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Three-dimensional facial growth studied by optical surface scanning

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Abstract *The objective of the investigation was to study the three-dimensional growth of the face, and to examine the hypothesis that there are three-dimensional differences between the faces of boys and girls. The subjects comprised 132 British Caucasians aged 5–10 years measured by optical surface scanning in this cross-sectional study. Average scans for each age and sex subgroup were superimposed to assess the differences with age and sex. Males were generally larger than females. The greatest difference was between the facial heights and the least in the mid-facial dimensions. The face height of both sexes increased by an average of 3–4 mm annually. Mid-face prominence and width altered little. Mandibular width increased by 1–3 mm a year, rising to 3–5 mm in some years at the inferior areas of the mandibular region. Mandibular prominence also increased. Nose height and prominence and alar base width increased by 2 mm per year on average. Dorsum width changed little. Boys were generally larger than girls. Growth in facial height was greatest. Mid-face prominence and width changed little with age, whilst the prominence and width of the lower face increased more. Nasal prominence and alar base width increased at most ages. Dimensions changed more than reported by cephalometric studies, possibly as this study included the soft tissues.*

Index words: Facial Growth, Childhood, Optical Surface Scanner, Three-dimensions.

Refereed Scientific Paper

Introduction

The volume of literature reporting research into facial growth is huge, reflecting the importance of the topic. Much of the measurement has been two-dimensional, but some studies have measured in three dimensions.

Vertical skeletal growth has been measured by cephalometrics and anthropometrics, and average annual changes of 1–2 mm in the pre-pubertal period have been found (Riolo *et al*., 1974; Farkas, 1981; Van der Beek *et al*. 1991). Using photography, Bishara *et al*. (1995) showed an increase of just under 2 mm a year. However, the method of landmark identification by eye on photographs could be a potential source of error. The sex difference in facial height varies from 1 mm (Nanda, 1955; Snodell *et al*., 1993) to just over 2 mm, with males larger than the females (Riolo *et al*., 1974; Bhatia and Leighton, 1993). Bishara *et al*. (1995) found the male face height to be 5–6 mm greater than the female. This could reflect the inclusion of the soft tissues in their measurements or the difficulty of accurately placing landmarks on a two-dimensional photograph.

Less data has been collected on facial width, due to the predominance of lateral cephalometry as an imaging technique. Woods (1950) found an average annual bi-gonial width increase of 1·5 to 2 mm. Farkas (1981) found the zygomatic and gonial widths each increased by about 7 mm from 6 to 10 years of age. As the gonial width was initially less, it proportionally changed more. This agrees with Snodell *et al*. (1993), who found a gradient of width growth, with the cranium growing least and the mandible the most. A number of studies have shown width increases to be less than vertical changes (Snodell *et al*., 1993; Bishara *et al*., 1995). Sex differences in zygomatic width of about 1 mm (Farkas, 1981) and bi-gonial width of 3 mm (Riolo *et al*., 1974; Farkas, 1981) have been found.

The soft tissue facial contour has been shown to change differently from the underlying hard tissues (Subtelny, 1959). The soft tissue convexity increases slightly from 3 to 6 years and remains quite stable after that, despite decreasing hard tissue convexity. This is due to the soft tissues overlying A point growing in thickness more than those overlying pogonion. This effect excludes the nose, whose forward growth causes an increasing convexity after 3 years of age. Chaconas and Bartroff (1975) also found that the increase in facial convexity was largely due to nasal growth. Woods (1950) found an increasing gradient of facial growth in terms of prominence, with the sella–nasion line attaining 95 per cent of adult length by five years, the maxilla 87 per cent and the mandible 81 per cent. The soft tissue integument of males is thicker than females at all pre-pubertal ages (Subtelny, 1959).

Many papers have reported on nasal growth, finding it to be an important contributor to changes in the overall facial profile. An increase in nasal size has been reported by many researchers (Subtelny, 1959; Burke and Hughes-Lawson, 1989; Nanda *et al*., 1990), although lateral cephalometry has been constrained to vertical and horizontal changes. Burke and Hughes-Lawson (1989), using stereophotogrammetry, and Snodell *et al*. (1993), using postero-anterior cephalometry, both found that nasal width grows markedly. Farkas (1981), and Burke and Hughes-Lawson (1989) both showed little change in dorsum width and a greater change in alar width, the latter concluding that the inter-canthal width relates to orbital growth. This would cause it to follow a neural growth pattern, and thus be nearer to its adult size than other parts of the nose. Burke and Hughes-

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Lawson (1989) showed a similar volumetric change in the sexes until 9 years of age, after which the male nose grew at a greater rate. The sex difference in nasal dimensions has generally been found to be quite small in the pre-pubertal period (Farkas, 1981; Nanda *et al.*, 1990; Snodell *et al.*, 1993), the male nose being up to 1 mm larger in most of its dimensions.

Much of the research on facial growth has been performed using lateral cephalometry (Riolo *et al.*, 1974; Bhatia and Leighton, 1993). Whilst it is an accurate reproducible method, there are shortcomings. The radiograph is a two-dimensional representation of a three-dimensional subject, leading to a simplified interpretation of the structures imaged and the process of facial growth. There is the inherent problem of measuring growth of three-dimensional curved surfaces by linear and angular measurements between artificially defined landmarks (Moyers and Bookstein, 1979). Structures out of the mid-saggital plane are subject to increased errors of magnification and identification (Steiner, 1953).

The cephalostat was originally devised to take postero-anterior, as well as lateral views (Broadbent, 1931), giving the ability for three-dimensional cephalometric measurements (Grayson *et al.*, 1988). However, most soft tissue points are not available for study as they do not appear on both views. Additionally, geometrically determined landmarks, such as menton, will be positioned in different locations depending on the direction from which the radiograph is taken. All the landmarks have different magnification factors in each view, as they are a different distance from the source and the film. Stereophotogrammetric cephalometry, using radiographs from two different views, has been developed as a method of three-dimensional analysis (Baumrind *et al.*, 1983), but the technique can be difficult and time-consuming to use.

Other methods of three-dimensional measurement of the face have been employed. Anthropometry (Farkas, 1981) requires only simple instruments and is an easy technique to learn. However, it is time-consuming to carry out comprehensive measurements, making it less suitable for the young subject. Obviously, it does not produce an image of the face, only linear and angular measurements. Photographic techniques suffer from image distortion and inaccuracy of measurement unless a telecentric lens is used (Robertson and Volp, 1981). Techniques relying on the digitization of contour maps such as moiré stripe photography (Takasaki, 1970; Kawai *et al.*, 1990) can be difficult to analyse and measure, especially in areas of high relief such as the nose, where the contour lines will be very closely placed. Measurement by stereophotogrammetry (Burke and Beard, 1967) has been applied to the face, but the technique is difficult and requires considerable expertise.

The optical surface scanner (Arridge *et al.*, 1985) has the advantage of rapid accurate data collection in three dimensions. The lack of ionising radiation allows data to be acquired of normal subjects for research. The associated software creates a visual image of the subject and an average image for a group of subjects, thus allowing differences between subjects or groups of subjects to be measured. The accuracy of the system has been tested (Aung *et al.*, 1995). The major disadvantage of the system is its cost.

Most recently, a video-capture stereoscopic method of imaging has been developed (Ayoub *et al.*, 1998). Two pairs of stereo cameras ensure that the curved facial surfaces are completely imaged within 2 seconds. The system allows photo-realistic image generation of the face that can be viewed from any direction. The polygonal facial model can be used to measure facial landmarks and volumes. An accuracy of landmark capture of 0·5 mm has been quoted and the system promises much for the future in terms of facial imaging, measurement, and surgical prediction.

The aims of this study were to compare the three-dimensional facial morphology of girls and boys of the same age, and to study the three-dimensional alterations in the facial morphology with increasing age.

Subjects and Methods

Data acquisition

One-hundred-and-thirty-two 5–10-year-olds comprising 72 males and 60 females, were recruited for the study. They were distributed as shown in Table 1.

To reduce the possible errors caused by the cross-sectional nature of the study, the following criteria were applied:

1. Caucasian, of British or North European ancestry.
2. Assessed clinically as Skeletal I, with average face height and no abnormal degree of facial asymmetry.

It was felt that without these, a child with abnormal facial morphology could have biased the average for their age and sex subgroup.

Each child was scanned once by the optical surface scanner (Figure 1). The subject was instructed to sit still with the facial muscles relaxed and the eyes lightly closed. With the room darkened, a lens fanned the helium-neon laser beam into a 0·7-mm wide line along the face. As the motorized chair rotated, the face was scanned by the laser over a period of about 10 seconds. A video camera read approximately 60,000 data points from across the face. A microcomputer processed the data points and joined adjacent points to form triangular facets. These facets were shaded to give a solid-looking image that could be viewed on a monitor. If the image obtained was of poor quality, the scan was repeated until one of a sufficiently high standard had been obtained.

TABLE 1 *Number of subjects in each subgroup (figures in brackets are the average ages of each group)*

	5 years	6 years	7 years	8 years	9 years	10 years
Males	13 (5 y 6 m)	12 (6 y 8 m)	16 (7 y 5 m)	13 (8 y 8 m)	9 (9 y 6 m)	9 (10 y 8 m)
Fe males	9 (5 y 5 m)	10 (6 y 6 m)	12 (7 y 4 m)	10 (8 y 8 m)	10 (9 y 4 m)	9 (10 y 6 m)

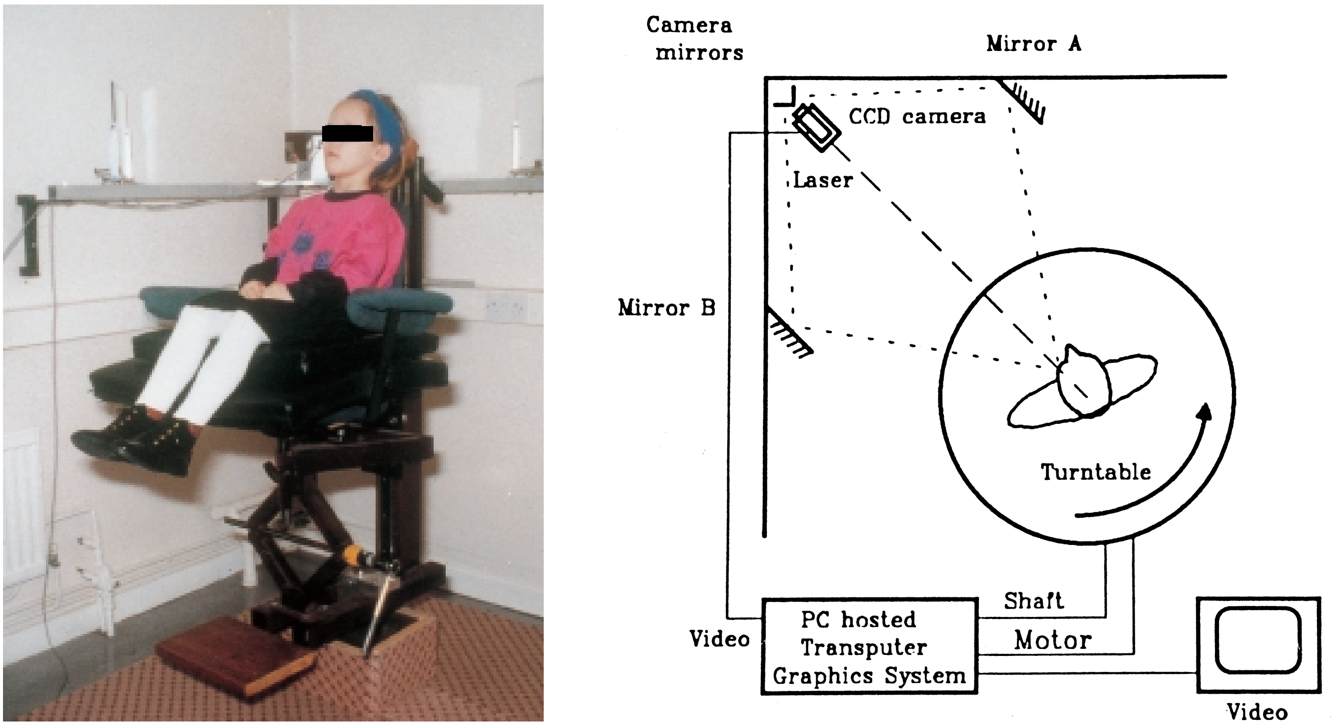

FIG. 1 Plan diagram and photograph of the optical surface scanner.

Landmarking

To allow processing and analysis, the scans were landmarked. To aid the identification of points of maximum and minimum curvature in three dimensions, the individual data points that make up each vertical and transverse profile were viewed, as well as the overall facial image. Five landmarks were placed by the operator:

1. Left lateral canthus.
2. Left medial canthus.
3. Soft tissue nasion—the point that is the most concave in the vertical profile and the most convex in the transverse profile.
4. Right medial canthus.
5. Right lateral canthus.

Five further points were automatically constructed by the computer across the forehead. The software program joined landmarks 1 to 5 by a line of best fit. A second, parallel line was then constructed thirty mm above this. A landmark was constructed on this line, above landmark 3. A further landmark was constructed 15 mm either side of this and a further landmark 15 mm lateral to each of these.

The final 5 points, like the first 5 were marked by the operator:

11. Left alar base—the most inferior, lateral point on the left alar base.
12. The mid-line of the base of the nose, at the most concave point in the vertical plane.
13. Right alar base—the most inferior, lateral point on the right alar base.
14. The most anterior point in the mid-line of the upper lip—the most convex point in both the vertical and transverse profiles.
15. The most anterior point in the mid-line of the lower lip—the most convex point in both the vertical and transverse profiles.

Averaging

Each scan was edited by the operator to remove unwanted data, such as the hair and the base of the neck, as during the averaging procedure the computer treats all areas of the scan image with equal importance.

The 15 landmarks were used by the computer to create a representative average scan for each age and sex subgroup. The set of scans were resampled on a cylindrical co-ordinate grid system, and the co-ordinates averaged to give the average scan and a one standard deviation facial form. The average for the 8-year-old males is shown from the frontal and right lateral views as an example (Figure 2).

Superimposition

To allow age and sex differences to be assessed, the averages were superimposed. Landmarks 1–10, to obtain an average, were superimposed over the same landmarks for the average with which it was to be compared. The landmarks were superimposed using a least-means squared method of 'best fit' with a RMS error of less than 0·5 mm. Radial measurements were calculated from the central axis of the head to the facial surface and the dimensional differences represented by colour superimposition.

FIG. 2 Eight-year-old male average scan.

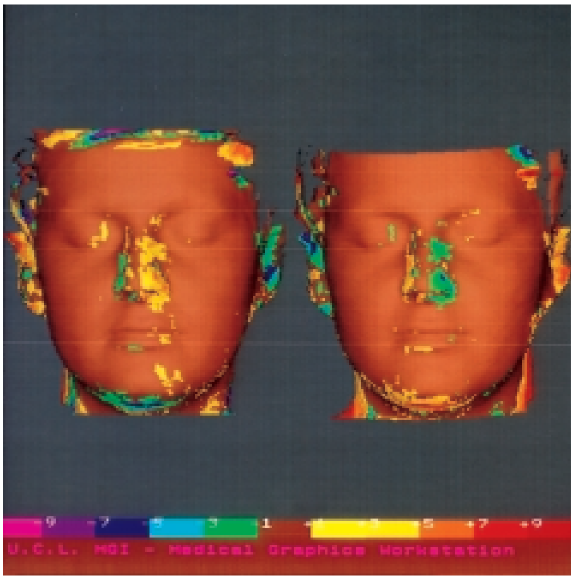

FIG. 3 Error study superimposition.

Each pair of average scans being superimposed and compared was displayed adjacently on a monitor. 'Warm' colours (yellow→orange→red) indicated positive differences and 'cold' colours (green→blue→purple) indicated negative differences. Each colour represented a 2-mm difference in dimensions from the previous colour. Areas with no dimensional difference were shaded brown. The left side of the screen displayed the result of the left image compared to the right, and the right side of the screen displayed the result of the right image compared to the left. Thus, the colour shading of one image was the exact opposite of the other. The superimposition images were produced in both the frontal and the lateral views.

Averages of the two sexes at each age were superimposed to examine the differences between the sexes. Averages of the same sex, but different ages were superimposed to examine the changes with increasing age.

Error Study

This was performed to assess the error due to scan acquisition and landmarking. Ten adults were scanned twice, with a 1-week interval between the scans. Each group of 10 scans was averaged and the two averages were superimposed. The superimposition was mostly brown, denoting no dimensional difference and, hence, indicating a consistent technique of scan acquisition and landmarking (Figure 3).

Results

The superimposition of the seven year old male and female averages illustrates how the results were analysed (Figure 4). The colour bar at the bottom of the picture shows the dimensional difference represented by each colour. The male face height is 7–9 mm greater than the female. There is very little difference in the infra-orbital regions in either width or prominence. The male face is 1–3 mm wider generally, increasing to 3–5 mm at the inferior region of the mandible and 5–7 mm at the lower border. The lower half of the face and much of the chin are 1–3 mm more prominent in the males than the females. The male alar base is 1–3 mm wider than the female on the right side, but less on the left side. The height and prominence of the noses are similar.

As explained before, each scan consists of approximately 60,000 data points, each of which is spatially located in three dimensions. It is not possible to statistically analyse three-dimensional data of this nature in any meaningful way at present. To try and apply statistical tests, one would have to ignore a great deal of the data acquired. The interpretation of the scans would then give little advantage over cephalometrics and the other two-dimensional imaging systems. It is for this reason that a number of superimposition scans are included in the paper, as the results of three-dimensional data acquired with the optical surface scanner cannot usefully be distilled into just the linear measurement of distances between two landmarks. An appreciation of the overall shape changes occurring in the face in three dimensions is a major advantage of the technique.

Female Changes with Age

The superimposition of the 9- and 10-year-old averages is shown in Figure 5 as an example. The face height increased each year. The actual amount varied from year to year, but averaged approximately 4 mm each year. The width and prominence of the mid-face varied very little each year. The width of the lower parts of the mid-face and the mandible increased more, with a 1–3-mm increase at most ages, and 3–5 mm in some of the most inferior parts of the mandibular region. The prominence of the chin varied little until eight years of age. After this age, the chin increased

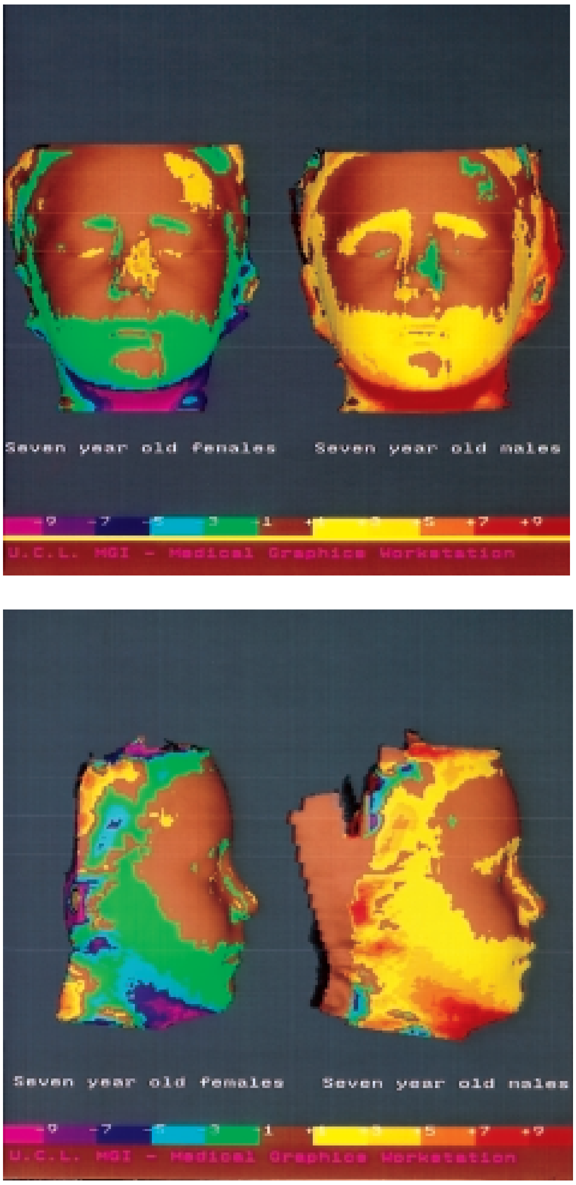

FIG. 4 Superimposition of the 7-year-old males and females.

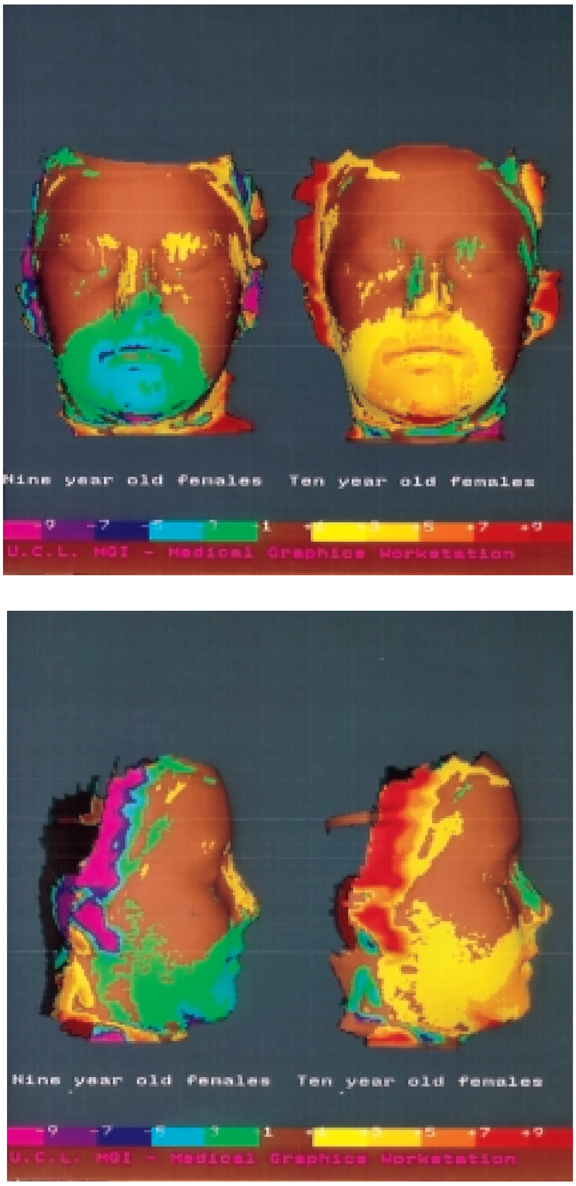

FIG. 5 Superimposition of the 9- and 10-year-old females.

in prominence: by 3–5 mm from 9 to 10 years of age. The nose increased by 1–3 mm in most of its dimensions each year.

Male Changes with Age

The superimposition of the 6- and 7-year-old averages is shown in Figure 6 as an example. The pattern of facial growth was very similar to that of the females. The face height increased by a variable annual amount, which averaged approximately 4 mm. The width of the mid-face varied little, only increasing by 1–3 mm from 5 to 6 and 7 to 8 years. The width increase of the lower part of the face was greater, rising to 3–5 mm in the most inferior regions. The prominence of the mid-face varied little, whilst the chin became 5–7 mm more prominent from 5 to 10 years. As with the females, the majority of the increase in prominence occurred after 8 years of age. The nose increased in width by 1–3 mm annually. The increase in nose height was generally greater, rising to 3–5 mm from 9 to 10 years of age.

Comparison of Males and Females

The face height of the males was consistently greater than the females: by 7–9 mm in most of the age groups. The width of the mid-face was very similar, with the males being 1–3 mm wider on average. The prominence of the mid-face showed very little difference between the sexes. The male mandibular region was 3–5 mm wider in most age groups. An even more pronounced difference of 5–7 mm was found at the lower border of the mandible, in all except the

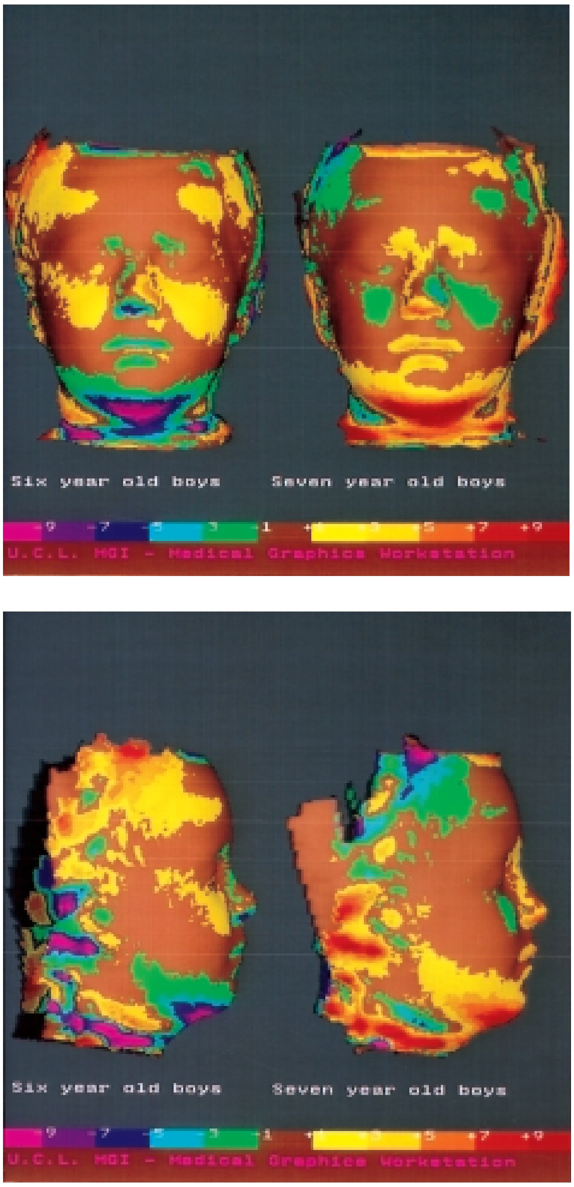

FIG. 6 Superimposition of the 6- and 7-year-old males.

6-year-olds. The male chin was more prominent, except in the 10-year-olds, whose prominence was almost identical.

There was very little difference between the nasal dimensions in the 5-, 6-, and 7-year age groups. However, in the older age groups the alar base width is 1–3 mm greater in the males. The 10-year-old male nose was 1–3 mm greater in all the dimensions of height, width, and prominence.

Discussion

This study was cross-sectional in design. The subjects used can, however, be re-scanned each year and so this data serves as the basis for a longitudinal study. It is quite possible that a child who was large or small for their age could have affected the average for their subgroup, thus giving rise to misleading results. This could explain some of the fluctuations in the annual changes for some measurements. Similarly, the 9-year-old boys were found to be smaller than the 9-year-old girls and the 8-year-old boys, in direct opposition to the pattern found for all other age and sex groups. This is most likely to be due to some small subjects in the 9-year-old male subgroup.

A subgroup containing a higher proportion of subjects at either the upper or lower end of the year's range could make the average larger or smaller, respectively, than the true average for that age. To minimize this problem, as many children of each age were scanned as possible and the average age of the subgroups was generally close to the middle of each year's range (Table 1).

All the landmarking was performed by one operator for consistency. The visualization of a landmark in three dimensions is not possible from a two-dimensional image. Therefore, the raw data points that make up the vertical and transverse profiles for the area to be landmarked are also viewed. This allows the location of points of maxima and minima on the curving surfaces of the face, and thus allows three-dimensional landmarks to be defined. As with any technique relying upon the use of landmarks, there is the possibility of operator error. In recognition of this fact, methods of mathematically defining the landmarks are being developed, which should hopefully lead to the automation of this procedure by the computer software (Moss *et al*. 1992).

Changes with Age

The increase in face height in both sexes is greater than found by Farkas (1981), Riolo *et al.* (1974), and Van der Beek *et al.* (1991), who found an annual change of approximately 2 mm. The difference could be due to this study including the soft tissues, whereas the other studies measured only the hard tissue face height.

The small change in mid-face width agrees with other studies (Farkas, 1981; Bishara *et al.*, 1995). The greater increase in the mandibular width also agrees with other studies (Riolo *et al.*, 1974; Farkas, 1981; Bishara *et al.*, 1995), but the magnitude of the changes found was greater in this study. As mentioned before, this could be because the cephalometric and anthropometric studies aim to measure only the hard tissues. Most studies measure the bi-gonial width and, indeed, this is the only measure of mandibular width studied by cephalometry. In contrast, this study included the soft tissues such as the masseter, which will also increase in dimensions with age, in the same way as the hard tissues. One of the advantages of the three-dimensional collection of data performed by the optical surface scanner was its ability to provide a more complete view of the width changes of the whole face than is available by cephalometry.

A gradient of change in facial width can therefore be seen. There is little or no increase in the upper face, small changes in the mid-face and, increasingly, greater increases in the lower face as the lower border of the mandible is approached.

Comparison of changes in facial prominence with other studies is not possible, as cephalometry usually measures some type of maxillary or mandibular unit length. However, the pattern of change, with small increases in the mid-face and greater increases in the lower face, agrees with other studies (Canon, 1970; Nanda, 1992).

The increase in alar base width, nasal height, and nasal prominence, but no increase in the dorsum width is in agreement with other studies (Meng *et al*., 1988; Burke and Hughes-Lawson, 1989). However, the annual alar base width increase of 1 mm bilaterally is more than Farkas (1981) and Bishara *et al*. (1995) who reported an increase of 0·5 mm per year. This may be due to the scan time allowing alar flaring with breathing. The increases in nasal height and prominence agree with other studies.

Comparison of Males and Females

The greater male face height agrees with other studies. However, Farkas (1981) found only 2 mm difference in the total face height using anthropometry. This, however, was with the soft tissues compressed over gnathion. Cephalometric studies also report less difference, possibly as they only measure the hard tissue face height. Bishara *et al*. (1995) used photography and found a more comparable difference of 5–6 mm. Whilst the soft tissues may be responsible for some of the difference between this study and others, it is considerable. This is difficult to account for, but the difference was consistent throughout the ages.

The small difference in the mid-facial widths is in agreement with other studies. Again, this study shows slightly greater differences than some, possibly as the soft tissues were included. The optical surface scanner measurement of width difference in the gonial region is generally greater than the cephalometric or anthropometric studies. As discussed before, this is likely to be as the soft tissues, such as the masseter, are included in the optical surface scanner measurements, but not the other studies.

As discussed earlier, other studies do not give comparable data on facial depth, as cephalometry usually measures some type of maxillary or mandibular length. Prominence of the cheek regions cannot be measured with cephalometry.

The small sex difference in the nasal dimensions agrees with the stereophotogrammetric study by Burke and Hughes-Lawson (1989), and the photogrammetric study by Bishara *et al*. (1995).

Conclusions

1. Three-dimensional data from the optical surface scanner allowed the study of many areas of the face not amenable to cephalometry. This included more data on facial width and prominence.
2. Males were generally larger than females, although the difference in the mid-facial region was small.
3. Both male and female face height increased annually in the order of 3–4 mm on average.
4. Mid-facial prominence altered little with age, whilst mandibular width increased with age. The increases were greatest at the inferior parts of the mandibular region. There was, therefore, a gradient of increasing width change from the upper to the lower face.
5. Nose height and prominence, and alar base width increased with age, all with average annual changes of about 2 mm. There was little or no sex difference in the younger age groups.
6. Many dimensions were greater than the cephalometric hard tissue changes reported in the literature, possibly due to the inclusion of the soft tissues.

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