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 a high degree of correlation to which the characteristics studied were determined by the variability of other facial parameters. Comparison with a number of identical analyses performed on adults 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, Švářilová 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, Švářilová 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.
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 were determined, with the exception of the upper jaw (N-S-Ns), which was determined by the black line of the cranial base (N-S-Ns). As in our previous study on adults (Šmahel, Škvářilová 1988b), the interrelations which are considered as causal for the first two independent variables (s₁ and s₂) 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, Škvářilová 1988b), representing dependent variables (y). Independent variables (x₁) 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 (x₂) were calculated, which determined the dependent variable with the highest possible accuracy, were also selected from the correlation matrix of 26 craniofacial parameters (Škvářilová et al., 1997). Our strategy was to select parameters determining 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. 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 the separate dimensions (upper face height N-Sp and height of the upper alveolar process Pr-PL and the mandibular body Ed-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 + b₁x₁ + b₂x₂ + b₃x₃, (x₁, x₂, x₃ = independent variables; a = intercept; b₁, b₂, and b₃ = regression coefficients). They allow calculation of the investigated parameter (dependent variable) on the basis of the 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 also in the interrelations of the lower series of craniofacial parameters (Šmahel, Škvářilová 1988b). Because of space limitations, we mention regression coefficients only in models which are suitable for anthropological reconstructions.

In conclusion, it is not possible to determine 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, in which it is only based on the probability of the causal 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, Škvářilová 1988b), certain types of causality were determined. Certain multiple correlations can show a predominantly uni-directional relationship, where a dependent variable is represented by a characteristic which is not actually determined by the variability of independent variables, without any clearly apparent reverse action. For example, the proportion of the upper jaw (N-S-Ns) was definitely determined by its length (S-Pn) and by the flexion of the cranial base (N-S-Ns). As in our previous study on adults (Šmahel, Škvářilová 1988b), the interrelations which are considered as causal for the first two independent variables (s₁ and s₂) are marked in the tables.

### Table 1: Multiple correlations between craniofacial characteristics in early childhood: an X-ray study

<table>
<thead>
<tr>
<th>x₁</th>
<th>x₂</th>
<th>x₃</th>
<th>y</th>
<th>rₓy</th>
<th>rₓ₁y</th>
<th>rₓ₂y</th>
<th>rₓ₃y</th>
<th>rₓ₁ₓ₂</th>
<th>rₓ₁ₓ₃</th>
<th>rₓ₂ₓ₃</th>
<th>rₓ₁ₓ₂ₓ₃</th>
<th>σₓ₁²</th>
<th>σₓ₂²</th>
<th>σₓ₃²</th>
<th>σₓ₁²σₓ₂²</th>
<th>σₓ₁²σₓ₃²</th>
<th>σₓ₂²σₓ₃²</th>
<th>σₓ₁²σₓ₂σₓ₃</th>
<th>σₓ₁σₓ₂σₓ₃²</th>
<th>σₓ₁³σₓ₂²σₓ₃²</th>
<th>σₓ₁²σₓ₂σₓ₃σₓ₄²</th>
<th>σₓ₁σₓ₂σₓ₃σₓ₄²σₓ₅²</th>
<th>σₓ₁σₓ₂σₓ₃σₓ₄σₓ₅σₓ₆²</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-S</td>
<td>Ca-Gn</td>
<td>N-S-Pn</td>
<td>y</td>
<td>rₓ₁y</td>
<td>rₓ₂y</td>
<td>rₓ₃y</td>
<td>rₓ₁ₓ₂</td>
<td>rₓ₁ₓ₃</td>
<td>rₓ₂ₓ₃</td>
<td>rₓ₁ₓ₂ₓ₃</td>
<td>rₓ₁σₓ₂σₓ₃²</td>
<td>σₓ₁²</td>
<td>σₓ₂²</td>
<td>σₓ₃²</td>
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</tr>
<tr>
<td>N-S-Ba</td>
<td>N-Pn-NSL</td>
<td>N-S-Br</td>
<td>y</td>
<td>rₓ₁y</td>
<td>rₓ₂y</td>
<td>rₓ₃y</td>
<td>rₓ₁ₓ₂</td>
<td>rₓ₁ₓ₃</td>
<td>rₓ₂ₓ₃</td>
<td>rₓ₁ₓ₂ₓ₃</td>
<td>rₓ₁σₓ₂σₓ₃²</td>
<td>σₓ₁²</td>
<td>σₓ₂²</td>
<td>σₓ₃²</td>
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<td>rₓ₂y</td>
<td>rₓ₃y</td>
<td>rₓ₁ₓ₂</td>
<td>rₓ₁ₓ₃</td>
<td>rₓ₂ₓ₃</td>
<td>rₓ₁ₓ₂ₓ₃</td>
<td>rₓ₁σₓ₂σₓ₃²</td>
<td>σₓ₁²</td>
<td>σₓ₂²</td>
<td>σₓ₃²</td>
<td>σₓ₁²σₓ₂²</td>
<td>σₓ₁²σₓ₃²</td>
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<td>σₓ₁σₓ₂σₓ₃σₓ₄σₓ₅σₓ₆²</td>
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</tbody>
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**m** - multiple correlation coefficients for adults (Šmahel, Škvářilová 1988b)  
**s** - causal relation between dependent variable and the first two independent variables  
**c** - correlation coefficients of models which are suitable for reconstructions (undetermined)  
**n** - substantial differences between multiple correlation coefficients in adults and children  
**mand** - insignificant increase of correlation coefficient after the addition of the second (s₂) or third (s₃) independent variable.
MULTIPLE CORRELATIONS BETWEEN CRANIOMETRIC CHARACTERISTICS IN EARLY CHILDHOOD: AN X-RAY STUDY

Sväkrivio (1988b). A coefficient for two independent variables \((t_{xy})\) illustrates the amount by which the initially simple correlation coefficient \((r_{xy})\) increases after addition of a second characteristic and, similarly, the coefficient for three independent variables \((t_{xyz})\) illustrates a further increase after addition of a third characteristic. The values of the same coefficients in adult males (A, 20-24 years) as recorded in our previous study (Sväkrivio, 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 in 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 postauricular 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 directly connected with the high correlation coefficient for the postauricular length of the upper face in children (Pn-Ns rl = 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 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 2 were described in the series of adult males (Sväkrivio, 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 \((x_i)\). 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 within the use of a single combination of characteristics, i.e., maxillary depth (S-Pn) and its protrusion (S-N-Ss), possibly supplemented by the posterior part of the cranial base (N-Sp) and the length of the maxillary sinus (ML-Rs). The drawback here consists in inclusion of the angle S-N-Ss, which shares a common structure (S-N-Ss) 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 (Pn-Ns), 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 horizontal axis of the maxilla (S-Pn) was defined on the basis of the posterior upper face height (Pn-Ns), in combination with the degree of protrusion of the maxilla (S-N-Ss). Posterior upper face height (Pn-Ns) is well defined by the maxillary depth (S-Pn) and its protrusion (S-N-Ss) and by the length of the maxilla (ML-Ns, ML-Rs). The estimation of position of the maxillary depth (S-Pn) and the height of the upper lip (S-N-Pg) is possible through the use of 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-Go) and by the length of the maxilla (S-N-Ss). 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 (Pn-Ns) with maxillary depth (S-Pn) and maxillary protrusion (Pn-Ns) (Cd-Go, 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 preauricular and postauricular length of the cranial base (N-S, S-Ba), the posterior upper face height (Pn-Ns), the gonial angle (ML-RL) and the slope and length of the mandibular body (ML-Ns, Pn-Ns), are suitable. The posterior upper face height (Pn-Ns), the gonial angle (ML-RL) and the length of the maxilla (S-Ba), as well as the angle of mandibular protrusion (S-N-Pg) and the anterior height of the upper lip (N-Sp), may be used in various combinations for the estimation of the length of the mandibular body (Pn-Ns). We decided to use a useful combination of characteristics.

Table 2. Simple \((r_{xy})\) and multiple \((t_{xy}, t_{xyz})\) correlation coefficients between dependent variable \((y)\) and independent variables \((x_1, x_2, x_3)\).  

<table>
<thead>
<tr>
<th>(x_1)</th>
<th>(x_2)</th>
<th>(x_3)</th>
<th>(t_{xy})</th>
<th>(t_{xyz})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-S</td>
<td>S-Pn</td>
<td>0.557</td>
<td>S-N-Ss</td>
<td>0.729</td>
</tr>
<tr>
<td>N-S</td>
<td>Cd-Go</td>
<td>0.553</td>
<td>S-Ps</td>
<td>0.630</td>
</tr>
<tr>
<td>N-S</td>
<td>S-Pn</td>
<td>0.557</td>
<td>N-Sp</td>
<td>0.635</td>
</tr>
<tr>
<td>S-Ba</td>
<td>Pn-NsL</td>
<td>0.307</td>
<td>S-Go</td>
<td>0.721</td>
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<tr>
<td>Pn-NsL</td>
<td>0.043</td>
<td>S-N-Ss</td>
<td>0.786</td>
<td>N-S</td>
</tr>
<tr>
<td>S-Ba</td>
<td>Pn-NsL</td>
<td>0.643</td>
<td>S-N-Ss</td>
<td>0.786</td>
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<tr>
<td>S-Pn</td>
<td>Pn-NsL</td>
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<td>S-N-Ss</td>
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<td>S-N-Ss</td>
<td>0.786</td>
</tr>
</tbody>
</table>

The correlation coefficient \((t_{xy})\) is italicized. The multiple correlation coefficient \((t_{xyz})\) indicates the degree of influence of the second \((x_2)\) and third \((x_3)\) independent variable.
tics for this purpose which would include the length of the mandibular rarus. We have likewise not discovered any useful combination of characteristics for estimation of the height of the mandibular body (Id-Go) and the vertical position of the temporomandibular joint (Cd-NSL). In accordance with the above-mentioned development 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-CL (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-Ns-Ss) and mandibular (S-Pg-Pn) protrusion, the angle of the cranial base (N-S-Ba), the angle S-Pn-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-Pn), i.e., the angle of the cranial base (N-S-Ba) and the inclination of the mandibular body (MLNSL) and ramus (RL/NSL), yields only values which are close to the coefficient 0.7.

Because of the high correlation between the angle of mandibular body offset (N-Pn-S-Pm) and the protrusion of the lower jaw (S-N-Pg) it is possible to use the angle of S-N-Pg as an approximation of the angle of protrusion of the lower jaw (N-Pn-S-Pm) in all cases which are not based on the angle of the cranial base. The evaluation of the mandibular protrusion for assessment of the mandibular protrusion, combinations which are not incident in the protrusion of the lower jaw (Table 1) 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 rarus within the skull (RL/NSL) could be assessed solely with the help of the gonial angle (ML/RL), combined with some other parameters (N-Pn-S-Pn, N-Pn, Ng-NS, AS/PL and S-Pg in Table 1). For assessment of the slope of the mandibular body (MLNSL) the gonial angle (in combination with S-N-Pg, S-N-Pn and as illustrated in Table 1 with S-Ns-Ss and Ng) and gonial angle (id-Go) was likewise good, 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 (MLNSL, Pg/Go-Sn) and ramus (RLNSL, Cd-Go), the height of the lower face (Sp-Sn) 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 RLNSL and MLNSL (Table 1). The mandibular angle was precisely defined by the inclination of the mandibular body and ramus (MLNSL and RLNSL, Table 1). The correlation coefficient of 0.995, recorded both in children and in adults, confirmed the height accuracy of the measurements and the correlation 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 the square of the pertinent correlation coefficients (the coefficient of determination). Coefficients below 0.2 have a low predictive reliability, as they explain less than 50 percent of the total variability of an estimated characteristic. A reliable estimate is given by coefficients above 0.8, which account for two-thirds of the total variability, as verified in daily orthodontic practice during the assessment of jaw development (Horowitz, 1966). These prerequisites were fulfilled in the majority of correlations even of about 0.9 (Table 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 the highest correlation (0.917), where the length (Pn-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, the evaluation of characteristics for estimation of the protrusion of the upper jaw which was not based on the angle of the cranial base. For assessment of the mandibular protrusion, combinations which are not incident in the protrusion of the lower jaw (Table 1) 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 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 1988a) 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 postseptal 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 ancestors, 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.

REFERENCES