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Original article

Craniofacial changes from 13 to 62 years of age

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Summary

Background: In long-term studies of orthodontic, orthognathic, and prosthodontic treatments, control subjects are needed for comparison.

Objectives: To study the craniofacial (skeletal, soft tissue, and dental) changes that occur in untreated subjects with normal occlusion between 13 and 62 years of age.

Materials/Methods: Thirty subjects with a Class I normal occlusion and harmonious facial profile were studied. X-ray examinations were performed at 13 (T1), 16 (T2), 31 (T3), and 62 (T4) years of age, and data were obtained from cephalograms. In total, 53 angular and linear parameters were measured using superimposition-based and conventional cephalometric methods to describe the craniofacial changes.

Results: The jaws showed significant anterior growth from T1 to T2, and significant retrognathism from T3 to T4. The anterior face height and jaw dimensions increased significantly until T3. Significant posterior rotation of the mandible and opening of the vertical jaw relation, in addition to significant retroclination of the incisors and straightening of the facial profile, were found from T3 to T4.

Limitations: Given the small sample size at T4, it was not possible to analyse the gender dimension.

Conclusions/Implications: Craniofacial changes continue up to the sixth decade of life. These changes are consistent, albeit to a lesser extent, with the adolescent growth patterns for most of the studied parameters, with the exceptions of incisor inclination, sagittal jaw position, vertical jaw relation and inclination, and posterior face height.

Introduction

Interest in the facial aesthetic and functional aspects of dental treatments has increased over time, particularly among the adult population. Fifty years ago, orthodontic treatment was rarely administered to adult patients, whereas today adults account for 30% of the orthodontic population (1). Knowledge of normal long-term changes of the craniofacial structures is necessary to enable long-term predictions of treatment outcomes and risk assessments of both treatment relapse and normal ageing changes. This issue includes questions related to the long-term stability of orthodontic, orthognathic, and prosthodontic treatments, including the infra-occlusion of osseointegrated implants (2,3).

Currently, there is a lack of an orthodontically untreated reference material, with subjects that have normal characteristics participating in a longitudinal follow-up study, which would allow for more-valid research protocols, and in relation to the corrective treatment of patients with abnormal craniofacial morphologies.

Accurate evaluation of craniofacial changes in all three dimensions requires three-dimensional (3D) superimposition. However, repetitive 3D imaging should be limited due to the high dosage of radiation used (4,5). Furthermore, the 3D imaging method used for longitudinal follow-up has been available only during the last two decades. Therefore, cephalometric analysis in two-dimensional (2D) cephalograms remains the method of choice for long-term evaluations of vertical and horizontal craniofacial changes.

Only a few studies have assessed craniofacial changes up to late adulthood (6,7). However, the results of the studies performed on adults vary and are questionable, in part because most of the data were based on conventional cephalometric analyses (8–10). In the growing craniofacial skeleton, sutures between craniofacial bones and synchondroses in the skull base together with periosteal bone formation, regulate the sizes and shapes of the bones. Physiological age-related alterations of hard and soft tissues will also generate changes in the craniofacial complex (11,12). Conventional cephalometric measurements are, unfortunately, based on landmarks that are situated in structures known to undergo longitudinal age-related changes. To provide more valid information, craniofacial changes need to be analysed in superimposed cephalograms, using stable structures of the skull base (13–15).

The aim of the present study was to investigate the craniofacial (skeletal, soft tissue, and dental) changes that occur from early adolescence to late adulthood in a group of orthodontically untreated subjects with Class I normal occlusion, using a superimposition-based method (16).

Materials and methods

The present study was approved by the Regional Ethical Board in Umeå, Sweden (registration no. 2012-410-31M). In the 1960s, it was sufficient for one of the co-authors (MP) to ask the parents of the included subjects for approval for participation in the study. However, written informed consent was obtained from all participants recruited in 2014. This prospective, longitudinal study with follow-ups performed in early adolescence (T1), late adolescence (T2), early adulthood (T3), and late adulthood (T4), was deigned to establish a reference material for other orthodontic, orthognathic, prosthodontic, and forensic anthropological studies. The subjects in this study, which was established in the 1960s, were born in the early 1950's and were all healthy and represented ordinary patients who were recruited from the Public Dental Health Care system in Umeå, Sweden (17).

Materials

The material includes lateral cephalograms acquired from 30 untreated subjects. The inclusion criteria were: Angle Class I normal occlusion; normal overjet and overbite, normal transversal relation, up to 1 mm space deficiency in each jaw and a harmonious soft tissue profile, as clinically assessed initially at 13 years of age (T1). The exclusion criteria were: orthodontic treatment; maxillofacial surgery; missing teeth anterior to the second molar; craniofacial anomalies; and using mandibular advancement devices for treatment of snoring throughout the observation period.

The 30 subjects were examined with a cephalogram at 13, 16, and 31 years of age (T1, T2, and T3), albeit with a missing cephalogram at 16 years of age for one subject. At 62 years of age (T4), 26 subjects were followed-up, no subject showed major attrition of the teeth, although 4 subjects were excluded due to the absence of one or more of the first molars (Figure 1).

Methods

The lateral cephalograms were exposed with the same cephalostat, Philips Super Rotalix X-ray tube (Philips, Germany), at T1, T2, and T3, using a magnification factor of 1.1 (in midline). At T4, a digital cephalostat, Cranex cephalostat (Soredex, Helsinki, Finland), was used, also with magnification factor of 1.1. All cephalograms were performed with habitual occlusion and the lips relaxed. The cephalograms from T1, T2, and T3 were scanned with the Epson Perfection V750 Pro (Epson Europe B.V.) with a resolution of 250 dpi (0.092120 mm/pixel). Thereafter, the cephalograms were imported as JPEG files into the FACAD ver. 3.9.2.1133 cephalometric software. A calibration ruler, included on each scanned cephalogram, was used to perform calibration.

Cephalometric analysis

The cephalometric landmarks and lines used in the study are shown in Figure 2a and 2b, respectively. In total, 53 angular and linear parameters were used in this study to describe the craniofacial changes (Figures 3–6). Linear measurements were adjusted to a standardized enlargement of 10% (18). Overall, 28 of these parameters were measured using the superimposition-based cephalometric method (16). Direct measurements (conventional cephalometric method) were used to measure the remaining 25 parameters, which were independent of the superimposition (19). Two lines, the Nasion-Sella line (NSL) and a perpendicular line through the Sella (NSLP), were used as reference lines and two landmarks, S and N, were used as reference landmarks in the T1 radiograph. Superimposition onto the anterior cranial base was performed using the TW method (16). Afterwards, landmarks S and N and reference lines NSL and NSLP are transferred digitally from the T1 radiograph to the T2, T3, and T4 radiographs. The FACAD program allows measurements of the 28 parameters (superimposition-based cephalometric measurements) on each of the T2, T3, and T4 radiographs in relation

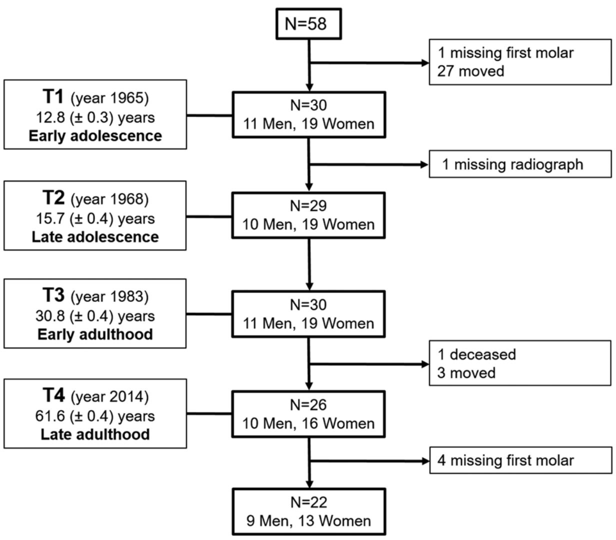

Figure 1. Flow chart showing the numbers of subjects, with their gender and mean age (SD) in years, who participated in the study and indicating the numbers of dropouts, for the four times (T1, T2, T3, and T4).

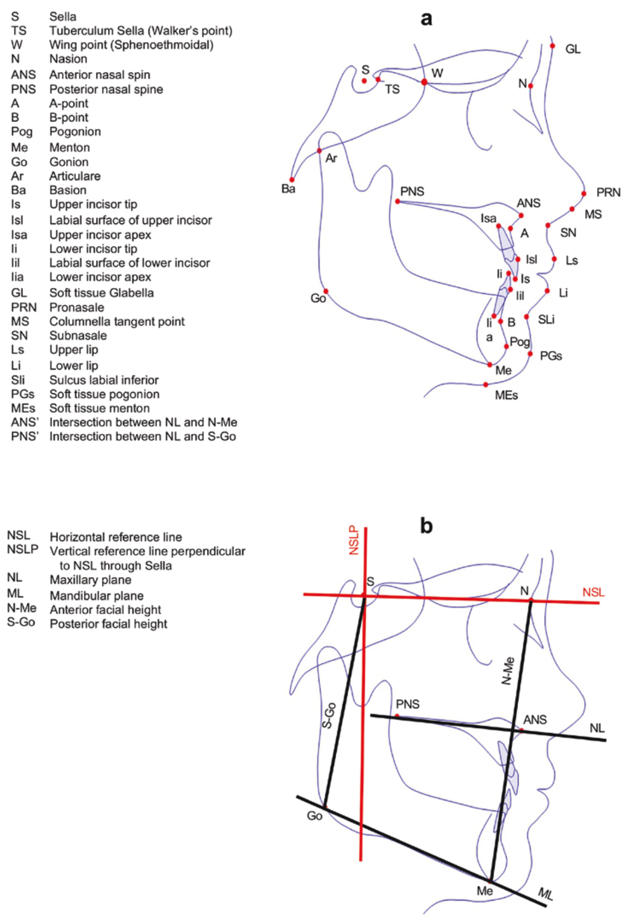

Figure 2. a. Landmarks and b. planes used in the study.

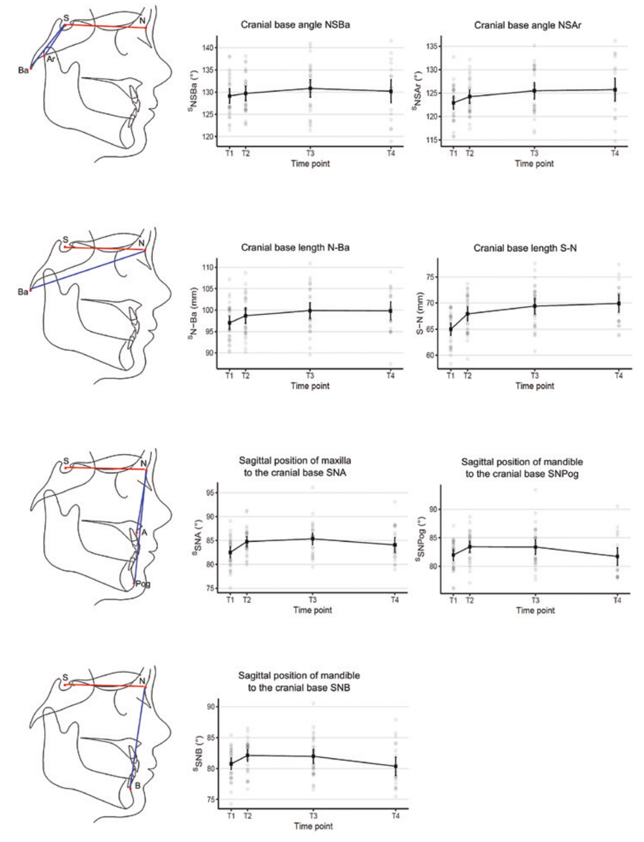

Figure 3. Skeletal changes. a. Cranial base and sagittal, b. Sagittal and vertical, c. Vertical. ^{S}Measured according to the superimposition-based cephalometric method.

to these transferred landmarks and reference lines from the T1 radiograph.

Error of method

Measurements of 53 parameters in 20 randomly selected radiographs were repeated by a single orthodontist (NA-T) on two occasions, with a 4-week interval, to assess the intra-observer reliability of the cephalometric measurements. After 3 months, another orthodontist (AW) performed tracings of the same 20 radiographs, to calculate the inter-observer reliability of the cephalometric measurements.

Statistical analysis

The intra-class correlation coefficient (ICC) with 95% confidence interval was used to determine the intra-observer and inter-observer reliability.

The mean values and standard deviations were estimated for all 53 parameters for the four times (T1, T2, T3, and T4). A paired *t*-test was used to establish if there were significant differences in the changes observed between the different times. The statistical significance level was set at $P < 0.05$. Statistical analyses were performed using the SPSS for Windows software.

Results

The intra- and inter-observer reliability levels were excellent, with ICCs in the range of 0.91–0.99 for all but three of the

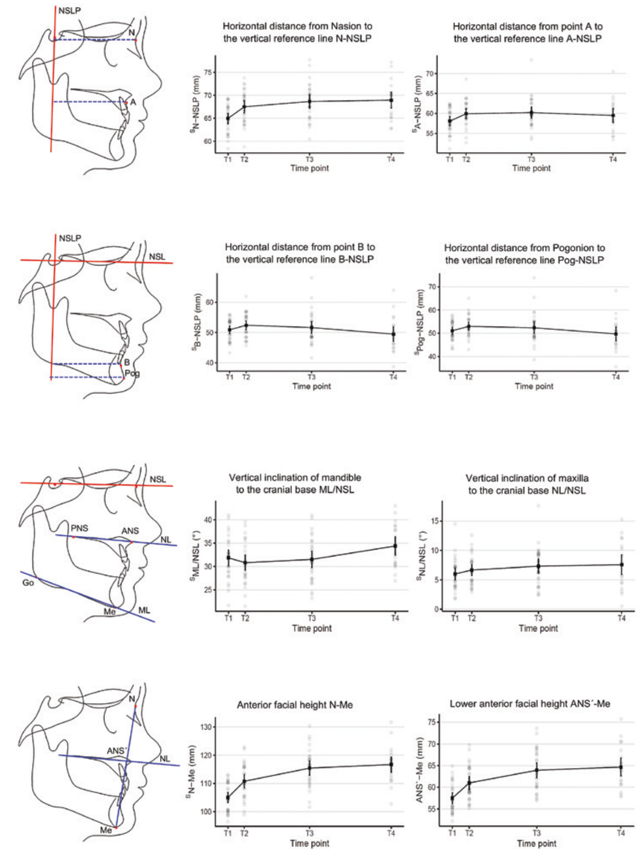

Figure 3. Continued.

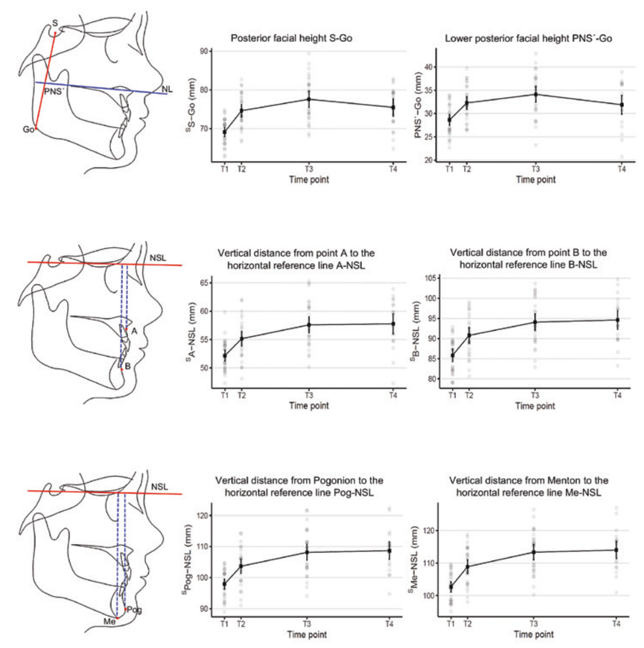

Figure 3. Continued.

parameters. The intra-observer reliability was good for the horizontal distance from Menton to the vertical reference line (Me-NSLP) with an ICC of 0.81, and the inter-observer reliability was good for Me-NSLP and the mentolabial angle with ICCs of 0.85 and 0.89, respectively (20).

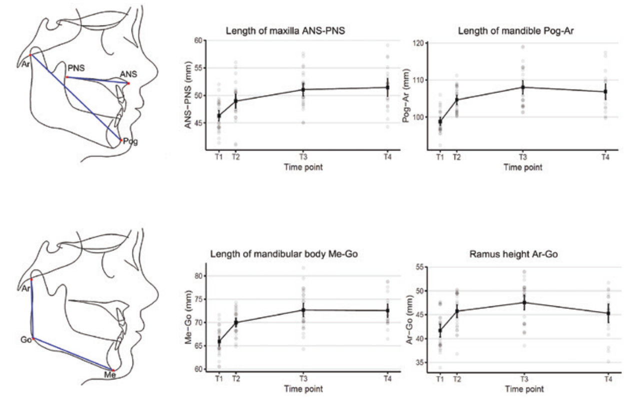

Figure 4. Changes in the jaw dimensions.

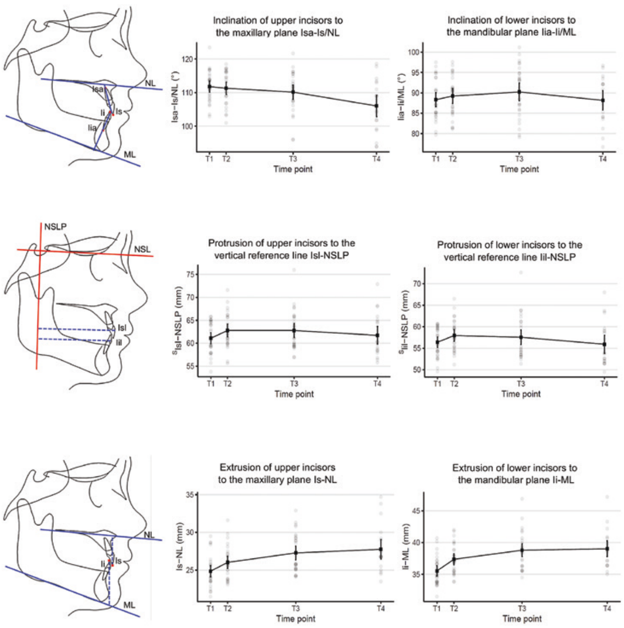

Figure 5. Changes in the dental relations. SMeasured according to the superimposition-based cephalometric method.

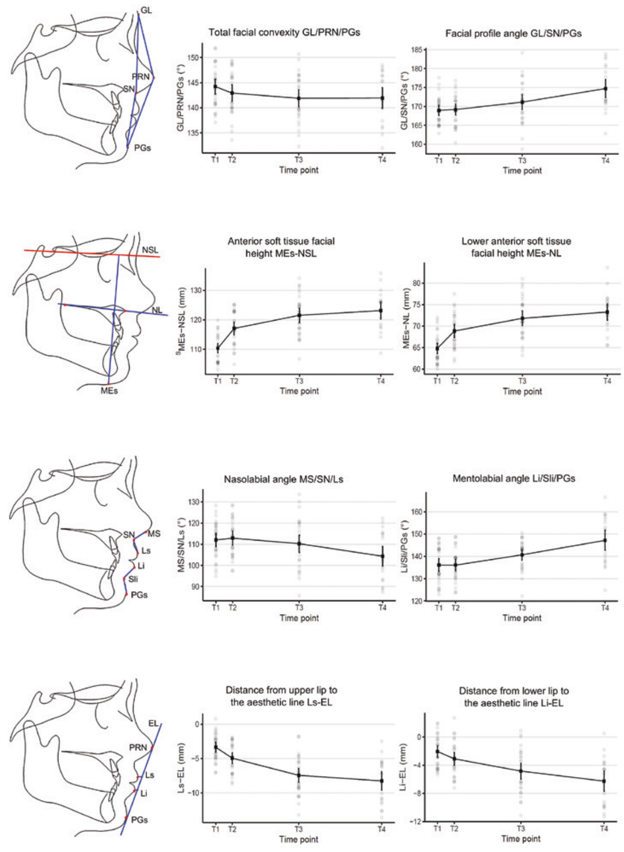

Figure 6. Changes in the soft tissue profile. SMeasured according to the superimposition-based cephalometric method.

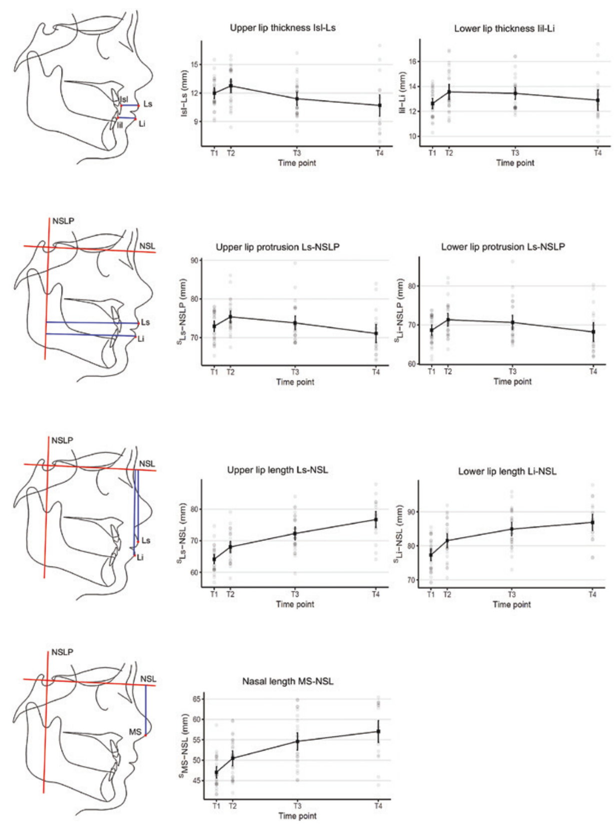

Figure 6. Continued.

Skeletal changes

The cranial base lengths (N-Ba and S-N) increased significantly (4 mm) throughout the observation period, with the largest increase occurring from T1 toT2 and from T2 to T3. The cranial base angle (NSAr) increased significantly (2.5°) from T1 to T2 and from T2 to T3 (Table 1; Figure 3a).

The angles representing the sagittal position of the maxilla and mandible in relation to the cranial base (SNA and SNB, SNPog, respectively) increased significantly by 1°–2° from T1 to T2, and thereafter decreased significantly by 1.5° from T3 to T4. The angle representing the sagittal jaw relation (ANB) increased significantly from T1 to T2 and from T2 to T3.

Landmarks A, B, Pogonion, and Menton moved significantly forward (2 mm) from T1 to T2 and moved backwards (2 mm) from T3 to T4 in relation to the vertical reference line (NSLP).

In all the studied periods, the Nasion landmark was displaced significantly forward (totally 4 mm) in relation to the vertical reference line (NSLP) (Table 1; Figure 3a and 3b).

Regarding the vertical changes, the vertical inclination of the mandible (ML/NSL) decreased significantly by 1° from T1 to T2, indicating anterior rotation. Furthermore, the ML/NSL angle increased significantly by 3° from T3 to T4, indicating

Table 1. Mean values (SD) for the skeletal changes at the four times, including the *P*-values obtained from paired *t*-tests for the changes that occurred between these times

Time point/parameters	T1	T2	T3	T4	Test of differences between time points		
					P-value T1-T2	*P*-value T2-T3	*P*-value T3-T4
Cranial base							
^{S}NSBa	129.1 (4.4)	129.7 (4.3)	130.8 (5.3)	130.2 (5.8)	0.196	0.032	0.684
^{S}NSAr	122.9 (3.8)	124.2 (3.8)	125.5 (4.7)	125.7 (5.5)	0.003	0.004	0.585
^{S}N-Ba	97.0 (4.1)	98.7 (4.7)	99.9 (5.0)	99.8 (4.7)	<0.001	0.004	0.047
S-N	65.0 (3.0)	67.9 (3.6)	69.4 (3.9)	69.9 (3.7)	<0.001	<0.001	0.035
Sagittal relation							
^{S}SNA	82.5 (3.2)	84.8 (2.7)	85.3 (3.3)	84.1 (3.5)	<0.001	0.144	0.007
^{S}SNB	80.8 (2.5)	82.1 (2.5)	82.0 (3.1)	80.4 (3.3)	<0.001	0.899	<0.001
^{S}ANB	1.8 (1.6)	2.6 (1.7)	3.4 (2.2)	3.7 (2.0)	<0.001	0.006	0.359
^{S}SNPog	82.0 (2.5)	83.4 (2.6)	83.4 (3.4)	81.7 (3.4)	<0.001	0.818	<0.001
^{S}N-NSLP	65.0 (3.0)	67.5 (3.5)	68.7 (3.9)	68.9 (3.9)	<0.001	<0.001	0.001
^{S}A-NSLP	58.1 (3.0)	59.9 (3.2)	60.2 (3.8)	59.5 (3.9)	<0.001	0.364	0.009
^{S}B-NSLP	50.9 (3.4)	52.4 (3.9)	51.6 (5.2)	49.5 (5.5)	0.006	0.514	<0.001
^{S}Pog-NSLP	51.1 (4.1)	53.0 (4.5)	52.3 (6.6)	49.7 (6.6)	0.003	0.831	<0.001
^{S}Me-NSLP	43.6 (4.0)	45.4(4.4)	44.5 (7.0)	41.8 (7.0)	0.004	0.692	<0.001
Vertical relation							
^{S}ML/NSL	31.9 (4.5)	30.8 (4.4)	31.5 (4.6)	34.4 (4.4)	0.015	0.357	<0.001
^{S}NL/NSL	6.0 (2.7)	6.7 (2.5)	7.3 (3.2)	7.6 (3.8)	0.023	0.150	0.441
ML/NL	25.8 (4.5)	24.2 (4.3)	24.2 (4.8)	26.8 (5.3)	<0.001	0.667	<0.001
^{S}N-Me	105.0 (4.8)	110.8 (6.1)	115.4(6.6)	116.7 (6.2)	<0.001	<0.001	0.528
ANS`-Me	57.5 (3.3)	61.0 (4.0)	63.9 (4.5)	64.7 (4.6)	<0.001	<0.001	0.597
^{S}S-Go	69.1 (3.2)	74.6 (4.3)	77.6 (5.5)	75.5 (5.1)	<0.001	<0.001	<0.001
PNS`-Go	28.6(3.1)	32.3 (3.6)	34.1 (4.4)	31.9 (4.5)	<0.001	<0.001	<0.001
^{S}N-NSL	0.0 (0.0)	0.4 (1.1)	1.2 (2.1)	1.6 (2.6)	0.056	0.039	0.090
^{S}A-NSL	52.2 (2.6)	55.1 (3.4)	57.6 (3.8)	57.8 (4.0)	<0.001	<0.001	0.267
^{S}B-NSL	85.8 (4.2)	90.8 (5.0)	94.1 (5.5)	94.6 (5.3)	<0.001	<0.001	0.488
^{S}Pog-NSL	97.9 (4.4)	103.7 (5.9)	108.1 (6.8)	108.7 (6.4)	<0.001	<0.001	0.187
^{S}Me-NSL	102.7 (4.2)	108.9 (5.6)	113.4 (6.2)	114.0 (6.0)	<0.001	<0.001	0.511

^{S}Measured according to superimposition-based cephalometric method.

posterior mandibular rotation. From T1 to T2, the vertical inclination of the maxilla (NL/NSL) increased slightly, albeit significantly, indicating a posterior rotation. The NL/NSL angle remained relatively unchanged from T2 to T3 and from T3 to T4. The vertical inter-maxillary angle (ML/NL) decreased significantly from T1 to T2, and increased significantly by 2.5° between T3 and T4.

The anterior facial height (N-Me) and lower anterior facial height (ANS`-Me) increased significantly by 5 mm and 3 mm, respectively, from T1 to T2, and in similar manner from T2 to T3. They continued to increase, albeit non-significantly, by about 1.3 mm and 0.8 mm respectively, from T3 to T4. On the other hand, the posterior facial height (S-Go) and lower posterior facial height (PNS`-Go) increased significantly from T1 to T2 (5 mm and 3 mm, respectively) and from T2 to T3 (3 mm and 2 mm, respectively), whereas they both decreased significantly (2 mm) from T3 to T4.

From T1 to T2 and from T2 to T3, the A, B, Pogonion, and Menton landmarks showed significant downward displacements in relation to the horizontal reference line (NSL). The Nasion landmark showed more anterior than downward displacement throughout the observation period. This might be explained by the occasionally observed upward displacement of the Nasion in some subjects. Nonetheless, the Nasion landmark showed a significant downward displacement from T2 to T3 (Table 1; Figure 3b and 3c).

Jaw dimensions and dental relations

The lengths of the maxilla (ANS-PNS), mandible (Ar-Pog), and mandibular body (Go-Me), as well as the ramus height (Ar-Go) increased significantly by 3 mm, 6 mm, 4 mm, and 4 mm, respectively, from T1 to T2 and continued to increase significantly by 2 mm, 3.5 mm, 2.5 mm, and 2 mm, respectively, from T2 to T3. While the maxillary length (ANS-PNS) and mandibular body length (Go-Me) were relatively unchanged from T3 to T4, the mandibular length (Pog-Ar) and ramus height decreased significantly in the corresponding period. The Gonial angle decreased significantly from T1 to T2 and from T2 to T3, and then increased significantly from T3 to T4 (Table 2; Figure 4).

Concerning the dental relations, the inclinations of the upper and lower incisors (Isa-Is/NL and Iia-Ii/ML) in relation to the maxillary and mandibular planes, respectively, remained relatively unchanged from T1 to T2 and from T2 to

Table 2. Mean values (SD) for the changes in the jaw dimensions and dental relations at the four times, including the *P*-values obtained from paired *t*-tests for the changes that occurred between these times

Time point/parameters	T1	T2	T3	T4	Test of differences between time points		
					P-value T1-T2	*P*-value T2-T3	*P*-value T3-T4
Jaw dimensions							
Maxilla length ANS-PNS	46.3 (2.5)	49.0 (3.3)	51.0 (3.0)	51.4 (3.7)	<0.001	<0.001	0.537
Mandible length Pog-Ar	98.8 (2.8)	104.6 (3.2)	108.0 (4.9)	106.8 (4.6)	<0.001	<0.001	<0.001
Mandible length Me-Go	66.0 (2.7)	70.0 (2.5)	72.7 (3.9)	72.5 (3.2)	<0.001	<0.001	0.459
Ramus height Ar-Go	41.7 (3.5)	45.7 (3.5)	47.6 (4.1)	45.3 (4.4)	<0.001	<0.001	<0.001
Gonial angle	128.7 (5.8)	126.2 (5.2)	124.9 (5.3)	127.2 (4.9)	<0.001	0.003	0.028
Dental relations							
Isa-Is/NL	111.8 (4.4)	111.3 (4.8)	110.2 (5.7)	106.0 (7.2)	0.205	0.164	<0.001
Iia-Ii/ML	88.3 (4.7)	89.2 (4.8)	90.2 (6.0)	88.2 (5.3)	0.080	0.165	<0.001
Isa-Is/Iia-Ii	134.0 (7.2)	135.3 (7.3)	135.4 (8.4)	139.0 (7.3)	0.049	0.869	<0.001
[S]Isl-NSLP	61.1 (3.3)	62.8 (3.6)	62.8 (4.1)	61.7 (4.4)	<0.001	0.750	0.007
[S]Iil-NSLP	56.4 (3.2)	58.0 (3.5)	57.5 (4.6)	55.9 (4.7)	<0.001	0.709	0.003
Ii-APog	1.2 (1.5)	1.0 (1.6)	0.8 (1.6)	0.8 (1.8)	0.117	0.311	0.367
Extrusion U inc Is-NL	24.9 (2.0)	26.0(2.1)	27.3 (2.4)	27.8 (2.9)	<0.001	<0.001	0.621
Extrusion L inc Ii-ML	35.5 (2.2)	37.4 (2.2)	38.8 (2.7)	39.0 (2.8)	<0.001	<0.001	0.679

[S]Measured according to superimposition-based cephalometric method.

Table 3. Mean values (SD) for the soft tissue profile changes at the four times including the *P*-values obtained from paired *t*-tests for the changes that occurred between these times

Time point/parameters	T1	T2	T3	T4	Test of differences between time points		
					P-value T1-T2	*P*-value T2-T3	*P*-value T3-T4
[S]MS-NSL	47.1 (3.7)	50.5 (4.7)	54.6 (5.6)	57.0(6.0)	<0.001	<0.001	<0.001
GL/PRN/PGs	144.2 (3.9)	142.9 (4.2)	141.9 (4.5)	141.9 (4.6)	0.027	0.200	0.429
GL/SN/PGs	168.9 (3.5)	169.2 (3.9)	171.1 (5.3)	174.7 (5.4)	0.851	<0.001	<0.001
[S]MEs-NSL	110.4 (4.4)	117.0 (5.6)	121.5 (6.6)	123.1 (6.3)	<0.001	<0.001	0.024
MEs-NL	64.8 (3.3)	68.8 (3.9)	71.8 (4.6)	73.3 (4.3)	<0.001	<0.001	0.008
MS/SN/Ls	112.0(8.6)	112.9(8.7)	110.3(11.0)	104.3(10.5)	0.718	0.131	0.001
Li/Sli/PGs	136.1 (7.8)	136.1 (6.8)	140.7 (6.3)	147.2 (10.1)	0.744	<0.001	0.006
Ls-EL	−3.4 (1.9)	−5.0 (2.0)	−7.5 (2.7)	−8.3 (3.1)	<0.001	<0.001	0.101
Li-EL	−2.1 (2.2)	−3.1 (2.4)	−4.8 (3.0)	−6.3 (3.2)	<0.001	<0.001	<0.001
Isl-Ls	12.0 (1.5)	12.7 (1.9)	11.4 (1.8)	10.7 (2.5)	0.016	<0.001	0.026
Iil-Li	12.6 (1.1)	13.6 (1.6)	13.4 (1.3)	12.9 (1.8)	<0.001	0.374	0.039
[S]Ls-NSLP	73.0 (3.6)	75.4 (4.0)	73.8(4.6)	71.1 (5.3)	<0.001	<0.001	<0.001
[S]Li-NSLP	68.7 (3.6)	71.3 (4.3)	70.7 (4.8)	68.2 (5.4)	<0.001	0.298	<0.001
[S]Ls-NSL	64.2 (3.8)	68.0 (4.6)	72.3 (5.4)	76.7 (5.7)	<0.001	<0.001	<0.001
[S]Li-NSL	77.3 (4.6)	81.5 (5.3)	84.9 (5.2)	86.9 (5.4)	<0.001	<0.001	0.093

[S]Measured according to superimposition-based cephalometric method.

T3. In contrast, from T3 to T4, the upper and lower incisors displayed significant retroclination (4° and 2°, respectively). The interincisal angle (Isa-Is/Iia-li) increased significantly by 1.3° and 3.6° from T1 to T2 and from T3 to T4, respectively. While the protrusions of the upper and lower incisors, in relation to the corresponding vertical reference line (IsI-NSLP and IiI-NSLP), increased significantly from T1 to T2, they decreased significantly from T3 to T4. The distance between the lower incisor and A-Pog line (Ii-APog) remained mostly unchanged throughout the studied periods. Eruptions of the upper and lower incisors were assessed by measuring the vertical distances from the upper and lower incisal edges to the maxillary (Is-NL) and mandibular planes (Ii-ML), respectively, and both of distances increased significantly from T1 to T2 and from T2 to T3 (Table 2; Figure 5).

Soft tissue profile

The angle of total facial convexity, including the nose, (GL/PRN/PGs) decreased significantly from T1 to T2, whereas the facial profile angle, without the nose, (GL/SN/PGs) increased significantly (5.5°) from T2 to T3 and from T3 to T4. The anterior soft tissue height of the face (MEs-NSL) and the nasal length (MS-NSL) increased significantly (13 mm and 10 mm, respectively) in all the studied periods. Most of the observed increase in anterior soft tissue height took place in the lower part (MEs-NL). However, the nasolabial angle (MS/SN/Ls) decreased significantly by 6.0° from T3 to T4, and the mentolabial angle (Li/Sli/PGs) increased significantly by 4.5° and 6.5°, from T2 to T3 and from T3 to T4, respectively. The distances between the lips and the aesthetic line (Ls-EL and Li-EL) increased significantly in all the studied periods. The thicknesses (lsl-Ls and lil-Li) and the protrusions (Ls-NSLP and Li-NSLP) of the upper and lower lips increased significantly from T1 to T2 and then decreased significantly from T3 to T4. In all the studied periods, significant downward displacements of the upper and lower lips in relation to the horizontal reference line (Ls-NSL and Li-NSL) were observed, with total displacement of 12 mm and 9 mm, respectively (Table 3; Figure 6a and 6b).

Discussion

The cohort used in the current study comprised orthodontically untreated subjects from a Caucasian population, with normal occlusion and harmonious facial profile. The 50-year follow-up period of this reference cohort shows that craniofacial changes continue to occur up to the sixth decade of life (Figure 7). These changes are consistent, albeit to a lesser extent, with the adolescent growth patterns for most of the studied parameters, with exceptions of incisor inclination, sagittal jaw position, vertical jaw relation and inclination, and posterior face height. Significant changes were seen for most of the soft tissue parameters throughout the observation period, during which the vertical changes of the soft tissue coincided with the underlying hard tissue, unlike the sagittal changes. In addition, prognathism of the maxilla and retroclination of the upper incisors were more-pronounced than in the mandible and lower incisors throughout the observation period. Moreover, from early to late adulthood, significant decreases in the jaw prognathism, posterior face height, and mandibular height and significant increase in the posterior mandibular rotation were observed. These are the most interesting findings of the present study. Thus, for a successful long-term outcome, clinicians should be aware of these age-related changes in patients who are scheduled for orthodontic, orthognathic, and prosthodontic treatments. During the years, some classic long-term follow-up studies of untreated materials have been reported (6–10,21,22). However, few studies (6,7) have presented radiographic follow-up examinations of untreated subjects aged >50 years. The study of Behrents consisted of an ageing population, although only four of the included subjects were aged more than 40 years (6). To date, no study has reported on the age-related craniofacial changes in subjects aged up to 60 years.

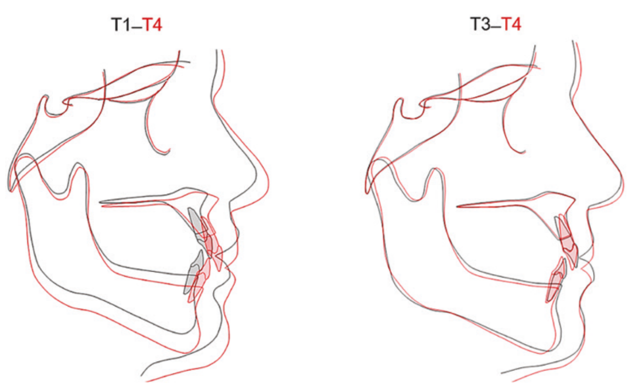

Figure 7. Superimposition-based cephalometric illustration of the craniofacial changes from T1–T4 and T3–T4.

In the present study, the measurements were performed according to the superimposition-based method (16), that is in relation to the original position of the Nasion and Sella landmarks and the NSL and NSLP reference lines at T1, following the superimposition. The TW method was used to perform superimposition onto the anterior cranial base (16). Thus, the age-related positional changes in the Nasion and Sella landmarks were excluded when measuring the angular and linear parameters. In addition, the intra- and inter-observer reliability tests showed good to excellent agreement. Consequently, the presented results for the cephalometric measurements can be considered to have a high level of precision.

Skeletal changes

The changes in the cranial base lengths and angles are in agreement with those described in other investigations (8,10), and indicate continuous alterations to the frontal sinus and basilar part of the occipital bone throughout adulthood, as reported earlier (6,23).

With regard to the skeletal sagittal changes, the increases in the SNA, SNB, and SNPog angles, together with the forward displacement of landmarks A, B, and Pogonion, observed during adolescence, imply anterior growth (prognathism) of the maxilla and mandible. Although different time intervals and ages were used, the anterior growth of the maxilla was also reported in previous studies (6,10). Meanwhile, the decreases in the SNA, SNB, and SNPog angles, together with backward displacements of landmarks A, B, and Pogonion, observed from early to late adulthood, point to minor retrognathism of the maxilla and mandible. This retrognathism may be due to the age-related decrease in cortical bone thickness (bone remodelling), as previously reported (11,24). Other longitudinal studies (7,8,22) have shown a relatively stable sagittal position of the jaws, since, in contrast to our study, the SNA, SNB, and SNPog angles were measured in relation to the anteriorly displaced Nasion.

Considering the skeletal vertical changes, the increases in lower anterior and posterior face heights, between early adolescence and early adulthood, constituted the major increases observed for the whole anterior and posterior face heights, respectively, and were caused by continuous eruption of the teeth, as reported earlier (6,21,22). Up to early adulthood, the increases in the face heights in conjunction with the downward displacements of landmarks B, Pogonion, and Menton, indicate downward growth of the mandible. However, the mandible displayed small changes in the vertical inclination up to early adulthood. After 30 years of age, a posterior mandibular rotation (3°) was observed, which is in line with the results of some studies (21,25), while other studies (6,7) have demonstrated anterior mandibular rotation among men and posterior rotation among women.

From early to late adulthood, a minimal increase in the anterior face height was noted, which was mainly in the lower anterior face height, in contrast to an observed decrease in the posterior face height (2 mm), which also occurred mainly in the lower posterior face height and was attributed to the upwards displacement of landmark Gonion. Taken together, these findings indicate that posterior mandibular rotation, from early to late adulthood, is likely due to upward inclination of the posterior part of the mandibular body, described as 'matrix rotation' (13). Thus, remodelling (resorption) occur within the region of the angle of the mandible from early to late adulthood, which may not necessarily clinically affect the treatment stability of the skeletal sagittal discrepancy.

As described in other studies (6,21,22), we observed downward growth of the maxilla from early adolescence to early adulthood, which can be explained by increases in the upper anterior and posterior face heights and downward displacement of the landmark A. However, the vertical inclination of the maxilla was rather stable during the observation period, and this is in line with Forsberg's results for a sample studied from 24 to 34 years of age (25).

That the ML/NL angle decreased during adolescence reflects deepening of the vertical jaw relation. However, between early and late adulthood, the ML/NL angle increased, reflecting opening of the vertical jaw relation. Thilander *et al.* (19). reported a deepening of the ML/NL during adolescence, whereas the study of Bishara *et al.* (10). demonstrated no significant changes of ML/NL angle from 25 to 46 years. Opening of the ML/NL angle must be considered during orthodontic treatment and orthognathic surgery, especially for patients with a skeletal vertical discrepancy.

Jaw dimensions and dental relations

The dimensions of the jaws increased up to early adulthood, which is in accordance with the results of other studies (6,7,10). Pecora *et al.* have reported that from early to late adulthood, the lengths of the maxilla and mandibular body remain stable (7). Nevertheless, the mandibular length and height decreased from early to late adulthood, as determined by the backward displacement of the Pogonion landmark and upward displacement of the Gonion landmark, respectively, which may depend on age-related bone remodelling.

Considering the total changes that occurred in the mandibular plane angle, mandibular length, and sagittal and vertical displacements of landmarks Menton and Gonion, from early adolescence to early adulthood, the decrease in the Gonial angle seems to depend on the amount of bone deposition at the angle of the mandible during the corresponding period. In contrast to the results of previous studies (6,25), the Gonial angle increased in the present study, from early to late adulthood, which may be due to upward displacement of landmark Gonion reflecting resorption at the angle of the mandible.

The upper and lower incisors demonstrated significant protrusions during adolescence and relatively stable inclination from early adolescence to early adulthood. Thereafter, from early to late adulthood, the incisors exhibited significant retrusion and retroclination. Other studies have also reported retroclination of the incisors (6,8). The clinical implications of the upper incisor retroclinations are important and must be taken in to account when planning extractions for patients with crowding and/or Class II malocclusion. Considering the minimal decrease in upper incisor protrusion and relatively stable vertical inclination of the maxilla, retroclination of the upper incisors (by about 4° in relation to the maxillary plane) from early to late adulthood likely results from forward displacement of the incisors apex. In addition, retroclination of the lower incisors from early to late adulthood is due to the posterior mandibular rotation and not to the change in the

Table 4. Age-related craniofacial changes reported by previous studies

Studies	Age/Years	S-N mm	SNA°	SNB°	ANB°	ML/NSL°	N-Me mm	S-Go mm	Mandible length mm	iLs/NL°	Ili/ML°
Forsberg (25)	24–34	X	X	X	+	+	+	X	X	–	+ M
Forsberg *et al.* (21)	25–45	X	X	X	X	+	+	X	X	–	+ n.s.
Bishara *et al.* (10)	25–46	+	+ M 0 F	– F + n.s. M	+	+ n.s. F 0 M	+	+	+	X	– n.s. M 0 F
West and McNamara (22)	30–47	X	0	0	0	0	+	+	+	X	– n.s.
Pecora *et al.* (7)	17–47	+	0	– F + n.s. M	+ F	+ F – M	+	+	+	X	+ n.s.
Pecora *et al.* (7)	47–57	0	0	0	+ n.s.	0	+ n.s.	+ n.s.	0	X	– n.s.
Bondevik (8)	22–33	+	– F – n.s.	– F – n.s. M	X	+ F 0	+	+	+	X	–
Bondevik (8)	33–43	+	– n.s. F + n.s. M	– F 0 M	X	+ n.s. F – n.s. M	+	+ M 0 F	+	X	– n.s.

+, Increased; –, Decreased; n.s., Non-significant; 0, No changes; M, Male; F, Female; X, Not examined.

axial inclination of the lower incisor, since the increase in the interincisal angle corresponds to the extent of retroclination of the upper incisors.

The relatively stable distances between the lower incisors and A-Pog line are in accordance with other studies (6,7) and indicate concomitant changes in the displacements of the A and Pogonion landmarks and in the protrusions of the lower incisors, particularly from early to late adulthood.

Up to early adulthood, the upper and lower incisors exhibit extrusions, (of about 3 mm) in relation to the maxillary and mandibular planes, respectively, which are consistent with the results of other studies (6,7,21). The incisors continued to erupt, although non-significantly, from early to late adulthood. The continuous eruption of the upper and lower incisors is a clinically relevant factor during implant installation, particularly in the anterior region.

Soft tissue profile

Almost all the changes observed in the facial soft tissues agree with the results from previous studies (6,7,9). The angle of total facial convexity (including the nose) decreased slightly between early adolescence and early adulthood, reflecting more-forward growth of the nose relative to the growth of soft tissues in the chin and glabella. The facial profile angle (without the nose) increased during the observation period, indicating the development of a straighter face profile with age, which may reflect thinning of the upper lip and thickening of the soft tissue at the chin and glabella. An increase of the facial profile angle was also noted by Bishara and colleagues between the ages of 25 and 46 years (9).

The retrusion of the lips in relation to the aesthetic line reflected the thinning of the lips and forward growth of the nose and chin, as reported earlier (6,9).

The upper and lower lips continued to be displaced downwards through to late adulthood. These displacements exceeded the skeletal downward growth, which resulted in a less-prominent display of the upper incisor.

The discrepancies between the results of the present study and those of previous studies (6–10,21,22,25) (Table 4) are attributable to several factors, including differences in significance levels, the landmarks used for the linear and angular measurements, and the chosen time intervals (7,9,22). In the previous studies (6–10,21,22), the age-related horizontal and vertical displacements of landmarks Nasion and Sella were not considered when measuring the craniofacial changes. In addition, some of those studies (8–10) used conventional cephalometric measurements.

Limitations

Considering the small sample size ($N = 22$ at T4), we could not analyse our sample in relation to gender. However, other studies (6,7) have shown differences between men and women for some craniofacial parameters. Since a change in body weight can affect assessments of the soft tissue profile, we should have included measures of weight at each follow-up. Although, several studies have shown that 2D lateral cephalometry has precision and accuracy levels similar to those of analyses with 3D-generated cephalograms (26–28), we could not describe the transversal changes in the frontal plane. This is an interesting issue for exploration in future studies. Finally, a limitation with the cephalometric examinations performed at T1–T3 is that the acquired films needed to be scanned. Scanning process can involve a somewhat lower resolution and blurring. However, with this method, we did not experience any problems with the image quality or with identifying anatomical structures.

Conclusions

The craniofacial changes were more-pronounced between 13 and 31 years of age and can be summarized as follows:

1. The length and inclination of the cranial base increased simultaneously with the increases in the dimensions of the jaws.
2. The upper and lower jaws showed more-downward than anterior movement, although the vertical inclination of the jaws was relatively unchanged.
3. The upper and lower incisors showed extrusion, although their inclinations remained unchanged.
4. The soft tissue face height, distance from the lips to the aesthetic line, and downward displacement of the lips, and nose length showed pronounced increases.

The craniofacial changes were less-pronounced between 31 and 62 years of age and can be summarized as follows:

1. The length and inclination of the cranial base were relatively stable, as were the lengths of the jaws.
2. The upper and lower jaws showed minor retrognathism, and while the lower jaw exhibited posterior rotation, the inclination of the upper jaw was unchanged.
3. The upper and lower incisors exhibited retroclination, with concomitant straightening of the soft tissue profile and thinning of the lips.
4. The soft tissue face height, distance from the lips to the aesthetic line, downward displacements of the lips, and nose length all continued to increase.

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Conflict of interest

Not to declare.

Data availability

The data underlying this article are available in the article and in its online supplementary material.

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