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Developmental interdependence between selected somatic features and the weight of internal organs in human male and female foetuses

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The study material comprised 3889 foetuses of both sexes, aged 20–42 weeks and focused on developmental interdependence between the weight of the internal organs and their relation to selected somatic features during the prenatal period. The study also attempted to distinguish potential sex-related differences in the degree of statistical interdependence between the analysed variables. As a result, the analysis of linear and canonical correlation coefficients for consecutive weeks of foetal life has been carried out. High correlation coefficients have been obtained which indicate strong developmental interdependence between those organs and the somatic features. However, no significant sex-related differences in the developmental interdependence of the analysed variables have been observed.

key words: developmental interdependence, correlation of morphological features, foetal sex dimorphism

INTRODUCTION

It seems interesting to determine the degree of interdependence of population describing measurable morphological characteristics. The degree of interdependence of measurable morphological organ characteristics may provide a background for the analysis of biological relationships between those organs. Developmental interdependence between organs is related to the specificity of the relations between these organs and the selected somatic features of the foetus. This issue is, however, related to the question of whether body shape determines the shape of the internal organs or maybe the reverse is true, i.e. that it is the organs that determine the body shape. Or, possibly, the development of any of these is independent of one another? Unfortunately, the results of available studies [2, 3, 6] are unconvincing and full of speculations and hypothesising, yet without providing definite answers.

Investigating the effects of organ development on the bodily form, the latter being a factor potentially limiting their growth, remains beyond the capacity of this research mainly because of an insufficiency of specimens from embryonic and early foetal periods and because of a limited number of organ features that can be measured in the foetus. Nevertheless, the available study material has made it possible to indirectly investigate those effects by employing statistical evaluation that analysed the character and potency of the developmental interdependence between the organs and somatic features of the foetus. This study also aimed to delin-

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eate potential sex-related differences in the degree of statistical interdependence between the weight of the internal organs and the selected somatic features during the prenatal period.

MATERIAL AND METHODS

The study material comprised 3889 foetuses of both sexes (2203 males and 1686 females) aged 20–42 weeks. The foetuses with any indication of pathology were excluded from the study. Statistical interdependence between the weights of brain, heart, lungs, liver, spleen, kidneys, adrenals, thymus, as well as between the weights of these organs and selected somatic characteristics, such as total body length, crown-rump length, body weight and circumferences of the head, shoulders, chest and the abdomen, were determined. Linear correlation coefficients were calculated for male and female foetuses for consecutive weeks of foetal life and for the foetal age normalised data. In order to determine the sex-related correlations, an inter-sex comparison of the calculated correlation ratios was carried out by test-u statistical method:

$$u = \frac{Z_1 - Z_2}{\sqrt{D^2 Z_1 + D^2 Z_2}}$$

Afterwards, a more complex relationship, i.e. the interdependence between two groups of characteristics, i.e. somatic ones (independent variables — p) and the weight of internal organs (dependent variables — q), carried out by means of canonical analysis, was performed. As a result, if $X = (X_1, X_2 \ldots X_p)$ and $Y = (Y_1, Y_2 \ldots Y_q)$ are column p and q vectors of random variables (X — the set of somatic characteristics; Y — the set of weights of internal organs; $p = 7$; $q = 8$), then the covariance matrix of those $p + q$ random variables will take the form of the following matrix:

$$\text{covar}\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \sum_{11} \sum_{12} \\ \sum_{21} \sum_{22} \end{bmatrix} \begin{matrix} p \\ q \end{matrix},$$

where $\sum_{21}' = \sum_{12}$

row $\sum_{12} = S \leq \min(p, q)$

As a result 7 pairs of canonical variables for each week and for each sex were obtained, as such was the number of variables in the smaller set of independent variables. The analysis comprised the first pair of canonical variables, which corresponded to the highest of the canonical roots, the latter being the squares of the canonical correlation coefficients. The number of characteristic roots equals the minimum from the number of independent and dependent variables' sets. The higher the value of the characteristic roots, the higher the correlation between the first and the second group of variables. As a result, the first pair of canonical variables is the pair of variables characterised by the highest correlation between each other. Each of the characteristic roots had a characteristic vector assigned to it, the coefficient of such a vector being referred to as a weight. The characteristic vector, when multiplied by the vector of independent variables, yields the first canonical variable for these independent variables. Similarly, if the vector that is characteristic of dependent variables is multiplied by the vector of dependent variables then the first canonical variable for the dependent variables is obtained.

The canonical variable for the primary X variables is:

$$U = 1'X = 1_1X_1 + 1_2X_2 + \ldots + 1_pX_p$$

The canonical variable for the primary Y variables is:

$$V = m'Y = m_1Y_1 + m_2Y_2 + \ldots + m_qY_q$$

The coefficients $l = (l_1, l_2, \ldots, l_p)'$ and $m = (m_1, m_2, \ldots, m_q)'$, known as the weights of canonical variables, were calculated in such a way that the correlation between U and V variables is maximal. The value of the weights of the canonical variables indicates the share of specific somatic characteristics and weights of internal organs in the canonical correlation. The higher the absolute values of those coefficients, the higher the impact of the X and Y sets variables on the degree of correlation of canonical variables. Moreover, the redundancy coefficients calculated for each of the analysed cases (each week, sex and the standardised data) for primary canonical variables — R^2_{YX} [1] (Table 1) were calculated. Those coefficients provide information about the share of primary variables in the new, canonical variable.

RESULTS

The highest correlations, close to 1 for male and female foetuses, were found for the period of 24 to 38 weeks of life between the weights of the brain, heart and liver, i.e. between the key organs both in prenatal and postnatal life. Such a close developmental interdependence between these organs may be the result of their functional interdependence, less so of their histological origin as each of the organs develops from a different germ layer — brain from the ectoderm, heart from the mesoderm and liver from the endoderm. High positive correlation

Table 1. Correlation and redundancy coefficients and the weights of canonical variables as calculated for the age normalised data

Sex		Male foetuses	Female foetuses
Canonical correlation coefficients		0.8930	0.9026
Redundancy coefficients for the set of variables	**x**	47.46	49.55
	y	47.78	50.98
The weights of canonical variables for specific characteristics			
Total body length	1	0.1790	0.0551
Crown-rump length	2	–0.0248	0.0138
Body weight	3	0.8352	0.8426
Circumference of the head	4	0.0192	0.1358
Circumference of shoulders	5	–0.0166	0.0402
Circumference of the chest	6	0.0017	0.0129
Circumference of the abdomen	7	0.0772	0.0454
Brain weight	8	0.3930	0.3821
Heart weight	9	0.1123	0.2038
Lung weight	10	0.1113	0.1395
Liver weight	11	0.2743	0.2030
Spleen weight	12	0.0986	0.0590
Kidney weight	13	0.0988	0.1317
Adrenals weight	14	0.0109	–0.0050
Thymus weight	15	0.1206	0.0755

coefficients were also reported between the weights of the liver and the spleen — both of which are known to carry out their haematopoietic and immunological functions already in foetal life. The lowest, often insignificant correlation coefficients were found between the lungs and the spleen, the adrenals and the thymus. Interestingly, there is almost a complete absence of correlation of the developmental weight of the analysed organs with regard to their origin and localisation, e.g. the lungs and the thymus come from the endoderm and develop in the chest, yet no correlation between each other was detected. Considering, however, that each of these organs fulfils different functions during foetal life, it may be postulated that the existing/non-existing statistical correlations between these organs may be, at least partially, a consequence of their functional similarity/dissimilarity.

The analysis of developmental interdependence between the internal organs and foetal somatic features revealed that the highest correlation ratios are those of some internal organs, namely brain and liver, with the total body weight, and this is understandable as the weight of those organs significantly determines the total body weight. High correlation ratios were also revealed between the brain weight and all the somatic features, in particular head and chest circumference and heart weight. Such results seem obvious once the localisation and the functions of those organs is taken into account.

The analysis of the results did not reveal any significant sex-related differences with regard to the correlations between the analysed characteristics and virtually all the correlations were found to be similar in both sexes. This similarity is exemplified by the fact that the weakest and the strongest correlations are found in both sexes for the same feature comparisons and the respective correlation values are highly similar. However, the strongest sex dimorphism was observed for the correlations between the head circumference and chest circumference, abdomen circumference, heart weight, and for the correlations between the total body length and heart weight, and between the total body weight and heart weight.

Table 2. Canonical correlation coefficients for consecutive weeks of foetal life in both sexes

Foetal week	Male foetuses	Female foetuses
20	0.9461	0.9130
21	0.9472	0.9705
22	0.9267	0.9623
23	0.9300	0.9118
24	0.9065	0.9235
25	0.9103	0.9319
26	0.9156	0.9235
27	0.9379	0.9082
28	0.9298	0.9222
29	0.8966	0.9328
30	0.9436	0.9025
31	0.9277	0.9057
32	0.9381	0.9386
33	0.9313	0.9595
34	0.9483	0.9462
35	0.9356	0.9147
36	0.8984	0.9449
37	0.9021	0.9271
38	0.9082	0.9538
39	0.9228	0.9401
40	0.9149	0.8771
41	0.9236	0.9003
42	0.8427	0.9008

Table 3. Redundancy coefficients for dependent and independent variables for consecutive weeks of foetal life in both sexes

Foetal week	The set of variables			
	Independent (x)	Dependent (y)	Independent (x)	Dependent (y)
	Male foetuses		Female foetuses	
20	72.12	55.51	64.72	54.61
21	60.68	54.05	82.92	66.21
22	54.65	39.95	57.08	68.92
23	52.01	46.80	59.89	45.93
24	49.85	46.72	53.11	42.30
25	40.08	44.60	53.80	56.27
26	49.08	52.81	55.33	49.85
27	47.30	57.69	53.40	54.70
28	56.58	60.36	45.83	55.12
29	54.06	46.46	56.99	57.89
30	62.57	65.13	43.00	54.23
31	49.82	59.53	51.96	53.68
32	57.57	61.18	56.73	61.74
33	62.36	60.08	70.99	70.87
34	59.62	58.97	62.68	63.18
35	50.01	57.57	55.73	59.17
36	55.33	51.17	63.37	65.99
37	39.64	45.96	59.33	60.13
38	55.73	49.07	62.53	63.22
39	47.12	52.02	49.09	61.85
40	48.68	45.03	43.93	44.66
41	60.32	55.45	53.63	55.52
42	38.47	38.47	58.04	55.28

The canonical correlation coefficients for the first pair of canonical variables for consecutive weeks of foetal life are presented in Table 2. These coefficients tend to decrease towards the end of the foetal period, this trait being most pronounced in male foetuses in week 42 and in female foetuses in week 40. These results may reveal some biological developmental regularity as the analysis of the linear correlation coefficients also revealed that during this period most coefficients were statistically insignificant.

The analysis of the redundancy coefficients for the first set of canonical variables (Table 3) revealed that for female foetuses aged 27 to 42 weeks the set of primary dependent variables, i.e. the analysed internal organs' weights, had a more potent effect, compared to primary independent variables, i.e. the analysed somatic characteristics, on the value of corresponding canonical variables. In contrast, such regularity could not be observed for the male foetuses. The correlation and redundancy coefficients and the weights of canonical variables for the age-normalised data are included in Table 3.

The analysis of the whole foetal period revealed higher redundancy coefficients in female foetuses, and in both sexes the organ weights had more effect in the creation of the corresponding canonical variable than the somatic features. The weight values of the canonical variables for the analysed features (Table 3) allowed us to find out which of the somatic features and internal organs weights had

the most potent effect on the value of canonical correlations between these two groups of characteristics. Interestingly, the body weight was found to be most potently correlated with the internal organs group, both in male and in female foetuses. In male foetuses the highest correlation between the weight of the internal organs and the somatic features was observed for brain, liver and heart weight, whereas in female foetuses these were brain, heart and liver weight (in order of importance).

Because of the large sizes of the tables this article does not include the data on the canonical variables separately for each week and only the variables for which those coefficients have the highest absolute values have been included (Table 4). Table 4 provides a confirmation of those observations, as in each foetal week (from week 20 to week 42) for both sexes it was total body weight (3) and brain weight (8) that were most critical for the correlation of the two groups of features.

The canonical correlation between the set of somatic features and the set of the weights of internal organs has been graphically presented for the two first canonical variables and the degree of correlation for each foetus has been indicated (Fig. 1).

DISCUSSION

The analysis of the results from all the methods applied to determine the type and strength of the developmental interdependence between the internal organs, as well as between the internal organs and selected somatic features, has revealed that the correlations are most pronounced between week 24 and week 38 of foetal life, whereas before week 24

Table 4. Somatic features and the weights of the internal organs (1–15) that have the highest share in the canonical correlation value for consecutive weeks of foetal life in both sexes

Foetal week	Male foetuses		Female foetuses	
	Somatic features	Weights of the internal organs	Somatic features	Weights of the internal organs
20	3	8	1	8
21	3	8	3	11
22	3	8	3	8
23	3	8	3	8
24	3	8	3	8
25	3	8	3	13
26	3	8	3	8
27	3	8	3	13
28	3	8	3	8
29	3	11	3	8
30	3	11	3	8
31	3	9	3	9
32	3	8	3	8
33	3	8	3	8
34	3	8	3	8
35	3	13	3	8
36	3	8	3	8
37	3	10	3	10
38	3	8	3	8
39	3	8	3	8
40	1	8	3	9
41	3	8	3	8
42	3	8	4	11

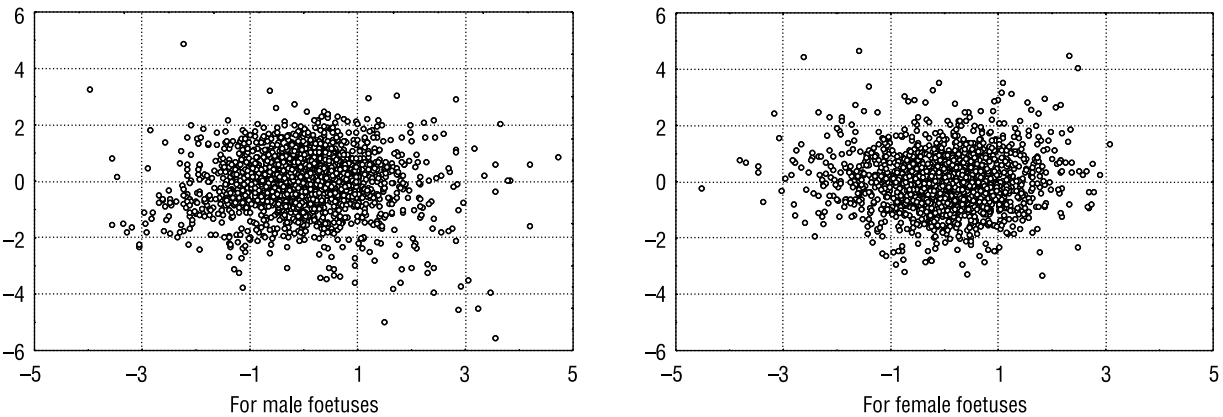

Figure 1. Canonical correlation between the set of somatic features and the set of the weights of internal organs.

such correlations are much weaker and, in most cases, statistically insignificant. Similarly, after week 38, a gradual decrease in the correlation strength between the analysed features can be observed. As a result, the weakest correlations have been observed at week 42 and only some of them were statistically significant. This phenomenon requires some attempt to be made to explain the implicated developmental mechanisms of the early and late period of intrauterine growth. The embryonic period is known to be characterised predominantly by cell and tissue restructuring and cell grouping in the process of organ development. During this period, when organ development and somatic features formation occur along individual, genetically determined lines, and when most of the organs only begin to develop their functional capacity, the developmental interdependence between the organs is weak, which is confirmed by low correlation coefficients between those variables. The subsequent periods witness not only further development of the function and structure of the organs, but also functional adjustment of the organs to one another. In the late prenatal period the foetus undergoes partial functional reorganisation before the expected environment change. The shift from intrauterine to extrauterine growth is preceded by functional maturation of the lungs and energy storage in the form of carbohydrates and fats, to name a few. The foetal mechanisms, which control the onset and maintain these processes, inhibit, or often block the functions of some organs to enhance the function of others which play a more vital role in this period, e.g. liver glycogen storage depends chiefly on the degree of adrenals activity in the foetus. As a result, the mechanisms of functional interdependence between some organs may become disrupted, as confirmed by weaker statistical correlations shown in our study.

The age-dependent decrease in the strength of the correlations between the measurable somatic characteristics has been reported by Neligan [4], Wich [5] and Marecki [3]. The decrease in the strength of the correlation observed during the last weeks of the foetal life signals the process of morphological differentiation. This process becomes more enhanced in postnatal life, whereas the foetal period is characterised by a limited morphological variability, which may be the consequence of intrauterine growth being dependent on the intrauterine environment which, in turn, precludes a more pronounced display of genetically determined variability.

The problem of sex-related differences in the developmental interdependence of measurable morphological features during the prenatal period has not been investigated so far, therefore the possibility of any discussion is highly limited.

CONCLUSIONS

High correlation ratios between the organs indicate the strong interdependence of their development, particularly between week 24 and 38 of foetal life. This strong interdependence is strongly determined by their biochemical and physiological functions. The organs whose physiological functions are intertwined in the foetal life are characterised by the strongest developmental interdependence.

A statistically significant dependence has been observed between the change in the organ weight and the somatic features, which confirms the current hypotheses on the influence of the internal organs on the growth and shape of some bodily parts of the foetus.

Strong developmental correlations have been observed in the foetuses of both sexes. No sex-related differences have been observed with regard to developmental correlations between the analysed characteristics.

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