Transverse Development of the Human Jaws Between the Ages of 8.5 and 15.5 Years, Studied Longitudinally With Use of Implants

E.L. Korn and S. Baumrind

J DENT RES 1990 69: 1298
DOI: 10.1177/00220345900690061501

The online version of this article can be found at: http://jdr.sagepub.com/content/69/6/1298

Published by:

SAGE
http://www.sagepublications.com

On behalf of:
International and American Associations for Dental Research

Additional services and information for Journal of Dental Research can be found at:

Email Alerts: http://jdr.sagepub.com/cgi/alerts

Subscriptions: http://jdr.sagepub.com/subscriptions

Reprints: http://www.sagepub.com/journalsReprints.nav

Permissions: http://www.sagepub.com/journalsPermissions.nav

Citations: http://jdr.sagepub.com/content/69/6/1298.refs.html
Transverse Development of the Human Jaws Between the Ages of 8.5 and 15.5 Years, Studied Longitudinally With Use of Implants

E.L. KORN and S. BAUMRIND

Biometric Research Branch, National Cancer Institute, Executive Plaza North, Room 739, Bethesda, Maryland 20892; and 1Department of Growth and Development, School of Dentistry, University of California, San Francisco, California

We report longitudinal data on the transverse widening of the maxilla and mandible from a sample of normal subjects (11 males and 20 females) with metallic implants of the Bjork type. Data were from measurements on lateral and frontal (posterior-anterior) cephalograms generated at annual intervals between the ages of 8.5 and 15.5 years (although data were not available for all subjects at all time points).

The maxillary data were, in general, similar to those reported by Bjork and Skieller (1974, 1977) for a smaller sample of slightly younger boys. During the age interval studied, transverse widening was greater in the more posterior part of the palate. [The mean annual rate of change in the posterior-most (zygomatic) region was 0.43 mm, sd = 0.18 mm; p<0.001.] Although the rate of palatal widening was not large in absolute terms, widening appeared to continue throughout the age interval under study, and there was no evidence to support the conventionally accepted idea that palatal growth in the transverse dimension tapers off substantially or even ceases during the age interval under observation.

Evidence of statistically significant widening of the mandibular arch by means of transverse rotation of the osseous matrix was noted in nine of the 29 subjects for whom three-dimensional mandibular information was available. For these nine subjects, the estimated annual increase in mandibular arch angle ranged from 0.52 degrees to 1.40 degrees. As far as we are aware, this is the first report of mandibular matrix rotation in the transverse direction from a sample of subjects with metallic implants. The finding that spontaneous changes in this dimension are relatively common raises the possibility that classical attitudes concerning the immutability of osseous relationships in the symphysial region during growth may be inappropriate.


Introduction.

By far, the major part of our currently available information on the in vivo remodeling of the human maxilla and mandible has come from the implant studies of Bjork and co-workers. Partitioning the developmental changes in the jaws of living subjects for a distinction between those involving remodeling of the bone surfaces and those involving re-orientation of the deeper-lying bone matrix is now possible only through the use of the metallic implant method pioneered by these investigators (Bjork, 1955, 1963, 1968). As one might expect, given the heavily profile-oriented focus of modern orthodontic cephalometrics, most of the studies reported by Bjork’s group deal with changes through time viewed in sagittal projection on lateral cephalograms (Bjork, 1947; Bjork and Skieller, 1972, 1983). These studies have provided major insights into growth-associated rotations of the mandibular and maxillary bony matrices, and (by inference) into the loci and magnitudes of mandibular and maxillary remodeling.

A small portion of Bjork’s reported work dealt with transverse (i.e., “width”) changes in the maxilla (Krebs, 1964; Bjork and Skieller, 1974, 1977). These contributions provided the first in vivo quantitative measurements of the widening of the palate as a consequence of developmental changes in the region of the mid-palatal palatal suture. In a sample of nine boys examined at annual intervals between four and 20 years of age, Bjork noted that width increase in the anterior portion of the palate was about one-third as great as that in the transzygomatic region. More specifically, in the period from 10 years to adulthood, the average increase in width between bilateral implants in the anterior palatal region was 0.9 mm, while that between posterior palatal implants was 3.0 mm. Bjork’s group has not, to our knowledge, reported on transverse changes in the mandible.

The corroboration or modification of these findings of transverse development in the maxilla has previously been impossible because no other sample of growing subjects with implants has been available. Records for a sample of growing boys and girls with implants of the Bjork type have recently become available to us, making it possible to perform an independent test of the universality of Bjork’s observations concerning transverse growth in the maxilla, as well as new observations on transverse growth of the mandible. In this article, we report the findings on the transverse growth of the maxilla and mandible for 31 boys and girls between the ages of 8.5 and 15.5.

Materials and methods.

The primary records set from which the data were derived consisted of lateral, frontal, and 45-degree cephalograms taken at approximately annual intervals for 36 subjects. Patients were recruited, and the records collection was organized and controlled by Dr. J. Rodney Mathews in the Section on Orthodontics, University of California School of Dentistry, during the years 1967 to 1978. All subjects attending the clinic for consultation between June, 1967, and February, 1972, were given the option of participating in the study. Thirty-six subjects agreed to participate and returned for follow-up for a substantial number of years.

Using an open surgical method, Dr. William Ware placed maxillary and mandibular implants prior to the acquisition of the first cephalograms for each subject. In general, from three to six implants were placed in the maxilla of each subject, and three or four were placed unilaterally in the mandible (Fig. 1). Subjects were then monitored radiographically at annual intervals, for an average period in excess of nine years. The data reported in this paper were acquired from frontal and lateral cephalograms of 31 subjects. Four subjects from the original sample of 36 were excluded from the present study because they had no satisfactory nominal 8.5-year reference film, and one additional case was unavailable due to misfiling of ce-
Fig. 1—(after Savara) The three-dimensional frame of reference used in this study: The “horizontal plane” (XZ) is the Frankfurt Horizontal Plane, as conventionally defined. (Porion and Orbitale are indicated by filled circles.) The “frontal plane” (YZ) is perpendicular to the “horizontal plane” and contains the porion-porion line. The “lateral plane” (XY) is perpendicular to the other two planes and passes midway between left porion and right porion. In a perfectly symmetrical subject, the lateral plane would be identical to the mid-sagittal plane.

The films were evaluated with use of an updated variant of the UCSF Computer-aided Head Film Analysis System (Baumrind and Miller, 1980). The coordinates of the implants were digitized on both frontal and lateral films. Each implant was located independently by each of two judges. The standard errors of the double determinations were 0.11 mm in the horizontal direction and 0.10 mm in the vertical direction. Furthermore, the landmarks Porion and Orbitale on the lateral films and points locating the mid-sagittal plane and the Porion-Porion axis on the frontal films were located and digitized. The locations of the latter points were used to aid in the computation of the three-dimensional coordinates (XYZ) of the implants. The method of computation is described in the Appendix.

Maxilla. — Pairs of implants that had been placed in roughly symmetrical positions on opposite sides of the mid-sagittal plane were considered as implant pairs. The Z distances (Fig. 1) between implant pairs were then plotted against age for each child. A linear regression was used for computation of the estimated annual rate of growth between the implants. It should be noted that errors in the Z distance calculations that occur due to inconsistency in head position between lateral and frontal cephalograms will become incorporated into the residual error term of the regression analysis. Thus, any inferences concerning annual growth rates that are drawn from these analyses will have taken into account these random errors in head position. Independently of these estimates, the anatomical region of location of each implant pair was marked by collaborative inspection of the lateral and frontal cephalograms by two observers, according to the following definitions:

Incisor region: Anterior to the incisor teeth on the lateral films and approximating the mid-sagittal plane on the frontal films.

Anterior palatal region: Lingual to the incisor teeth, but anterior to the canines on the lateral films.

Middle palatal region: In the region of the premolars on the lateral films.

Posterior palatal region: Posterior to the premolars on the lateral films.

Zygomatic region: Lateral to the alveolar processes on the frontal films (and generally superiorly positioned on the lateral films).

Within each region, estimates of the population mean and standard deviation of the growth rates were computed as described above.

In order to compare our results with those of Bjork and Skieller (1974, 1977), it was convenient to convert their data given in absolute millimeters of growth for nine cases into annual growth rates. This was done on a case-by-case basis, as follows. For a given case, let X be the amount of growth reported over the interval from age A1 to age A2. Bjork and Skieller reported that growth was completed by about age 17. So we consider the time of active growth to be T = Minimum(A2, 17) - A1. The annual growth rate was then estimated as X/T. For each of the two regions Bjork considered (our Incisor and Zygomatic regions), the mean and standard deviations of the growth rates were computed across the nine subjects.

Mandible. — Implants that had relatively displaced over time, based on the time sequence of lateral films, were removed from consideration on the assumption that they probably were not originally placed securely in bone. Since implants were only placed on one side of the mid-sagittal plane in the mandible, direct calculation of growth rate of the mandible was not possible. Instead, the following indirect method was used, as illustrated in Fig. 3. First (Measure A), the Z distance between the implant placed in the mandibular body and the implant placed in the chin region was calculated. (The positions were averaged if there were two implants in a region.)

![Diagram of cephalograms](image)

**Table 1:** Distribution of cases and films.
An increase in this distance over time would suggest a widening of the mandibular arch (Fig. 3). As a control, the distance between these implants in three-dimensional space (Measure B) was computed mathematically. A change in this distance over time would suggest that one or both implants were not fixed in bone, or possibly the existence of some measurement artifact. Additionally, as a mathematical operation, a line was drawn between the two implants in three-dimensional space and extended to intersect the mid-sagittal plane. The angle between this line and the mid-sagittal plane (Measure C) was then mathematically computed:

\[
\text{Angle} = \arctan \left\{ \frac{Z_2 - Z_1}{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \right\}
\]

where \((X_1, Y_1, Z_1)\) and \((X_2, Y_2, Z_2)\) are the coordinates of the mandibular body and chin implants, respectively. We considered twice the rate of change of this angle over time as a representation of the widening of the mandibular arch (Fig. 3).

Estimation of the population means and standard deviations across cases of these rates of change were computed as described below.

Each case can be thought of as having a “true” growth rate for each parameter discussed above. The slope derived from the linear regression estimates this true growth rate. Other factors being equal, the slope derived from a case with data available only at ages eight and nine would be less reliable than one derived from a case with data at ages eight and 15. These estimates in turn would be less reliable than the estimate derived from a case with data available annually from ages eight to 15. We are interested in the population mean of the true growth rates from all the cases. Although the sample mean of the slopes of the case does estimate this population mean, it is not a very efficient estimator when the reliability of the slopes varies greatly from case to case. Instead, we used a weighted average of the individual slopes to estimate the population mean efficiently. The weights are inversely proportional to the squares of the estimated within-case standard deviations of the slope estimates plus the square of the estimated between-case standard deviations of the true slopes. This latter standard deviation is calculated with use of the method described by Palta and Cook (1987) (“method 2”, without the modification for small sample sizes). Another output of this
### TABLE 1A

**ANNUAL RATES OF GROWTH (WITH 95% CONFIDENCE INTERVALS) IN WIDTH OF MAXILLA (mm/YEAR)**

<table>
<thead>
<tr>
<th>Case</th>
<th># of TPs</th>
<th>Incisor</th>
<th>Anterior Palate</th>
<th>Mid-palate</th>
<th>Zygomatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>0.33(0.26, 0.40)</td>
<td>0.31(0.24, 0.38)</td>
<td>0.40(0.30, 0.49)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.03(0.01, 0.05)</td>
<td>0.16(0.12, 0.44)</td>
<td>0.44(0.32, 0.55)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>7*</td>
<td>0.13 (−0.04, 0.29)</td>
<td>0.32(0.22, 0.42)</td>
<td>0.49(0.39, 0.59)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>0.28(0.22, 0.33)</td>
<td>0.28(0.22, 0.33)</td>
<td>0.43(0.24, 0.63)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.25(0.10, 0.39)</td>
<td>0.37(0.09, 0.64)</td>
<td>0.65(0.48, 0.82)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>0.02 (−0.07, 0.11)</td>
<td>0.24(0.22, 0.26)</td>
<td>0.45(0.38, 0.51)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>8</td>
<td>0.29(0.22, 0.36)</td>
<td>0.37 (−0.36, 1.10)</td>
<td>0.26 (−0.19, 0.71)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>−0.04 (−1.72, 1.65)</td>
<td>0.37 (−0.36, 1.10)</td>
<td>0.26 (−0.19, 0.71)</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>6*</td>
<td>−0.01 (−0.10, 0.09)</td>
<td>0.39(0.09, 0.68)</td>
<td>0.46(0.40, 0.52)</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>6</td>
<td>0.03 (−0.18, 0.23)</td>
<td>0.31(0.08, 0.53)</td>
<td>0.35(0.22, 0.48)</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>7</td>
<td>0.02 (−0.07, 0.11)</td>
<td>0.28(0.17, 0.38)</td>
<td>0.35(0.22, 0.48)</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>4</td>
<td>0.04 (−0.21, 0.14)</td>
<td>0.02 (−0.17, 0.21)</td>
<td>0.32(0.21, 0.44)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>0.29(0.21, 0.37)</td>
<td>0.35(0.25, 0.46)</td>
<td>0.47(0.36, 0.57)</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>8</td>
<td>0.35(0.25, 0.46)</td>
<td>0.30(0.22, 0.48)</td>
<td>0.35(0.22, 0.48)</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>5*</td>
<td>0.10 (−0.24, 0.43)</td>
<td>0.18 (−0.01, 0.37)</td>
<td>0.51(0.45, 0.58)</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>7</td>
<td>0.13 (−0.01, 0.26)</td>
<td>0.19(0.04, 0.33)</td>
<td>0.50 (−0.15, 1.14)</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>5</td>
<td>0.34(0.24, 0.44)</td>
<td>0.42(0.35, 0.48)</td>
<td>1.00(0.75, 1.24)</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>0.36 (−0.21, 0.94)</td>
<td>0.50 (−0.15, 1.14)</td>
<td>0.51(0.45, 0.58)</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>7</td>
<td>0.30(0.25, 0.34)</td>
<td>0.37 (−0.01, 0.37)</td>
<td>0.50 (−0.15, 1.14)</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>7</td>
<td>0.16(0.06, 0.26)</td>
<td>0.29(0.09, 0.49)</td>
<td>0.32(0.24, 0.41)</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>5</td>
<td>0.16 (−0.05, 0.37)</td>
<td>0.29(0.09, 0.49)</td>
<td>0.32(0.24, 0.41)</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>6</td>
<td>0.15(0.09, 0.21)</td>
<td>0.27(0.23, 0.32)</td>
<td>0.32(0.26, 0.33)</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>5*</td>
<td>0.04</td>
<td>0.05</td>
<td>0.18*</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Weighted</td>
<td>Mean*</td>
<td>0.15(0.09, 0.21)</td>
<td>0.27(0.23, 0.32)</td>
<td>0.29(0.26, 0.33)</td>
</tr>
<tr>
<td>37</td>
<td>Males only</td>
<td>0.11*</td>
<td>0.04</td>
<td>0.05</td>
<td>0.18*</td>
</tr>
<tr>
<td>38</td>
<td>Females only</td>
<td>0.22(0.14, 0.29)</td>
<td>0.30(0.27, 0.33)</td>
<td>0.29(0.22, 0.35)</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Gender difference</td>
<td>0.06(0.01, 0.11)</td>
<td>0.25(0.18, 0.31)</td>
<td>0.29(0.26, 0.33)</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Diff.</td>
<td>0.16(0.07, 0.25)</td>
<td>0.05 (−0.01, 0.12)</td>
<td>0.14 (−0.02, 0.30)</td>
<td></td>
</tr>
</tbody>
</table>

1For individual case rates, the null hypothesis is that the true annual rate of increase is 0.
2For weighted means, the null hypothesis is that the average growth is 0.
3For standard deviations, the null hypothesis is that there is no inter-individual variability in the true growth rate.
4For gender difference, the null hypothesis is that there is no difference between the average growth rates of males and females.

**Situations** in which these null hypotheses may be rejected at statistically significant levels are indicated by superscripts "a" (p < 0.05), "b" (p < 0.01), and "c" (p < 0.001).

*Case 3 had only 4 time points for mid-palatal implants.
Case 10 had only 4 time points for mid-palatal implants.
Case 17 had only 3 time points for anterior palatal implants.
Case 24 had only 7 time points for mid-palatal implants.
Case 27 had only 5 time points for zygomatic implants.
Case 28 had only 4 time points for incisor implants.
Case 29 had only 6 time points for incisor and mid-palatal implants because of digitization error.
Case 31 had only 4 time points for zygomatic implants.
Case 31 had only 4 time points for incisor implants because of digitization error.
Case 36 had no paired implants.

Analysis was an estimate of the population standard deviation of the "true" rates of growth. It should be stressed that if data at the same time points were available for each case, then the weighted average would be the usual sample mean, which would be an efficient estimate of the population mean. To examine gender differences in growth rates, we calculated weighted means separately for each gender. Since in this calculation the weights assigned to the cases are not exactly the same as the weights assigned to the cases in the combined gender analysis, the separate male and female weighted means do not necessarily average to the total population weighted mean. Because of the limited sample size, gender differences would have to be quite large to be statistically significant.

The above analyses are most easily interpretable when the growth rates are constant over time, i.e., the growth is linear over time. This assumption can be checked by examination of plots of growth for individual cases. Also, one could use the fact that all the films were initially grouped into eight annual time points corresponding to nominal ages 8.5 years to 15.5 years. Attention is first restricted to those cases with data at...
TABLE 1B
ANNUAL MAXILLARY GROWTH RATES (mm/YEAR) FROM THE BJORK-SKIELLER SAMPLE

<table>
<thead>
<tr>
<th>Case #</th>
<th>Incisor</th>
<th>Zygomatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10</td>
<td>0.34</td>
</tr>
<tr>
<td>2</td>
<td>0.11</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>0.04</td>
<td>0.24</td>
</tr>
<tr>
<td>4</td>
<td>0.21</td>
<td>0.50</td>
</tr>
<tr>
<td>5</td>
<td>0.17</td>
<td>0.53</td>
</tr>
<tr>
<td>6</td>
<td>0.15</td>
<td>0.42</td>
</tr>
<tr>
<td>7</td>
<td>0.04</td>
<td>0.31</td>
</tr>
<tr>
<td>8</td>
<td>0.14</td>
<td>0.47</td>
</tr>
<tr>
<td>9</td>
<td>0.13</td>
<td>0.60</td>
</tr>
<tr>
<td>Mean</td>
<td>0.12</td>
<td>0.42</td>
</tr>
<tr>
<td>SD</td>
<td>0.06</td>
<td>0.12</td>
</tr>
</tbody>
</table>

1Re-calculated from Bjork and Skieller (1974, 1977) by the method described under “Materials and methods”.
2Equal to “Anterior” in Bjork’s nomenclature.
3Equal to “Lateral” in Bjork’s nomenclature.

Results.

Maxilla.—The results for the individual cases and average results for all cases in the present sample are given in Table 1A. Case 1, for example, had implant pairs in the anterior palate and zygomatic regions for which seven time points of data were available. In the anterior palate region for this case, the best estimate of mean growth was 0.33 mm per year, which is significantly different from zero growth (p<0.001). The 95% confidence interval for mean annual growth in this region was from 0.26 mm to 0.40 mm. In the zygomatic region for this case, the best estimate of mean growth was 0.40 mm per year, with a 95% confidence interval from 0.30 mm to 0.49 mm, which is also significantly different from zero (p<0.001).

For comparison, corresponding values for each individual case in the Bjork-Skieller sample (1974, 1977) are provided in Table 1B. The original absolute millimetric values have been converted into annual growth rates, as described in “Materials and methods”.

Weighted average results for our sample are given at the bottom of Table 1A. For the incisor region, the (weighted) average estimate of the growth between the implants is 0.15 mm/year [p<0.001, 95% conf. int. = (0.09, 0.21)]. There was a significant amount of variability between cases (s.d. = 0.11 mm/years, p<0.05). For example, case 15 showed 0.29 mm/year of growth, while case 17 showed essentially no growth. The growth in the incisor region was, on average, less than the growth in the anterior palate region (p<0.001) and in the mid-palatal region (p<0.001). (Case 7 had an implant pair in the posterior palate that was grouped with the mid-palatal implant pairs for convenience.) The (weighted) average estimate of the growth in the anterior palate was 0.27 mm/year [p<0.001, 95% conf. int. = (0.23, 0.32)], and for the mid-palate was 0.29 mm/year [p<0.001, 95% conf. int. = (0.26, 0.33)]. There was no significant between-case variability in the growth rates for these two regions. The growth in the zygomatic region was significantly greater than in the anterior palateal region (p<0.001) and the mid-palatal region (p<0.01). The (weighted) average estimate of the growth in the zygomatic region was 0.43 mm/year [p<0.001, 95% conf. int. = (0.35, 0.52)]. There was significant variation between cases for this region (s.d. = 0.18 mm/year, p<0.01). For example, case 15 showed 0.45 mm/year of growth, while case 22 showed essentially no growth.

Fig. 4, which contains a plot of the time course of the growth in the four anatomical regions, demonstrates that there was no gross departure from linearity. A comparison of growth between males and females shows that there was greater growth for males in the incisor and zygomatic regions, with about equal growth in the anterior and mid-palatal regions. In the incisor region, this gender difference was statistically significant (p<0.001), with males and females showing, on average, 0.22 mm/year and 0.06 mm/year of growth, respectively.

Analogous grouped statistics for the Bjork-Skieller sample are provided in Table 1B. We used unweighted means and standard deviations of growth rates for this sample because the annual raw data were not readily available to us. However, since these investigators apparently collected data annually on all patients, the unweighted means should equal the weighted

Fig. 4—Plot of mean increase in width of the maxilla in four anatomical
regions restricted to those cases with data at the time point corresponding
at 15.5 years. O = incisor implants, ▲ = anterior palatal implants, ● =
mid-palatal implants, and [] = zygomatic implants. For the incisor region
(n = 9 cases), there were (on average) 1.2 values interpolated per case.
For the anterior palatal region (n = 5 cases), there were (on average) 0.8
values interpolated per case. For the mid-palatal region (n = 10 cases),
there were (on average) 0.9 values interpolated per case. For the zygomatic
region (n = 10 cases), there were (on average) 0.9 values interpolated
per case.

the last time point (15.5 years). If each of these cases had data
at each of the other time points, the sample mean at each time
point could be used to represent the time course of the growth.
However, since some cases had missing data at some inter-
mediate time points, a linear interpolation was used to fill in
these missing values. The sample means at each time point
then contained data from the same set of cases. It is stressed
that the time course of growth given by these sample means
should only be used for evaluation of the shape of the growth
curve. In particular, if the curve is linear, the weighted esti-
mate of the population growth rate described previously is a
better estimate of the average growth rate than any estimate
derived from this mean growth curve. This is because the
weighted estimate uses the data from all the cases, whereas
the growth curve uses the data from only a subset of the cases.
### TABLE 2
ANNUAL RATES OF CHANGE (WITH 95% CONFIDENCE INTERVALS) FOR MANDIBULAR BODY TO CHIN IMPLANT DISTANCE (HORIZONTAL AND TOTAL 3D) AND ANGLE OF MANDIBULAR ARCH

<table>
<thead>
<tr>
<th>Case</th>
<th># of TPs</th>
<th>Distance Between Mandibular Body and Chin Implants</th>
<th>Mandibular Arch Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizontal (in mm)</td>
<td>Total 3D (in mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Measure A)</td>
<td>(Measure B)</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>0.32* (0.23, 0.42)</td>
<td>0.12* (0.00, 0.24)</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>−0.01 (−0.21, 0.18)</td>
<td>−0.01 (−0.19, 0.17)</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>0.05 (−0.11, 0.22)</td>
<td>0.10 (0.06, 0.25)</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>0.13 (−0.11, 0.36)</td>
<td>0.04 (−0.07, 0.15)</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0.26a (0.08, 0.35)</td>
<td>0.01 (−0.15, 0.17)</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>0.22 (−0.05, 0.49)</td>
<td>0.09 (−0.03, 0.20)</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>0.30* (0.11, 0.48)</td>
<td>0.05 (−0.22, 0.33)</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>0.16 (−0.33, 0.65)</td>
<td>−0.12 (−0.47, 0.22)</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>0.12a (0.00, 0.24)</td>
<td>0.03 (−0.06, 0.12)</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>−0.08 (−0.34, 0.21)</td>
<td>−0.01 (−0.27, 0.25)</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>0.05 (−0.17, 0.28)</td>
<td>0.15 (−0.07, 0.36)</td>
</tr>
<tr>
<td>14</td>
<td>8</td>
<td>0.49a (0.31, 0.67)</td>
<td>0.03 (−0.08, 0.15)</td>
</tr>
<tr>
<td>15</td>
<td>7</td>
<td>0.10 (−0.04, 0.24)</td>
<td>−0.00 (−0.21, 0.21)</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>−0.48* (−0.95, −0.01)</td>
<td>−0.03 (−0.37, 0.31)</td>
</tr>
<tr>
<td>17</td>
<td>6</td>
<td>0.22 (−0.18, 0.63)</td>
<td>0.11 (−0.12, 0.34)</td>
</tr>
<tr>
<td>19</td>
<td>6</td>
<td>0.22a (0.08, 0.36)</td>
<td>0.07 (−0.10, 0.24)</td>
</tr>
<tr>
<td>20**</td>
<td>7</td>
<td>0.41a (0.12, 0.70)</td>
<td>0.64b (0.26, 1.01)</td>
</tr>
<tr>
<td>21</td>
<td>7</td>
<td>0.08 (−0.23, 0.40)</td>
<td>−0.06 (−0.29, 0.17)</td>
</tr>
<tr>
<td>22</td>
<td>*</td>
<td>−0.01 (−0.20, 0.18)</td>
<td>0.01 (−0.07, 0.08)</td>
</tr>
<tr>
<td>24</td>
<td>8</td>
<td>0.19 (−0.13, 0.52)</td>
<td>0.11 (−0.07, 0.29)</td>
</tr>
<tr>
<td>26</td>
<td>8*</td>
<td>0.36c (0.23, 0.50)</td>
<td>0.12 (−0.04, 0.28)</td>
</tr>
<tr>
<td>27</td>
<td>8</td>
<td>0.10a (0.01, 0.20)</td>
<td>−0.07 (−0.16, 0.02)</td>
</tr>
<tr>
<td>28</td>
<td>5</td>
<td>0.11 (−0.09, 0.31)</td>
<td>0.11 (−0.05, 0.28)</td>
</tr>
<tr>
<td>29</td>
<td>7</td>
<td>0.16 (−0.13, 0.45)</td>
<td>−0.04 (−0.17, 0.09)</td>
</tr>
<tr>
<td>30</td>
<td>*</td>
<td>−0.35 (−0.86, 0.16)</td>
<td>−0.46 (−1.20, 0.27)</td>
</tr>
<tr>
<td>32</td>
<td>8</td>
<td>0.43c (0.37, 0.49)</td>
<td>−0.03 (−0.12, 0.06)</td>
</tr>
<tr>
<td>33</td>
<td>7*</td>
<td>0.28b (0.14, 0.41)</td>
<td>0.11c (0.02, 0.20)</td>
</tr>
<tr>
<td>35</td>
<td>5</td>
<td>−0.14 (−0.77, 0.48)</td>
<td>−0.12 (−0.50, 0.26)</td>
</tr>
<tr>
<td>36</td>
<td>3</td>
<td>−0.27* (−0.47, −0.08)</td>
<td>0.22 (−1.39, 1.83)</td>
</tr>
</tbody>
</table>

Weighted Mean$^2$

| Measure B | (0.08, 0.21) | 0.03* (0.00, 0.06) | 0.39* (0.19, 0.59) |
| S.D.$^3$ | 0.15b | 0.05 | 0.45$^b$ |

Males only:

| Wid. Mean | 0.12a (0.00, 0.23) | 0.01 (−0.04, 0.06) | 0.37* (0.07, 0.67) |

Females only:

| Wid. Mean | 0.16c (0.08, 0.24) | 0.01 (−0.08, 0.09) | 0.38$^b$ (0.10, 0.65) |

Gender difference$^a$:

| Diff. | −0.04 (−0.18, 0.09) | 0.00 (−0.10, 0.10) | −0.01 (−0.42, 0.40) |

---

1 For individual case rates, the null hypothesis is that the true annual rate of increase is 0.

2 For weighted means, the null hypothesis is that the average growth rate is 0.

3 For standard deviations, the null hypothesis is that there is no inter-individual variability in the true growth rate.

*For gender difference, the null hypothesis is that there is no difference between the average growth rates of males and females.

**Case 20 had the mandibular body implant loosely loose (based on lateral films), and therefore, the case was not included in the weighted means and standard deviations.

Means. However, because the former contains a component reflecting the within-case variabilities of the slope estimates, the unweighted standard deviation is a slight overestimate of the weighted standard deviation.

Mandible. —The average rate of mandibular growth and the values for the individual cases in the present sample are given in Table 2. The results of each case were first analyzed individually. In each of 13 cases, the horizontal width of the mandible (Measure A) changed over time with statistical significance (p<0.05). Eleven of these 13 cases had a widening rate with p<0.05, one with p<0.01, and four with p>0.001. The other two had narrowing with p<0.05. These two cases were the only ones in the sample for which data were available at only three time points. The rate of change in the total three-dimensional distance between the implants (Measure B) was significant in three cases, two with p<0.05 and one with p<0.01 (case 20). This was a “control” calculation. On an a priori basis, no change had been expected in this distance. On a retrospective review of the lateral films of case 20, the mandibular body implant was found to be loosely loose. (This looseness had been missed on the first review of the case.) Therefore, case 20 was not included in the estimation of the
population parameters. There appeared to be no significant
gender differences in the annual rates of change in the
mandible.

The (weighted) estimate of the mean change of the angle
of the mandibular arch (Measure C) for all the cases was 0.39
degrees/year [p<0.001, 95% conf. int. = (0.19 degrees, 0.59
degrees)], representing a widening of the mandibular arch. Fig.
5, which contains a plot of the time course of the change in
mandibular arch angle, demonstrates that there was no gross
departure from linearity; the “dip” at age 15.5 years was not
statistically significant (p = 0.41, paired t test, n = 18). Even
though we can be confident that there was a widening on av-
average, the individual cases had different behaviors and, for
the purposes of discussion, can be roughly classified into three
groups. For some cases, the widening of the mandibular arch
was large and, in fact, for a subset of nine of these cases,
individually statistically significant (p<0.05). For a second
group of cases, the rate of change of the angle was close to
zero, and there was a narrow 95% confidence interval includ-
ing zero. Fig. 6 displays the time course of the angular change
for cases 26 and 12, which fall into these two groups of cases,
respectively. For a third group of cases, there were too few
time points available or too much residual variability for con-
clusions concerning the change in angle to be drawn. Cases 8
and 16 are examples of this group. Fig. 7 summarizes graph-
ically the annual rates of change and the confidence intervals
for the 29 cases.

Discussion.

In the maxilla, the results were remarkably similar to those
of Bjork and Skjeller (1974, 1977). Transverse widening was
greater in the more posterior part of the palate. In order to
make a quantitative comparison between our results and those
of Bjork and Skjeller, we computed the annual rates of growth
between incisor implant pairs and between zygomatic implant
pairs for their cases (as described in “Materials and meth-
ods”). For the incisor region in the Bjork-Skjeller sample, the
unweighted mean (+ standard deviation) of the growth rates
was 0.14 ± 0.06 mm/year. For the zygomatic region, the
unweighted mean was 0.42 ± 0.12 mm/year. The correspon-
dence between these results and our own is excellent (Table
1A). For the males in our sample, the weighted means and
standard deviations for the annual growth rate in the incisor
and zygomatic regions were 0.22 ± 0.10 mm (n = 8) and 0.51
± 0.16 mm (n = 9), respectively.

In our sample, measurements of the separation of implant
pairs in the anterior palatal and mid-palatal regions were avail-
able for most subjects in addition to the incisor and zygomatic
measurements. The data from these palatal implants were con-
sistent with a finding of regular and progressively increasing
edge-shaped widening through time between the incisor re-

An important observation from a clinical point of view is
that there was no evidence to support the idea of a progressive
slowing down in the rate of spontaneous transpalatal widening
during the time frame studied here. If such an effect had taken
place, the slopes of the lines in Fig. 3 would have been ex-
pected to become reduced through time rather than remain
constant, as they did. (Inter-individual differences in the tim-
ing of cessation of transpalatal growth could, of course, mask
some of this effect, but it is unlikely that they would hide it com-
pletely.) To some extent, this observation seems to be at odds
with Melsen’s (1975) direct histological observations at au-
topsy on subjects of this age. Currently-held conceptions con-
cerning the fusion of the mid-palatal suture by the time of the
14th birthday are thus brought into question.

The mandibular data which we report in this paper are, to
our knowledge, the first of their kind. On the basis of strongly
held beliefs by craniofacial biologists, we had expected that
there would be no systematic changes through time in the angle
of intersection between the left and right halves of the man-
dibular body. [Such long-term changes are to be distinguished
from the quite different small transient bending and recovery
of the mandible, which have been demonstrated to occur as
For example, the horizontal distance between two implants symmetrically placed about the mid-sagittal plane would be enlarged about 4-8%, depending upon their distance to the film plane. The implications of this enlargement will now be discussed. Consider a hypothetical pair of implants with a true 0.400 mm/year of horizontal growth between them (and with no forward displacement). If measurements of sufficient precision could be made, these implants would appear to be growing apart 0.416 mm/year to 0.432 mm/year on the frontal cephalogram, depending on their distance to the film plane. An additional complication is encountered because the jaws are displacing forward as the subject grows. Consider a pair of implants with no horizontal growth, but whose positions have displaced forward 25 mm over a five-year period. The horizontal distance between these implants on the frontal cephalograms will increase approximately 1.7% over the five-year period. Thus, two implants separated by a constant 20 mm would appear to have an additional separation of 0.34 mm (= 20 x 0.017) over the five years, while two implants separated by a constant 80 mm would appear to have an additional separation of 1.4 mm (= 80 x 0.017). The magnitudes of these overestimates due to projective enlargement were of sufficient concern that it was decided to locate the implants in three-dimensional space. The horizontal distances required could then be easily calculated from the three-dimensional coordinates of the implants. Our method for computing the three-dimensional coordinates of the implants will now be discussed in detail. It should be noted, however, that the computed Z distances between implant pairs are relatively insensitive to the exact method used for correction of projective enlargement and small changes in head position between frontal and lateral cephalograms.

On the frontal cephalograms, the implants were expressed in terms of a coordinate system in which the horizontal axis ($Z_F$) was defined by the Porion-Porion axis, and the vertical axis ($Y_F$) was defined to be perpendicular to the horizontal axis, with the origin determined by the dropped perpendicular closest to the mid-sagittal plane. On the lateral cephalogram, the implant positions were expressed in terms of a coordinate system in which the horizontal axis ($X_L$) was the Frankfort plane, and the vertical axis ($Y_L$) was perpendicular at Porion. It was assumed that the orientation of the head was similar for both frontal and lateral cephalograms, with the Frankfort plane in both cases perpendicular to the plane of the film.

Let $(x, y, z)$ represent the three-dimensional coordinates of the implants (Fig. 1). In this coordinate system, the Z axis is defined as the Porion-Porion line, the XY plane is coincidental to the mid-sagittal plane, and the origin is taken as the intersection of the Z axis with the mid-sagittal plane. It is assumed that the central ray passes through this origin for both the frontal and lateral cephalograms. Let D and d be the distances from the x-ray source to the origin and film plane, respectively. Then by similar triangles,

$$x/X_L = (d - z)/D \quad y/Y_L = (d - z)/D$$

$$z/Z_F = (d + x)/D \quad y/Y_F = (d + x)/D$$

Since the values of $(X_L, Y_L)$ and $(Z_F, Y_F)$ can be measured from the lateral and frontal cephalograms, there are four equations with three unknowns $(x, y, z)$. If we assume circular measurement error in locating the positions of the implants on each film (which is reasonable for metallic implants), the optimal estimated value of $(x, y, z)$ would be that which minimizes the following sum of squares (SS):

$$SS = (X_L - xD/(d - z))^2 + (Y_L - yD/(d - z))^2$$

$$+ (Z_F - zD/(d + x))^2 + (Y_F - yD/(d + x))^2$$

### Appendix.

The primary focus of this paper is on the horizontal distances between implants as viewed from the front, i.e., the Z distance between implants as displayed in Fig. 1. Because of projective enlargement, the horizontal distances as measured on a frontal cephalogram will be an overestimate of the actual distance.
This minimization can be performed by any nonlinear regression computer program. For this paper, the following excellent approximate solution was used:

\[
X = \frac{dX_F(D - Z_F)}{(D^2 + Z_F X_F)}
\]

\[
Z = \frac{dZ_F(D + X_F)}{(D^2 + Z_F X_F)}
\]

and then,

\[
Y = (d - Z)(d + X)[Y_F(d + X) + Y_Y(d - Z)]/\left\{D[(d - Z)^2 + (d + X)^2}\right\}
\]

This solution \((X, Y, Z)\) is such that \((X, Z)\) reduces the first and third terms of \(SS\) to zero. Given this value of \((X, Z)\), \(Y\) minimizes the sum of the second and fourth terms. The above calculations assume an unambiguous association of images of a single implant on the frontal and lateral cephalograms. In ambiguous cases, determinations of association were made by inspection of the cephalograms.

Acknowledgments.

We wish to recognize the dedication and devotion of the late Dr. J. Rodney Mathews, University of California, San Francisco, who assembled the original sample of mixed dentition subjects, arranged for the placement of implants, and supervised the process of longitudinal records acquisition over a period of more than ten years. We also wish to thank Dr. Luis Alberto Bravo, University of Murcia, Spain, for assistance in the interpretation of the anatomical locations of the implants and the preparation of the cephalometric data.

REFERENCES


