762
Pgn-Go	: Pm-NSL =	0.692 +	S-N-Pg =	0.766 +	N-Sp =	0.805
Pgn-Go	: Cd-Go =	0.492 +	RL/NSL =	0.587 +	S-Ba =	0.620
Id-Gn	: Pr-PL =	0.442 +	Ss-Pm =	0.499 +	Cd-NSL =	0.546
Cd-NSL	: Id-Gn =	0.413 +	N-S-Ba =	0.572 +	Ss-Pm =	0.654
Cd-NSL	: Id-Gn =	0.413 +	N-S-Ba =	0.572 +	S-Ba =	0.594
N-S-Ba	: N-S-Cd =	0.616 +	S-N-Ss =	0.666 +	N-S-Pm =	0.687
N-S-Ba	: N-S-Cd =	0.616 +	ML/NSL =	0.655 +	S-N-Ss =	0.684
N-S-Cd	: S-N-Ss =	–0.624 +	N-S-Pm =	0.696 +	Cd-NSL =	0.800
N-S-Cd	: S-N-Ss =	–0.624 +	N-S-Ba =	0.697 +	S-N-Pm =	0.697?
N-S-Cd	: N-S-Ba =	0.616 +	Cd-NSL =	0.735 +	S-N-Pg =	0.762
N-S Pm	: N-S-Ba =	0.542 +	S-N-Ss =	0.598 +	N-Sp =	0.644
N-S-Pm	: N-S-Ba =	0.542 +	N-Sp =	0.627 +	ML/NSL =	0.678
N-S-Pm	: N-S-Ba =	0.542 +	ML/NSL =	0.625 +	RL/NSL =	0.689
N-S-Pm	: S-N-Ss =	–0.522 +	ML/NSL =	0.608 +	RL/NSL =	0.654
S -N-Ss	: S-N-Pg =	0.815 +	N-S-Ba =	0.831 +	N-S =	0.878
S-N-Ss	: S-N-Pg =	0.815 +	N-S =	0.867 +	N-S-Cd =	0.898
S-N-Ss	: S-N-Pg =	0.815 +	N-S =	0.867 +	Cd-NSL =	0.891
S-N-Pg[1]	: S-N-Ss =	0.815 +	ML/NSL =	0.887 +	Pgn-Go =	0.917
S-N-Pg[1]	: S-N-Ss =	0.815 +	N-S-Pm =	0.830 +	ASL/PL =	0.857
S-N-Pg[1]	: S-N-Ss =	0.815 +	ASL/PL =	0.855 +	N-S-Ba =	0.859?
S-N-Pg[1]	: S-N-Ss =	0.815 +	ASL/PL =	0.855 +	ML/NSL =	0.907
RL/NSL	: ML/RL =	–0.558 +	N-S-Pm =	0.707 +	N-Sp =	0.744
RL/NSL	: ML/RL =	–0.558 +	N-Sp =	0.688 +	ASL/PL =	0.714
RL/NSL	: ML/RL =	–0.558 +	N-Gn =	0.752 +	N-S-Pm =	0.788
ML/NSL	: ML/RL =	0.658 +	S-N-Pg =	0.791 +	Cd-Go =	0.796?
ML/NSL	: S-N-Pg =	–0.601 +	N-Gn =	0.685 +	N-S-Pm =	0.688?
ML/NSL	: ML/RL =	0.658 +	S-N-Pg =	0.791 +	N-S-Pm =	0.814
ML/RL	: ML/NSL =	0.658 +	Pgn-Go =	0.738 +	Sp-Pg =	0.739?
ML/RL	: RL/NSL =	–0.558 +	Cd-Go =	0.677 +	N-S-Ba =	0.721

1 = causal relation between dependent variable and the first two independent variables

0.766 = correlation coefficients of models which are suitable for reconstructions (underlined)

mand = Pgn-Go + Cd-Go

? = insignificant increase of correlation coefficient after the addition of the second (x_2) or third (x_3) independent variable

Škvařilová 1988b). A coefficient for two independent variables ($r_{y1,2}$) illustrates the amount by which the initially simple correlation coefficient (r_{y1}) increases after addition of a second characteristic and, similarly, the coefficient for three independent variables ($r_{y1,2,3}$) illustrates a further increase after addition of a third characteristic. The values of the same coefficients in adult males ($A_{y1,2}$, $Ar_{y1,2,3}$) as recorded in our previous study (Šmahel, Škvařilová 1988b) are given in parentheses after these coefficients of multiple correlations.

The comparison of multiple coefficients in children and adults showed good agreement as to the degree of similarity of the great majority of the relations investigated. However, in about one quarter of the correlations there was only slight agreement and, but for one exception (S-Ba), the coefficients of multiple correlations were definitely lower in children than in adults (marked by!). This fact represented a logical result of the method used in choosing individual combinations of independent variables which were selected as most suitable in the series of adult males. The exception was represented by the postsellar length of the cranial base (S-Ba), where we failed to disclose any combination of independent variables in adults which would be highly correlated to the dependent variable. This was due to the high correlation coefficient for the posterior height of the upper face in children (Pm-NSL r = 0.707; in adults r = 0.497). The addition of further characteristics (independent variables x_2 and x_3) resulted only in a negligible increase of the value of this coefficient, and the use of multiple correlation failed to improve determination of this dependent variable.

The agreement of three quarters of the relations investigated in the values of multiple correlation coefficients between children and adults does not imply that all these models would prove useful in children. As with the length of the posterior cranial base S-Ba, in some cases the addition of further characteristics (independent variables) resulted only in a slight increase of the highest simple correlation coefficient (e.g., in N-S, N-Sp, Id-Gn and in some combinations of characteristics determining other dependent variables). This was again due to the fact that these models were devised on the basis of the matrix of correlations in adult age. However, agreement between most multiple correlation coefficients in children and in adults confirmed that the appropriate characteristics had been used as an independent variable. If the correlation of some of them with the dependent variable was closer during childhood than in adulthood, then addition of further characteristics resulted in a less marked increase of the multiple correlation coefficient (and vice versa). Therefore, the final result would be similar. All models presented in *Table 1* were described in the series of adult males (Šmahel, Škvařilová 1988b). Their implication follows from the given equations.

The models presented in *Table 2* were devised on the basis of the matrix of correlation coefficients obtained in children. They thus represent the most useful combinations of independent variables from the given matrix that made it possible to attain the highest degree of accuracy in the assessment of dependent variables. The first place in the equations (x_1) always represents the highest of the single coefficients between the dependent variable and the corresponding independent variables (r_{y1}). A prerequisite for prediction is represented by a correlation coefficient of at least 0.7, which defines 50 percent of the variability of a dependent variable. Under these conditions, estimation of the length of the anterior cranial base (N-S) was possible only with the use of a single combination of characteristics, i.e., maxillary depth (Ss-Pm) and its protrusion (S-N-Ss), possibly supplemented by the length of the mandibular ramus (Cd-Co). The drawback here consists in inclusion of the angle S-N-Ss, which shares a common structure (N-S) with the dependent variable. Thus it only illustrates the degree of interrelation, and cannot be applied in practice (e.g. for reconstructions). The other models, which are more suitable for use in practice, fail to attain the required values of correlation coefficients. The length of the posterior cranial base (S-Ba) is well defined by the posterior upper face height (Pm-NSL), yet we failed to discover any other characteristics which would improve the estimate. These findings are in agreement with the independent development of the cranial base.

The anterior height of the upper face (N-Sp) could be defined on the basis of the posterior upper face height (Pm-NSL), in combination with the degree of protrusion of the maxilla (S-N-Ss). Posterior upper face height (Pm-NSL) is sufficiently well-defined by the size of the mandible alone (mand) or by the length of the clivus (S-Ba), and especially by a combination of the two. The estimation of maxillary depth (Ss-Pm) and the height of the upper alveolar process (Pr-PL) was not possible with the available combination of characteristics. The posterior height of the total face (S-Go) is well defined by the vertical position of the temporomandibular joint (Cd-NSL) and by the length of the posterior cranial base (S-Ba). The interrelation is even closer after addition of the anterior height of the face (N-Sp). It is also possible to use a combination of the posterior height of the upper face (Pm-NSL) with maxillary depth (Ss-Pm) and the characteristic Cd-NSL *(Table 1)*. The inclusion of the length of the mandibular ramus (Cd-Go, *Table 1*) allows achievement of a high correlation. This is due to the fact that this parameter forms a substantial part of the investigated dimension, and therefore the model is not of great value.

In estimating the length of the mandibular ramus (Cd-Go), various combinations, including the presellar and postsellar length of the cranial base (N-S, S-Ba), the posterior upper face height (Pm-NSL), the gonial angle (ML/RL) and the slope and length of the mandibular body (ML/NSL, Pgn-Go), are suitable. The posterior upper face height (Pm-NSL), the gonial angle (ML/RL) and the length of the clivus (S-Ba), as well as the angle of mandibular protrusion (S-N-Pg) and the anterior height of the upper face (N-Sp), may be used in various combinations for the estimation of the length of the mandibular body (Pgn-Go). We failed to devise a useful combination of characteristics for this purpose which would include the length of the mandibular ramus. We have likewise not discovered any useful combination of characteristics for estimation of the height of the mandibular body (Id-Gn) and the vertical position of the temporomandibular joint (Cd-NSL).

In accordance with the above-mentioned developmental independence of the cranial base, we failed to devise a combination of characteristics which would determine with sufficient accuracy the flexion of the cranial base (N-S-Ba), despite good correlation to the angle N-S-Cd ($r = 0.616$). This angle, i.e., the curvature of the cranial base in its lateral parts, could be determined by using the angles of maxillary (S-N-Ss) and mandibular (S-N-Pg) protrusion, the angle of the cranial base (N-S-Ba), the angle N-S-Pm and the vertical position of the temporomandibular joint (Cd-NSL). The most accurate combination of characteristics for determination of the anteroposterior position of the maxilla in relation to the cranial base (N-S-Pm), i.e., the angle of the cranial base (N-S-Ba) and the inclination of the mandibular body (ML/NSL) and ramus (RL/NSL), yields only values which are close to the coefficient 0.7.

Because of the high correlation between the angle of maxillary (S-N-Ss) and mandibular (S-N-Pg) protrusion ($r = 0.815$; in adults $r = 0.780$), each of these two characteristics can be readily determined with the help of the other. The addition of other independent variables provides the possibility of attaining correlation coefficients even of about 0.9 (*Table 1 and 2*). Most models can be used for reconstructions, and models which estimate the protrusion of the lower jaw (S-N-Pg) illustrate a causal relationship. This is particularly evident in the highest correlation (0.917), where the length (Pgn-Go) and slope (ML/NSL) of the mandibular body and the protrusion of the upper jaw (S-N-Ss) definitely determine the protrusion of the mandible. However, we failed to devise a combination of characteristics for estimation of the protrusion of the upper jaw which was not based on the angle of mandibular protrusion. For assessment of the mandibular protrusion, combinations which did not include maxillary protrusion *(Table 1)* but were based on characteristics of the mandibular body (ML/NSL, mand.), and thus shared a common structure with the estimated angle S-N-Pg, were devised.

The inclination of the mandibular ramus within the skull (RL/NSL) could be assessed solely with the help of the gonial angle (ML/RL), combined with some other parameters (N-S-Pm, N-Sp, N-Gn, ASL/PL and S-N-Pg in *Table 1*). For assessment of the slope of the mandibular body (ML/NSL) the gonial angle (in combination with S-N-Pg, N-S-Pm and as illustrated in *Table 1* with S-N-Ss and N-Gn) was likewise useful, but it proved sufficient to use the anterior height of the face (N-Gn) in combination with the length of the mandibular ramus (Cd-Go, *Table 1*). This relationship was causal. For determination of the gonial angle (ML/RL), the inclination and length of the mandibular body (ML/NSL, Pgn-Go) and ramus (RL/NSL, Cd-Go), the height of the lower face (Sp-Pg) and the angle of the cranial base (N-S-Ba) could be used. The highest correlation was yielded by a combination of the characteristics Sp-Pg, Cd-Go, (causal relationship) and RL/NSL *(Table 1)*. The mandibular angle was precisely defined by the inclination of the mandibular body and ramus (ML/NSL and RL/NSL, *Table 1*). The correlation coefficient of 0.995, recorded both in children and in adults, confirmed the height accuracy of the measurements (a measurement error accounted for the remaining 1% of variability of the given characteristics). We failed to find a combination of variables which could be used for assessment of the chin angle (CL/ML, *Table 1*).

DISCUSSION

The results showed the degree to which the variability of the dependent variable was determined by the variability of a combination of other facial characteristics. This degree is expressed in terms of a percentage by the square of the pertinent correlation coefficients (the coefficient of determination). Coefficients below 0.7 have a low predictive reliability, as they explain less than 50 percent of the total variability of an estimated characteristic. A reliable estimation is given by coefficients above 0.8, which account for two-thirds of the total variability, as was verified in daily orthodontic practice during the assessment of jaw development (Horowitz, Hixon 1966). These prerequisites were fulfilled in numerous applied combinations, including correlation coefficients with two independent variables. Since limited numbers of characteristics of the correlation matrix were used for selecting individual combinations, it was probable that these did not include some parameters which could also prove useful. Inclusion of these parameters could increase the determination rate of a dependent variable. This could also be attained by a combination of a larger number of independent variables, though the inclusion of any further variable usually increases the total coefficient of multiple correlation by gradually decreasing value. This is because of the high integration of cranial structures. Because of this, numerous craniofacial correlations include a larger or smaller share of variance produced by shared common components or mediated by some other structures. Therefore, independent variables in the equations are mutually correlated, due to the effect of topographic correlations. However, a combination of large numbers of independent variables is not useful in practice, especially in reconstruction of the missing parts of skeletal remains, where numerous parameters are not available. More useful is the use of a larger number of combinations of a smaller number of characteristics, which can allow use of a method chosen according to a given situation. It was also shown (Šmahel, Škvařilová 1988a) that, for practical purposes, the distinction between topographic and non-topographic correlations is not important, since it is not precise, and because the correlations reflect the actual situation within the skull.

TABLE 3. Regression coefficients (b_1, b_2, b_3) and intercept (a) for the estimation of dependent variable in models suitable for reconstructions.

y	x_1	b_1	x_2	b_2	x_3	b_3	a
S-Ba	: Pm-NSL	0.8009	–	–	–	–	7.791
Pm-NSL	: mand	0.3135	–	–	–	–	4.416
Pm-NSL	: mand	0.2207	N-S-Ba	0.0042	S-Ba	0.3555	0.122
Pm-NSL	: S-Go	0.4184	–	–	–	–	11.078
Pm-NSL	: S-Go	0.2583	N-S-Ba	0.0198	S-Ba	0.4078	2.980
Pm-NSL	: Id-Gn	0.2006	N-S-Ba	–0.0133	S-Ba	0.5825	11.348
S-Go	: Pm-NSL	1.1218	–	–	–	–	20.090
S-Go	: Pm-NSL	0.9511	Ss-Pm	0.5911	–	–	0.719
S-Go	: Pm-NSL	0.8736	Cd-NSL	0.8920	–	–	15.181
S-Go	: Pm-NSL	0.7913	Cd-NSL	0.7944	Ss-Pm	0.3789	3.298
Pgn-Go	: Cd-Go	0.1161	N-Sp	0.0026	Pm-NSL	0.9749	17.234
Pgn-Go	: Pm-NSL	1.0701	–	–	–	–	19.041
S-N-Ss	: S-N-Pg	0.8576	–	–	–	–	15.268
S-N-Pg	: S-N-Ss	0.7740	–	–	–	–	13.584
S-N-Pg	: S-N-Ss	0.7500	RL/NSL	–0.1324	–	–	26.687
ML/NSL	: S-N-Pg	–0.6983	N-Gn	0.3002	–	–	148.580
N-Sp	: Pm-NSL	0.7178	N-S-Pm	0.2304	–	–	0.130
N-Sp	: Pm-NSL	0.4886	N-S-Pm	0.3469	N-S	0.3916	–24.662
Pm-NSL	: mand	0.2204	S-Ba	0.3553	–	–	0.721
Pm-NSL	: mand	0.1766	S-Ba	0.3084	N-Sp	0.2010	–1.534
Pm-NSL	: S-Ba	0.6204	–	–	–	–	13.520
S-Go	: Cd-NSL	1.0099	S-Ba	0.6270	–	–	21.957
S-Go	: Cd-NSL	0.8787	S-Ba	0.5527	Ss-Pm	0.4614	6.788
S-Go	: Cd-NSL	1.0285	S-Ba	0.4097	N-Sp	0.4309	11.521
Cd-Go	: Pm-NSL	0.6284	N-S	0.3760	–	–	–2.540
Cd-Go	: Pm-NSL	0.6644	N-S	0.2996	ML/NSL	–0.2188	28.458
Cd-Go	: N-S	0.3994	Pgn-Go	0.2393	ML/NSL	–0.1641	25.615
Pgn-Go	: Pm-NSL	1.0024	S-N-Pg	0.3556	–	–	–5.342
Pgn-Go	: Pm-NSL	0.8824	S-N-Pg	0.3983	N-S	0.2444	–19.915
Pgn-Go	: Pm-NSL	0.6070	S-N-Pg	0.5236	N-Sp	0.4447	–22.378
Pgn-Go	: S-Ba	0.1484	S-N-Pg	0.6616	N-Sp	0.1321	–28.822
N-S-Cd	: S-N-Ss	–0.8864	N-S-Pm	0.8315	–	–	140.328
S-N-Ss	: S-N-Pg	0.7458	N-S-Ba	–0.1486	–	–	43.633
S-N-Ss	: S-N-Pg	0.7161	N-S-Ba	–0.1284	N-S	–0.3399	65.006
S-N-Ss	: S-N-Pg	0.8114	N-S	–0.3530	–	–	41.442
S-N-Ss	: S-N-Pg	0.6340	N-S	–0.3896	N-S-Cd	–0.1422	75.234
S-N-Ss	: S-N-Pg	0.7146	N-S	–0.4069	Cd-NSL	0.4296	45.470
S-N-Pg	: S-N-Ss	0.6830	N-S-Pm	–0.1985	–	–	34.581
S-N-Pg	: S-N-Ss	0.6555	N-S-Pm	–0.0801	ASL/PL	0.1615	14.117
S-N-Pg	: S-N-Ss	0.6835	ASL/PL	0.1790	–	–	4.770
RL/NSL	: ML/RL	–0.3728	N-Sp	0.5765	–	–	108.657
RL/NSL	: ML/RL	–0.3786	N-Sp	0.5257	ASL/PL	–0.1995	129.479
RL/NSL	: ML/RL	–0.4513	N-Gn	0.3846	–	–	105.628
ML/RL	: ML/NSL	0.6657	Pgn-Go	–0.5247	–	–	77.880
ML/RL	: RL/NSL	–0.6878	Cd-Go	–0.6859	N-S-Ba	0.2943	179.921

Upper part of the table refers to Table 1, lower part to Table 2 (the latter does not include models presented in the upper part of the table)

Models with insignificant increase of correlation coefficients after the addition of a further independent variable are not included

Statistical methods also proved useful for the definition of confidence intervals within which, with a given probability, the estimated dependent variable could lie, as was illustrated in our previous report (Šmahel, Škvařilová 1988b). For these calculations the following values were required: residual variance, intercept, regression coefficients, and mean values of independent variables. These data were not included in the present paper, since they characterized the Czech population.

As was documented in our previous study, the findings obtained could prove useful in orthodontic therapy or jaw orthopedics, as well as for anthropological reconstructions (Šmahel, Škvařilová 1988b). Correlation coefficients showed to what extent certain characteristics were determined by the combination of other parameters, how easily they could be modified, and which characteristics should be actively affected in the interest of an actual therapeutic benefit. Therefore, the results of these studies might contribute to predicting the outcome of the applied therapy, and the causal relations determined could explain the cause of the actual findings. However, the causality of interrelations is not important for reconstructions which require the availability of pertinent independent variables. For an orthodontist, it is the interrelations which exert their effects on the characteristics of the jaws and the extent of their saturation, even when it occurs from their own sources (from the components of the jaws per se), which are of interest. Conversely, an anthropologist is interested primarily in relations which could prove useful during reconstruction of the missing parts of the skull, and thus independent variables cannot be based on these missing parts. Combinations which fulfilled this requirement and attained a sufficiently accurate reliability of estimation are presented in *Table 3*.

Comparison of our findings with results obtained in adults (Šmahel, Škvařilová 1988b) disclosed that the usefulness of individual models was not necessarily identical in these two age groups. However, it was possible to devise combinations of independent variables for both age levels based on the same series of characteristics which would yield similar values of coefficients of multiple correlations. An exception was represented only by the length of the presellar and postsellar parts of the cranial base, where, contrary to the case in children, we failed to disclose in adults any combination of characteristics which could prove useful for estimation of their size. This could be due to the lower growth rate of the cranial base and the early termination of the growth of its anterior part, which resulted in reduction of the initially higher correlation of these dimensions with other facial variables.

In our previous analysis of single correlations (Šmahel, Škvařilová 1988a), a comparison with the data reported in the literature disclosed identical intracranial relations, as well as adaptive and compensatory mechanisms in various distinct ethnic populations. Certain adaptive mechanisms, in particular those induced by the development of the curvature of the cranial base, proceeded in similar ways as in monkeys (Björk 1955, Doskočil 1962). Thus, many relationships could be of a general character and occur in all primates. They could therefore be used in reconstructing human anccestors, in particular in association with the use of multiple correlations. A prerequisite here is, however, undertaking comparative studies on intracranial correlations in the actual human population, as well as in various primates and on skulls from prehistoric and paleoanthropological remains. These studies can make use of numerous collections of skulls from various prehistoric and historical periods. A variety of data on contemporary mankind are available in the orthodontic literature, which is mostly situated outside the sphere of interest of anthropologists.

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