The relationship between facial morphology, body measurements and socio-economic factors

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ABSTRACT: Background and aim: The effect of socio-economic factors (living conditions) and parental smoking habits on development of facial morphology and body measurements was studied on a longitudinal Czech sample of 25 girls and 25 boys.
Subjects and methods: A set of studied digitalized photographs taken from 0.5 to 18 years in intervals of 6 months originated in the Brno Longitudinal Study. Facial shape changes of sub-adult participants were described using a configuration of 27 landmarks and further studied by using methods of geometric morphometric and multivariate statistics. In order to localize growth-related shape changes within the face, the studied region was divided into upper, middle and lower facial units and analyzed separately.
Results and conclusion: The results show that in the course of ontogenesis there is a strong correlation between facial shape change and body measurements, height included (r=0.10 and r=0.24 in boys and in girls, respectively). The pubertal spurt of the facial shape change rate was revealed at 10.5 years in girls and at 11.5 years in boys. The earlier onset of the pubertal rate increase in facial shape changes in boys was associated with records of poor living conditions. In addition, the mother's smoking habits were linked to a noticeable facial shape change.

KEY WORDS: Human face, sexual dimorphism, living conditions, smoking, longitudinal study

Introduction

The human face, the most noticeable part of human body, expresses information about individual's age, sex, ethnicity or health (Alley 1998). During ontogenesis the facial features undergo marked changes in size and shape, associated mostly with growth and development of underlying bone structures. Following basic growth concepts, which include two fundamental mechanisms – remodeling and displacement, cranial bones (neurocranium, splanchnocranium and mandible) develop sequentially within their own timeframe (Enlow 1968; Enlow and Hans 1996). These time-restricted changes generally occur in the superior-inferior gradient. While in the neurocranium the development is the most intensive at the first years after birth, the upper face, the mid-face and the mandible grow in the course of

childhood and puberty (Enlow and Hans 1996).

Basic concepts of facial growth have been well-recognized (Enlow and Hans 1996). The new-born's wide and vertically short face becomes altered with vertical growth due to the enlarging airway, establishment of dentition and growth of the mandible. The growth of the nasal region depends on the growth of the lungs as the airflow modulates the establishment of bone airways, and ultimately on the body size, as appropriately sized lungs provide necessary functional support to the enlarging body (Enlow and Hans 1996). The overall body size, in terms of height, is also known to be related to the dimensions of the basicranium and thus indirectly to the face. It has been shown that individuals with taller statures are associated with longer basicrania and narrower mandibles. As a result, faces are prone to so-called leptoprosonic forms, i.e., narrow and high (Enlow and Hans 1996). In addition, Lieberman et al. (2000) showed that the breadth of the upper face mirrors the breadth of the upper cranial fossa, while the breadth of the midface is linked to the breadth of the middle cranial fossa.

The timing and intensity of age-related changes have individual, sexual, temporal and population specificity, which requires them to be constantly re-visited and re-evaluated (Goldstein 1936; Enlow 1968; Farkas et al. 1992; Enlow and Hans 1996; Ferrario et al. 1998; Smith and Buschang 2002; Bulygina et al. 2006; Trenouth and Joshi 2006; Mellion et al. 2013; Wellens et al. 2013). In general, the growth and development of each individual is conditioned by interactions of internal, genetic and external, environmental factors (Tanner 1962; Tanner 1990; Bogin et al. 1992; Bogin 1999;

Cameron 2002; Martorell and Zongrone 2012). The contribution of genetics has been assessed on the basis of twin studies (Naini and Moss 2004; Djordjevic et al. 2013; Weinberg et al. 2013). The shape of the midface, taken as a triangular area among right and left exocanthion and subnasale, was identified as under strong genetic determination (Naini and Moss 2004). Similarly, Weinberg et al. (2013) provided an evidence of strong heritability in shape variation of the central midfacial structures and Djordjevic et al. (2013) agreed that the lower facial thirds were the least similar in male monozygotic twins. On average, the heritability of the facial skeleton was estimated to be 0.26, of which the highest value of 0.43 was attributed to the nasal height (Martínez-Abadías et al. 2009). For comparison, the growth of height is approximately 80% controlled genetically (Silventoinen et al. 2003). In contrast to the above, Baydaş et al. (2007) stressed that facial soft tissues, rather than facial proportions, are under stronger heritability.

Of environmental factors, growth has been reported to be affected by a variety of factors such as health, socioeconomic status or physical activity (Rona et al. 1978; Eveleth and Tanner 1990; Bogin 1999; Richards et al. 1999; Rogol et al. 2000; Malina et al. 2004; Martorell and Young 2012; Bogin 2013). More importantly, it has been emphasized that quality and quantity of food intake primarily affect facial tissues and their depths in cheeks, chin and jaw regions (Wilkinson 2004). Windhager et al. (2013) showed that during adolescence a level of body fat explained 8.7% of the facial shape variation in girls. In addition, a low level of body fat was related to a wider forehead and a more angular lower face whilst a high level of body fat was associated

with generally rounder faces. The same link between body fat and the rounder face was revealed in males (Windhager et al. 2011).

Waddington (1957) states that a plan of the future growth is established by the inception of the genome. Once the plan is broken by an occurrence of unfavorable conditions, the growth slows down and the growth curve shows so-called lag-down growth. To an extent, homeostatic mechanisms have dispositions to restore the original plan. Once the body recovers from the deprivation that caused the stagnation of growth, an increase in growth velocity, known as the catch up growth, occurs. It applies that the shorter time of the lag-down growth, the easier comeback to the initial morphology (Cameron 2002). Although manifested evidently for body height (Tanner 1981), this phenomenon has been also observed in facial growth (Funatsu et al. 2006; Al-Thomali and El-Bialy 2012).

Until puberty the human face is almost asexual, and sexually dimorphic appearance occurs later as a result of increased levels of sex hormones (Enlow and Hans 1996). This appears to be in contradiction with Bulygina et al. (2006), who states that the sexual dimorphism in the size of the face is established as early as at the age of 6 months. The greatest changes of soft tissue in the facial profile are shown from 10 to 15 years in girls, whereas in boys they occur in a period from 15 to 25 years (Bishara et al. 1998). Additionally, in boys, contrary to girls, the growth of the face carries on once the growth of body height is completed (Hunter 1966). This extended growth in men is reflected in male face shape whereas an adult female face retains infant appearance (Enlow and Hans 1996). Baughan and Demirjian (1978), who

investigated sexual dimorphism of the head in association with height by using a cephalization index (head length*head width/stature), revealed that boys had significantly higher values of cephalization index in the course leading up to the age of 15 years. Once having reached this age they showed no significantly sex-related differences from girls. In other words up to the age of 15, girls had smaller crania proportionally to stature than boys of the same age. If, however, corresponding maturational stages for both sexes were considered, no presence of sexual dimorphism was observed (Gomes and Lima 2006).

The growth of the face has been a subject of extensive research due to the importance of the region and population specificity. The longitudinal research of boys' faces was conducted by Goldstein (1936), who revealed growth acceleration between 3 and 5 years and then adolescent growth acceleration between 13 and 15 years, followed by a slowed down rate of growth until the age of 21. Ferrario et al. (1998) showed that in Italians, facial growth of girls is almost completed in the age group between 14 and 15 years. Unlike in girls, in boys of the same age the large increase was yet to appear. The growth spurt of the lower third of the face was attained at the age 11 to 12 years and 12 to 13 years in girls and boys, respectively. Smith and Buschang (2002) showed that for midsagittal facial growth, while conducting a research on cephalographs from a semi-longitudinal study dated to the 1960s and 1970s, the velocities peaked between 11.9 and 12.5 years in girls and between 13 and 14 years in boys. The age at which the human skull reaches fully formed adult features was probed by Ross and Williams (2010). They revealed that children's

faces attain the shapes they will have in adulthood much earlier than previously thought, because no significant morphological differences between the teen and young adult age groups were found out.

The purpose of the present study was to investigate longitudinal growth-related shape changes of face in conjunction with other body measurements (height in particular) and selected socio-economic factors in Czech sub-adults and to identify onsets of growth and development changes in separate units of the human face for the studied sample as whole, as well as for boys and girls separately.

Materials and methods

The studied sample of 1115 photographs corresponding to 25 girls and 25 boys was selected from the Brno Longitudinal Study, an extensive 20-year project that took place in Brno, Czech Republic from the 1960s to 1980s. Photographs of faces in the standardized frontal view were taken periodically (from birth to 18 years) together with other somatic measurements such as, for example, height, weight, length of limbs, width of shoulders, bicristal width or dimensions of the head. Additional available records included socioeconomic information about children's families (Bouchalová 1987). The sampling was based on quality and a number of images available for each individual, as many sets of photographs in the original longitudinal study were incomplete. Photographs showing the head rotated to right/left along the vertical axis or inclined backwards/forwards were discarded in order to maintain the set standards. A moderate degree of head side tilt was allowed as it was further corrected by a method of standardization. Finally, in comparison with the

maximum available images, 30.1% of images were not further processed.

All selected photographs were scanned by a flatbed scanner MikroTek ScanMaker 9800XL, the scanning resolution set to 1000dpi. 2D Cartesian coordinates of 27 landmarks (Table 1, Fig. 1) were registered by using tpsDig2 (Rohlf 2009). As the location of some landmarks (forehead) is subjective, digitizing of landmarks was provided by one experienced observer to minimize inter-observer error.

As the photographs were not supplemented with a scale and were not obtained by standardized conditions, it was not possible to compute inter-landmark distances corresponding to real distances. Therefore our study focused only on shape changes of face during growth. For this purpose, the entire set of 27 land-
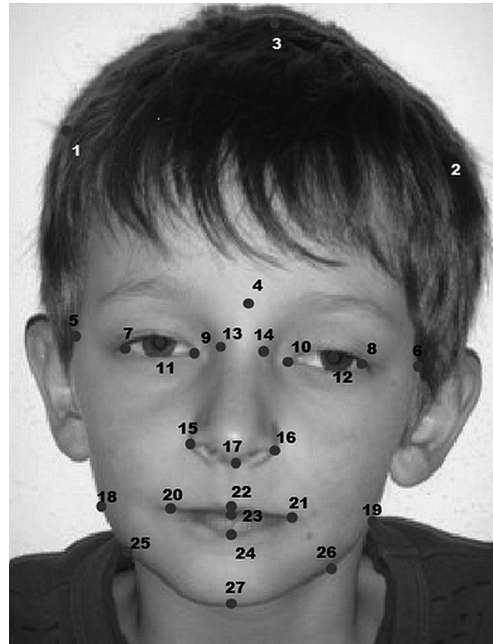

Fig. 1. Digitalized landmarks (Table 1). Landmarks 1–4 represent the upper part of the face, landmarks 5–17 represents the middle part of the face and landmarks 18–27 represents the lower part of the face.

Table 1. Definitions of landmarks (Fig. 1) according to Fetter et al. (1967). Landmarks 1–4 represents the upper part of face, landmarks 5–17 represents the middle part of face and landmarks 18–27 represents the lower part of face.

Landmarks	Definition
(1,2) euryon II	The point of intersection of straight lines of points 21–9 and 20–10 with the edge of the head (right and left)
(3) vertex	Midpoint located at the top part of the head
(4) optyryon	Midpoint located on the straight line between medial edge of the eyebrows
(5,6) zygion II	Point located on the edge of the face (possibly at the beginning of hair) and lying on the straight line between pupils (right and left)
(7,8) exocanthion	Outer commissure of the eye fissure (right and left)
(9,10) endocanthion	Inner commissure of the eye fissure (right and left)
(11,12) pupila	Midpoint of the pupil
(13,14) radix nasi	The upper least protruding portion of the external nose situated between the two orbits (right and left)
(15,16) alare	The most point on the anterior margin of the nasal aperture (right and left)
(17) subnasale	Midpoint of angle at columella base
(18,19) gonion II	The most lateral point on the lower jaw lying on the straight line that is perpendicular to midline and crosses the stomion (right and left)
(20,21) cheilion	Point located at labial commissures (right and left)
(22) labrale superius	Midpoint of the straight line between the highest points of upper vermilion line
(23) stomion	The median point of the oral slit
(24) labrale inferius	Midpoint of the lower vermilion line
(25,26) ramus mandibulae	The point of intersection of straight lines of points 11–21 and 12–20 with the lower jaw (right and left)
(27) gnathion	The lowest point of the midline of the lower jaw

marks (raw coordinate data) was standardized following an algorithm incorporated in FIDO software (Urbanová et al. 2011). Firstly, the centroid size and centroid were computed and sets of coordinates were scaled so the centroid size for each of them equaled 1. Then, Cartesian coordinates were rotated to the vertical axes set identically to the mid-sagittal plane. Once the plane of symmetry was established, pairs of bilateral landmarks were averaged and unilateral landmarks aligned ideally in the mid-sagittal plane. In order to identify growth-related shape changes in separate facial units, the original set of landmarks was divided into partial configurations, representing three parts of the face – the upper (forehead), middle (orbital and nasomaxillary complex) and lower (lips and mandible) (Table 1).

Once standardized, the coordinates were further processed in order to calculate the magnitude of the facial shape change throughout developmental stages. The shape change was defined as the difference between an initial and target shape in later ontogenetic stages. In order to do so an initial facial shape, i.e., an appropriate photograph from the early age of 6 months up to 2 years for each specimen had to be identified. In this particular time span infants still continue to maintain neonatal features and postnatal growth design is yet to fully unfold. Subsequently, values of vectors between

initial and target coordinates of a given age were computed. Ultimately, vectors of all landmarks were summed up in order to compute values of the Procrustes distance (PD). The Procrustes distance describes a complete change of the face shape up to a given age. Thus, PD exclusively represents the amount of shape change, whereas direction of the shape change is omitted.

Values of PD and selected somatic measurements (height, sitting height, weight, length of lower limb, length of upper limb, height of symphysis, acromion-stylion length, width of shoulder, transversal diameter of trunk, bicristal width, circumference of head, length of head, width of head, circumference of trunk, circumference of upper arm, circumference of forearm, circumference of thigh, circumference of shank) were plotted for each individual in order to explore individual specific irregularities and fluctuations in growth rate, which indicate and define the lag-down and catch-up growth. The individual trends were examined in relation to the sample average and sex-specific curves.

Socioeconomic data were extracted from personal questionnaires filled in by parents and investigators over the course of the longitudinal study. The selection contained information on living conditions (the area and quality of a household, a number of live-in family members); family background (parents' state of health, smoking or non-smoking habits, divorce, and death of a family member); position in a family (birth order, a number of siblings) and sporting activities. The category describing living conditions was divided into three levels based on a value of m^2/person per household, where specimens of <8 m^2/person were classified as poor living conditions,

the moderate level ranged from 8 to 15 m^2/person and good living conditions exceeded 15 m^2/person.

Although data on both parents' smoking habits were recorded, only the mother's smoking habits were tested due to presumably having a larger impact on child's development. Mothers were classified as non-smokers, occasional smokers (0–5 cigarettes per day) or mild smokers (10–15 cigarettes per day). The level of heavy smokers (more than 15 cigarettes per day) was not present in the studied sample.

The relationship between the studied facial shape changes (represented by Procrustes distances) and somatometric variables was expressed in terms of the Pearson correlation coefficient. As the body measurements are highly correlated, the residuals of regression analysis, that was carried out to remove the effect of age, were analyzed by the Principal Components Analysis (PCA) to reduce the number of dimensions. The regression analysis and PCA were computed for each sex separately. Thereafter, the obtained principal components (PCs) were associated to the relevant measurements on the basis of the values of loadings associated with (PCs). PCs which accounted for more than 1% of variance were finally correlated with Procrustes distances. All measurements in analysis were completed, except the values of height of symphysis, which were missing at the age up to two years in all individuals.

Differences in Procrustes distances and height among defined socio-economic categories were tested by analysis of variance (ANOVA). The assumptions of the homogeneity of covariance matrix were tested by the Levene test. There was used the age of individuals as co-factor in ANOVA. Tests were computed separately

for facial configurations as well as for five age categories ranging from 2–5 years, 5.5–7 years, 7.5–10 years, 10.5–14 years and 14.5–18 years, created based on developmental stages and the nature of the studied dataset. As there was a purpose to compare the shape change of face at the same age and not at the same developmental stage, age categories were chosen identical for both sexes.

The descriptive characteristics and data analyses were performed by using Statistica 10 software (StatSoft, 2011), except regression analysis and PCA for which PAST programme was used (Hammer et al. 2001). For all statistical tests the level of statistical significance was set at 5%.

Results

The correlation between facial shape change and body measurements

According to PCA, the first principal component (PC1) accounted for more than 62.17% and 65.47% of variance for boys and girls, respectively (Table 2 and 3) and according to loadings was primarily associated with the height (Table 4 and 5). Additionally, PC2 was associated with the circumference of trunk, PC3 with height of symphysis and PC4 with the sitting height in both sexes. Further, PC5 was associated with the circumference of trunk and PC6 with the circumference of head in girls, while in boys PC5 was associated with the circumstance of thigh, PC6 with the length of upper arm and PC7 with the circumference of head. Other PCs explained less than 1% variability and were not further analyzed.

In general, girls exhibited stronger correlations between PD and body measurements than boys (Table 2 and 3), especially for height (middle facial unit: r=0.24 and r=0.10 for girls and boys, respectively). Except the height of symphysis in both sexes and sitting height and the circumference of head in boys, all measurements showed significant correlation. In boys, the strongest relationship was revealed with the length of upper

Table 2. Correlation coefficients between PD (representing facial shape change) and PCs (representing somatometric traits).

Variable	% variability	Complete face	Upper part of face	Middle part of face	Lower part of face
		PD (boys)			
PC 1	62.19	0.02	–0.07	0.10*	–0.01
PC 2	15.74	0.09*	0.10*	–0.01	0.18*
PC 3	10.34	0.04	0.08	0.04	0.00
PC 4	3.37	0.08	0.03	0.08	0.07
PC 5	2.55	0.14*	0.14*	0.11*	0.10*
PC 6	1.51	0.26*	0.16*	0.29*	0.22*
PC 7	1.27	–0.03	–0.08	–0.05	0.06

Notes: PD – Procrustes distance.
Coefficients are divided by the parts of the face - the whole of the face, upper, middle and lower parts.
PCs are supplemented with the percentage of variability obtained in PCA analysis.
PC1is associated with the height, PC2 with the circumference of trunk, PC3 with height of symphysis, PC4 with the sitting height, PC5 with the circumstance of thigh, PC6 with the length of upper arm and PC7 with the circumference of head. Coefficients marked with asterisk are statistically significant.

Table 3. Correlation coefficients between PD (representing facial shape change) and PCs (representing somatometric traits).

Variable	% variability	Complete face	Upper part of face	Middle part of face	Lower part of face
			PD (girls)		
PC 1	65.47	0.09*	–0.07	0.24*	0.02
PC 2	20.05	0.15*	0.02	0.12*	0.21*
PC 3	6.05	0.02	0.02	0.01	0.01
PC 4	2.95	0.23*	0.21*	0.22*	0.15*
PC 5	1.49	0.13*	0.08	0.12*	0.10*
PC 6	1.08	0.09*	0.17*	0.04	0.04

Notes: PD – Procrustes distance.
Coefficients are divided by the parts of the face - the whole of the face, upper, middle and lower parts. PCs are supplemented with the percentage of variability obtained in PCA analysis.
PC1is associated with the height, PC2 with the circumference of trunk, PC3 with height of symphysis, PC4 with the sitting height, PC5 with the circumference of trunk and PC6 with the circumference of head. Coefficients marked with asterisk are statistically significant.

arm (r=0.29 for the middle facial unit). In girls, except the height, the strongest correlations were showed with the sitting height (for the whole face: r=0.23) and with the circumference of trunk (for the lower facial unit: r=0.21).

Sex-related and individual development

The averaged trend for girls and boys showed evidence for sex-related specificity in facial development (Fig. 2). While boys exhibited higher values of PD initially, by the age of 4 years the trend inverted due to faster shape changes of the face in girls. The trend endured until the age of approximately 11 and 12 years when boys started to prevail again. At this point both sexes started to reflect a noticeable pubertal spurt. In boys, however, the spurt was extended and more intense (Fig. 2). In girls, the faces began their descent in PD values after the age of 13 years while boys' faces reached their peak at 16 years followed by a fall of PD values. Confirming these results, a t-test showed statistically significant differ-

ences between boys' and girls' PD in the second (5.5 to 7 years) (t-value=–3.12, p-value=0.002) and in the fifth (14.5 to 18 years) (t-value=4.55, p-value=0.000) age category.

Focusing on the separate facial units, an intensive pubertal spurt was revealed in the middle facial unit. The onset of
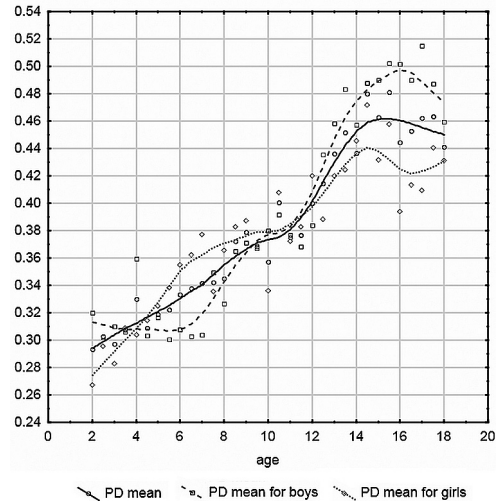

Fig. 2. Graph of variables that characterized face growth (PD) – mean for both sex, mean for boys and mean for girls (at the relevant age). Points are fitted by fit type Lowless.

the spurt was showed at the age of 10.5 years in girls, 11.5 years in boys respectively. The facial shape change increased gradually until puberty. The growth and development of the upper and lower facial units was characterized by an inconspicuous shape change until puberty. The timing of the pubertal spurt of the upper part of the face was similar to the middle part (10.5 and 11.5 years in girls and boys, respectively), in total contrast to the lower part of face in girls (12.5 years).

In boys, the beginning of the pubertal spurt (of the lower part of the face) was shown at the age of 11.5 years, while the girls had consistently higher values of PD until the age of 12.5 years.

Individual curves created for each individual and each somatometric trait showed the specific growth pattern of each individual (data not shown). The graphs of individual data of representative specimen (Fig. 3) showed evidently the onset and course of the pubertal spurt at the age about 11 years for height

as well as in the graph of PD – the similar trend is observable in the graphs of other somatometric traits, especially in the graphs of the head dimension. Other individual curves revealed possible "lag-down growth" and "catch-up growth" in girls who took part in gymnastics and stopped exercising later.

Facial shape changes and socio-economic factors

Tests (ANOVA and Kruskal-Wallis ANOVA) showed statistically significant results in facial shape changes for living conditions and the mother's smoking habits. Post-hoc tests revealed that the category of poor living conditions had significantly higher values of Procrustes distance than the category of good living conditions. The same results were revealed when age categories were taken into account, except for the first age category (2 to 5 years), which did not show statistically significant differences (Fig. 4).
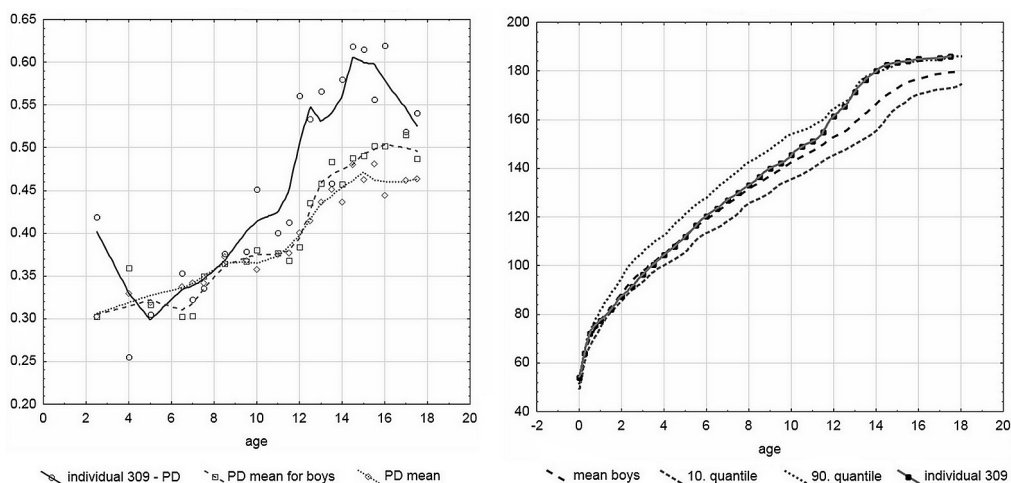

Fig. 3. Graphs of PD (left) and height (right) for selected boy from study. There is PD according to age on the left side of figure, which is supplemented by mean for both sex and mean for boys. Points are fitted by fit type Lowless. There is height according to age on the right side of figure which is supplemented by graphs of the 10th and 90th quantile of height of all children. Points are fitted by fit type Spline.
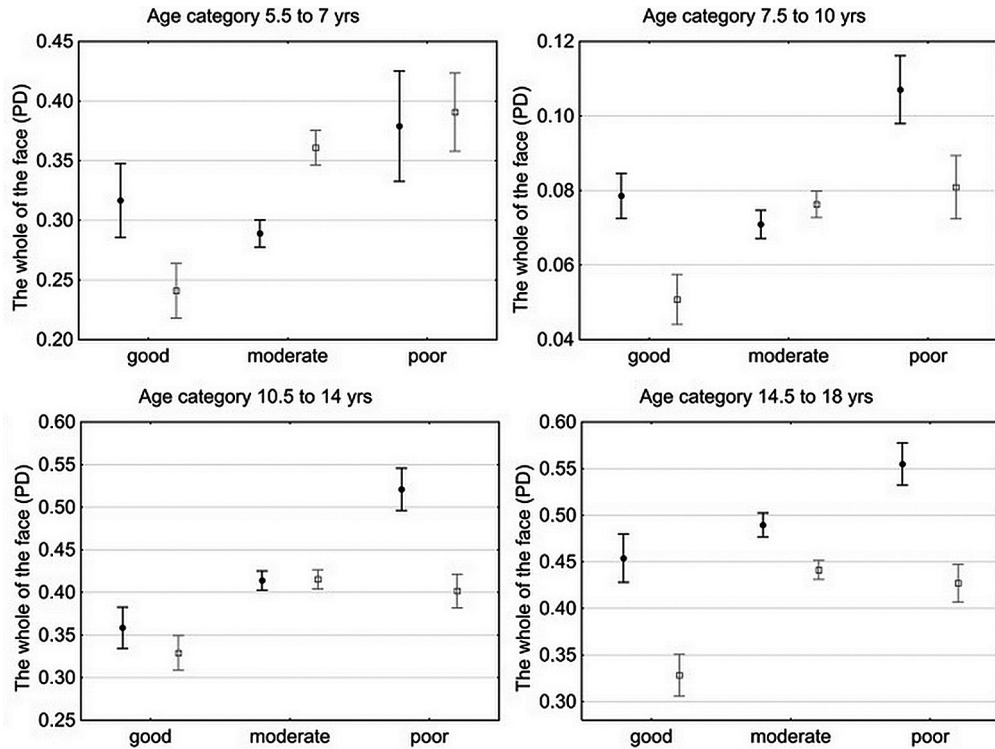
Fig. 4. Range plots of PD of the whole of the face according to category of living conditions (left – good; middle – moderate; right – poor) in age categories which give statistical significant results. The mean and standard error of the mean were used. Boys are drawn in black, girls in grey.

For the separate facial units (Fig. 5), the shape change of the upper facial unit did not show statistically significant differences among categories of living conditions, if tracked up to the age of 7.5 years. Thereafter, higher values of PD were observed in the category of poor living conditions, while PD values fell in the category of good living conditions in comparison to the categories of moderate and poor living conditions. The tests did not reveal any differences in the shape change of the mid-face until the age of 7.5 years. In the third age category (10.5 and 14 years) the values of PD were significantly lower in the category of good living conditions than in the other two groups. Beyond this age, there were no

statistically significant differences. The values of PD of the mandible were at their peak between the ages 5.5 and 14.5 years in the category of poor living conditions. Beyond that age no associations with living conditions were observed.

In general, similar trends were observed in both sexes, although in boys aged from 10.5 to 14 years the differences between poor and moderate living conditions were revealed as statistically significant. Unlike in boys, in girls the values of PD in the category of moderate living conditions were closer to values in the category of poor living conditions (Fig. 4).

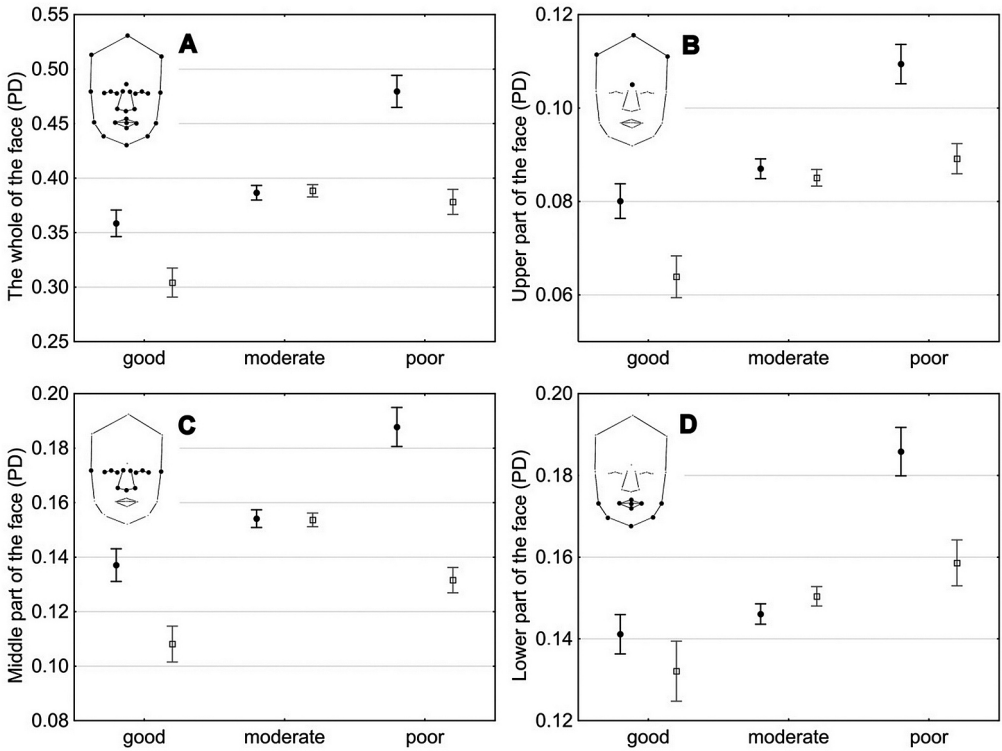For the mother's smoking habits, tests revealed higher values of PD in chil-

Fig. 5. Range plots of PD according to category of living conditions (left – good; middle – moderate; right – poor) when age categories are pooled. The mean and standard error of the mean were used. Boys are drawn in black, girls in grey. A) Range plots for the whole of the face. B) Range plots for the upper part of the face. C) Range plots for the middle part of the face. D) Range plots for the lower part of the face.
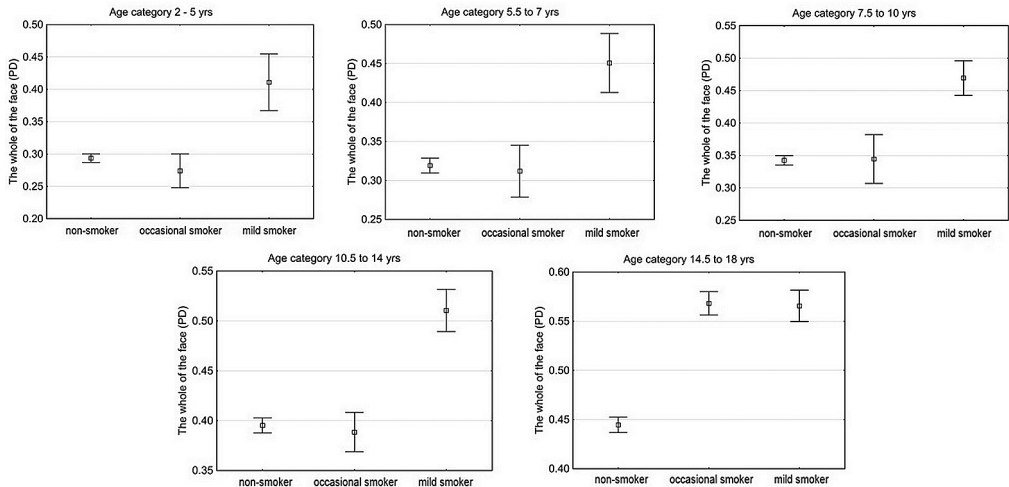

Fig. 6. Range plots of PD of the whole of the face according to category of mother's smoking habits (left – non-smoker; middle – occasional; right – mild) in age categories which give statistical significant results. The mean and standard error of the mean were used.
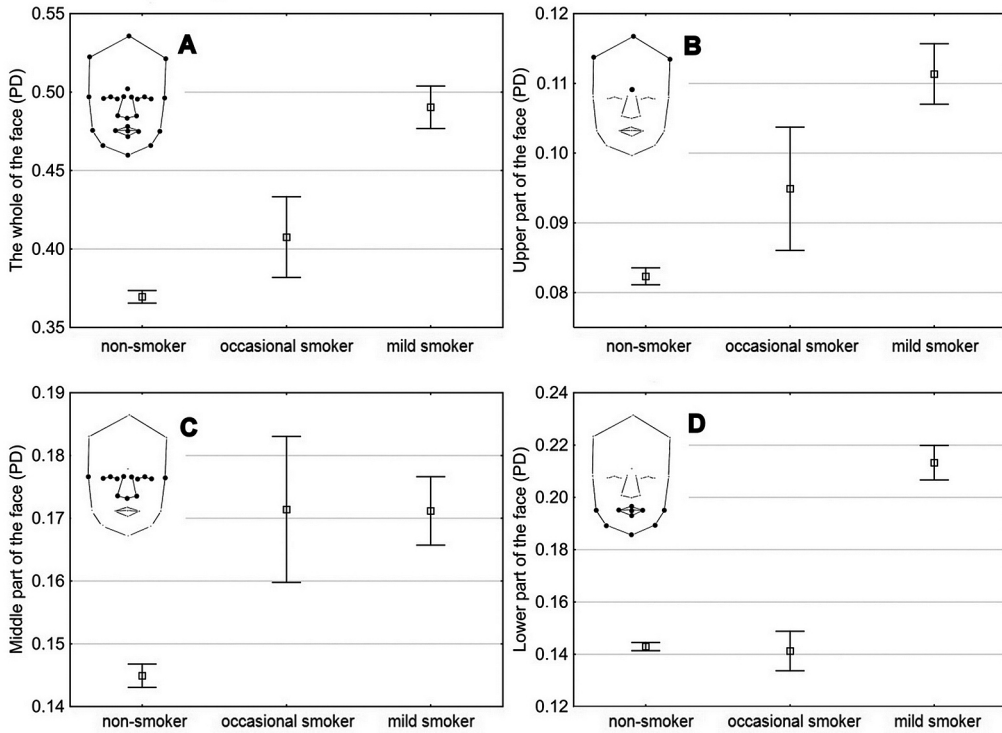
Fig. 7. Range plots of PD according to category of mother's smoking habits (left – non-smoker; middle – occasional; right – mild) when age categories are pooled. The mean and standard error of the mean were used. A) Range plots for the whole of the face. B) Range plots for the upper part of the face. C) Range plots for the middle part of the face. D) Range plots for the lower part of the face.

dren living with mild smokers and lowest in non-smokers. The similar trend was revealed in all age categories (Fig. 6). If compartmentalized into the facial units, the shape change of the upper part of face (Fig. 7) was not significant until the age of 7.5 years. In the middle facial part, there was an apparent slowdown of the trend in the third and fourth age category (7.5 to 14 years), while at ages from 14.5 to 18 years (5th age category) the lowest values there were, again, observed in non-smokers category. The analysis was not performed separately for girls and boys due to an insufficient number of observations.

Height and socio-economic factors

ANOVA revealed no statistically significant association between height and living conditions. The same applied when age categories were taken into account. Still, in boys it was revealed that for the third and fourth age category (7.5 to 10 years and 10.5 to 14 years) the average increment in height was larger in the group of poor living conditions than in the one with good conditions (data not shown).

For mother's smoking habits, ANOVA showed that children living with mothers who were mild smokers were significantly shorter than children of

non-smokers and occasional smokers. Similar results were shown if age categories were included, except for the first and fifth age category where no significant results were revealed.

Discussion

The aim of the present study was to investigate facial age-related shape changes in children by using a dataset originated in an extensive longitudinal study. Despite having ended almost three decades ago (Bouchalová 1987), the study continues to be a valuable source of information on interplay between somatometric (size and shape-related) and socio-economic factors. In addition to studying age-related growth and developmental changes as a function of living environment, longitudinal data enabled the identification of individual-specific interferences in developmental paths which remain undetected while studying cross-sectional data.

Our results show that facial shape change and the growth of other parts of the body are strongly interconnected. The stronger overall association between face and body measurements (height, sitting height, circumference of trunk and circumference of head) was revealed in girls. On the contrary, the facial maturation seems to be linked primarily to an increment in the length of upper limbs and in addition to that with the circumstance of trunk and circumstance of tight in boys. They also are in agreement with the known relationship among height, dimensions of basicranium and face (Enlow and Hands 1996, Lieberman et al. 2000) as the strong relationship between height and facial morphology was revealed. Our results suggest that girls exhibit tighter and narrower range of variation that is linked with height, con-

trary to boys whose facial morphogenesis is more influenced by additional factors.

Although, no association between facial shape and dimensions of the head was revealed in boys in our study, girls exhibited relatively mild correlations with upper facial unit. It points directly to different timing of the facial shape change and the growth of the head. Unlike the facial skeleton, the neurocranium grows rapidly and intensively in the first years of postnatal, attaining 85% of adult width by the second to third years of life (Enlow 1968; Enlow and Hans 1996). In addition, individuals exhibit periods with limited or even absence of growth of the head dimensions. While their occurrence appears to be highly individually specific and the duration of growth stasis is about two years, a lack of larger growth of the neurocranium has been shown at the age of 4 to 6 (Hajniš, Kárníková 1971).

Of separate facial units, the middle part was identified as heavily determined by body measurements. It indicates the continuous shape change of the orbital and nasal regions, opposite to that of the other two parts the face, where the change is more time-restricted, the upper part early in development and the lower part at puberty. The zygomatic bones relocating laterally and posteriorly and the nasal region enlarging anteriorly are two major maturational changes in facial skeleton. Although given the 2D frontal projection, the studied dataset reflects only lateral expansion of the face wherein the increment of anteriorposterior depth is not included, the shape changes in the mid-facial unit dominate as the central age-related modification is clearly associated with the overall skeletal growth. The lack of a significant relationship between the lower face and the head length

Table 4. Values of loadings associated with (PCs) according to body measurements for boys.

Body measurements	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
height	0.58	–0.21	–0.35	–0.05	–0.02	–0.30	0.16	0.07
sitting height	0.29	0.13	–0.20	–0.42	0.44	–0.07	0.13	0.02
length of upper limb	0.26	–0.12	–0.17	0.17	0.13	0.50	–0.35	–0.19
length of lower limb	0.29	–0.34	–0.15	0.37	–0.46	–0.23	0.03	0.05
height of symphysis	0.32	–0.45	0.80	–0.16	0.11	0.03	0.05	–0.02
acromion-stylion length	0.21	–0.12	–0.13	0.16	0.11	0.39	–0.24	–0.18
width of shoulder	0.12	0.10	0.03	0.18	0.14	0.17	–0.17	0.10
transversal diameter of trunk	0.06	0.15	0.08	0.22	0.09	–0.04	0.02	–0.04
bicristal width	0.08	0.05	–0.03	–0.03	0.19	0.00	–0.03	0.05
circumference of head	0.08	0.09	–0.02	0.13	–0.01	0.47	0.72	0.16
length of head	0.03	0.02	–0.01	0.00	0.00	0.23	0.22	0.05
width of head	0.01	0.03	0.01	0.11	–0.02	0.03	0.25	0.01
circumference of trunk	0.32	0.54	0.26	0.49	0.18	–0.24	0.03	–0.03
circumference of upper arm	0.13	0.26	0.11	–0.03	–0.10	–0.04	–0.16	–0.17
circumference of forearm	0.10	0.19	0.07	–0.06	–0.04	–0.12	–0.05	–0.03
circumference of thigh	0.23	0.33	0.08	–0.35	–0.59	0.19	0.06	–0.42
circumference of shank	0.17	0.20	0.07	–0.16	–0.27	0.19	–0.29	0.82

suggest that by mandibular maturation, the ontogenetic dolichocephalization (Dokládal 1971) is completed.

Values of average PD indicate that there is a noticeable presence of sexual dimorphism in facial shape change and show the importance of the pubertal spurt in the facial morphogenesis. The relatively asexual period of facial development was identified between ages of 7 and 12 years. Prior to this age a larger amount of change is first observed in boys then more consistently for girls. At puberty, boys once again prevail. This agrees with Bulygina et al. (2006), where male faces are delayed in development of facial shape compared with females until puberty. According to Liu et al. (2010), who investigated mandibular growth in children from birth to five years, boys

have a larger, but less mature mandible than girls. This is in contradiction with our study, where the values of PD (which represent facial shape change) are higher in boys than in girls until 3 years in the lower part of face. This early dimorphism is presumably related to hormonal levels (Loth and Henneberg 2001). A higher secretion of gonadotropin during the end of foetal and the beginning of postnatal life was detected in boys, who are born taller because of this phenomenon (Tanner 1990). The increase rate of all three facial parts is coincident with the increase of height in puberty, which is in accordance with Hunter (1966). Contrary to expectations, mandibles exhibit less pronounced pubertal increase compared to the mid-face. The growth of the mandible is directed mainly forward (Enlow

Table 5. Values of loadings associated with (PCs) according to body measurements for girls.

Body measurements	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
height	0.64	–0.17	0.30	0.16	–0.01	–0.21	–0.12	–0.12
sitting height	0.23	–0.04	0.24	0.49	–0.40	0.21	0.01	–0.08
length of upper limb	0.28	–0.03	0.12	–0.34	0.03	0.41	0.31	0.22
length of lower limb	0.41	–0.13	0.06	–0.33	0.38	–0.41	–0.13	–0.04
height of symphysis	0.40	–0.07	–0.89	0.19	–0.03	0.11	–0.02	0.04
acromion-stylion length	0.22	–0.02	0.07	–0.30	0.02	0.34	0.32	0.12
width of shoulder	0.10	0.07	0.00	–0.11	–0.02	0.20	0.16	–0.06
transversal diameter of trunk	0.05	0.16	0.00	–0.12	–0.12	0.14	0.02	–0.21
bicristal width	0.05	0.08	0.04	0.06	0.16	0.30	–0.10	–0.73
circumference of head	0.02	0.07	0.09	0.11	0.39	0.46	–0.49	0.13
length of head	0.00	0.01	0.03	0.01	0.18	0.23	–0.22	0.16
width of head	0.01	0.02	0.01	0.04	0.01	–0.01	–0.05	–0.03
circumference of trunk	0.17	0.65	–0.04	–0.37	–0.44	–0.09	–0.34	–0.06
circumference of upper arm	0.01	0.30	0.01	0.05	0.11	–0.03	0.04	0.18
circumference of forearm	0.03	0.17	0.01	0.03	0.00	0.04	0.08	0.14
circumference of thigh	0.09	0.55	0.04	0.35	0.42	–0.11	0.15	0.16
circumference of shank	0.07	0.24	0.02	0.18	0.10	–0.09	0.54	–0.21

1968; Enlow and Hans 1996; Franchi et al. 2001), which remains undetected on frontal view portrait photographs. Our results of mandible shape change are, however, in agreement with the results on the growth of mandibular height by Farkas et al. (1992).

Our results revealed that the pubertal spurt of facial shape change in boys starts earlier, which is in contrast to Goldstein (1936). The timing of the beginning of increase rate of shape change and its ending in girls during adolescence coincides with Ferrario et al. (1998). For boys, however, Ferrario et al. (1998) reported a later start of the pubertal growth spurt than was revealed in our study. Bulygina et al. (2006) found out that the pubertal spurt in girls slowed down at the age of 13 and that the growth finished at about

15 years, which, once again, agrees with our results. The male hypermorphosis (extended period of the growth and development) (Bogin 1999) characteristic for facial (hard as well as soft tissue) growth and development (Bishara et al. 1998; Bulygina et al. 2006), was detected weakly in our study, probably due to the scarcer data in the oldest age category as participants tended to take part in the study less rigorously. On the contrary, our study is more in agreement with Ross and Williams (2010), who revealed no significant morphological differences in skull between the teen and young adult age groups.

The individual graphs allowed us to investigate certain aspects of the growth, which are undetectable in cross-sectional data, such as to identify the lag-down

growth, catch-up growth or the time of the spurt for each individual separately. Comparing averaged and individual body measurement data, two individuals (girls) whose growth was affected by demanding physical activity and professional sports (gymnastics) were identified. Gymnastics is known to be a causative factor in the slowdown of growth as a result of its extreme physical demandingness. If a child stops daily exercises, reparative mechanism of the catch-up growth are activated and the original plan may be restored (Richards et al. 1999). These changes are, however, not noticeable in graphs of facial change data, suggesting that physical demands do not affect the facial skeletal growth and shape change or that other compensatory mechanisms intervene.

In the present study records on living conditions were utilized as an indicator of participants' socio-economic status, which is a well-recognized environmental factor affecting growth and development (Tanner 1990; Bogin 1999; Malina et al. 2004). To our surprise, the analysis yielded a lack of differences in height among categories of living conditions. Individual's height is generally considered a very sensitive indicator of socio-economic conditions. Our results are in contradiction to Bouchalová (1987), who firmly stated that for the Brno sample as whole, boys provided with good living conditions were taller than the rest of the reference sample.

In contrast, the facial shape changes throughout the ontogenesis were clearly affected. Still, there were no differences in the facial shape change among categories of living conditions until the age of 5 years suggesting a resistance in early stages of development. This applies particularly to the upper and middle facial

units where no differences were observed until the age of 7 years. More noticeable facial shape changes were revealed in children from the category of poor living conditions, where a slowdown of shape change was detectable in mid-face and mandible after the age of 14.

Age-restricted sexual differences were observed in facial development in relations to the living conditions, where boys' faces appear to react to nuances of the factor while girls resist up to a certain threshold. This follows the generally accepted knowledge that boys are more sensitive to the effect of environment while females are known to be buffered against environmental stress. This may also be a product of the lesser amount of overall changes female faces undergo during development as females retain a more infant appearance than males (Enlow and Hans 1996). Furthermore, the comparison of differences between age categories in boys revealed that pubertal increase in PD as well in height started earlier in individuals from the poor living category (data not shown).

Smoking is another known environmental health risk factor. The mother's active as well as passive smoking influences the growth of the foetus. Luciano et al. (1998) found out that newborns of smoking mothers had significantly reduced fat mass and most other anthropometric measurements such as the birth-weight or arm length. Lampl et al. (2003) states that after the 27th week of gestation, smoking mothers' foetuses exhibit tendencies towards dolichocephalic headform. It is presumably caused by foetal hypoxia. The dolichocephalic head establishes a narrow, long and protrusive face. This facial form is called leptoprosonic (Enlow and Hans 1996). Kieser and Groeneveld (1994), in contrast, ar-

gue that both parents' rather than only the mother's smoking habits are pivotal in order to have a noticeable effect on human face, such as dental asymmetries.

Our results show that facial development was significantly different in the category of mild smokers in comparison to non-smoking mothers and casual smokers for all age groups consistently exhibiting higher PD values. This indicates larger variation between initial shape and each stage in subsequential development. It can be due to either facial retardation in early phases of life, something that is not present in smoking free environment, but which eventually affects later development (Luciano et al. 1998; Lampl et al. 2003) or the shape change is intensified throughout the entire course of childhood and adolescence. Interestingly, a mother's occasional smoking habits do not become influential until the latest stage of maturation. This may point to the fact that adolescents have a tendency to adopt parents' habits, smoking included, which may add up and increase the overall effect. Exposure to cigarette smoke during pregnancy is also known to result in short stature and overweight in the later stages of child's life (Koshy et al. 2010). Our results, however, revealed no differences in timing of pubertal spurt between categories of non-smoker and mild smoker mothers.

Conclusion

The results obtained in this study suggest that the shape change in children's face is characterized by considerable diversity among individuals and is influenced by body proportions and environmental factors, such as living conditions and the mother's smoking habits. The result shows that all changes are intensified in boys while girls possess coping mechanisms preventing them from being affected by unfavorable conditions.

Poor living conditions as well as mothers' smoking habits were linked to more noticeable facial shape changes during development when compared to the facial shape at early stages of life.

Timing of the increase rate of the facial shape change in puberty coincides with that reflected in height. In girls, the beginning of pubertal increase rate of facial shape change was revealed at 10.5 years and the changes are completed at 14.5 years. In boys the pubertal increase rate starts at 11.5 years. Prior to the onset of puberty, girls exhibited more matured facial shape than boys.

Authors' contributions

MJ is the contractor of the research project as well as statistical analysis. MJ drafted manuscript. PU is the initiator and head of research who supervised the whole process and gave feedback. Both authors gave their final approval of the version to be published.

Conflict of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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