A three dimensional observation of palatal vault growth in children using mixed effect analysis: a 9 year longitudinal study

Sung-Tae Yang, Hong-Kyun Kim, Young Seol Lim, Mi-Sook Chang, Seung-Pyo Lee and Young-Seok Park

Department of Oral Anatomy, Dental Research Institute and School of Dentistry, Seoul National University, Korea

Correspondence to: Young-Seok Park, Department of Oral Anatomy, Dental Research Institute and School of Dentistry, Seoul National University, 275-1 Yeongeon-Dong, Jongro-Gu, Seoul 110-768 Korea (ROK).
E-mail: ayoayo7@snu.ac.kr

SUMMARY The understanding of palatine vault growth in normal subjects is important to orthodontists. The aim of this study was to evaluate three dimensional (3D) longitudinal changes in the palatal vault from 6 to 14 years of age.

Complete dental stone casts were biennially prepared for 50 subjects (25 girls and 25 boys) followed up from 6 to 14 years of age. Virtual casts were constructed using 3D laser scanning and reconstruction software. The reference gingival plane was constructed. The palatal heights were measured from a total of 12 quadrisectional points between the most gingival points of the palatal dentogingival junctions from the canine to the first molar. In addition, the palatal heights were measured from a total of 12 lateral and medial endpoints of the palatine rugae. The measurement changes over time were analyzed using a mixed-effect analysis.

There were significant annual increases in all of the variables related to palatal height. However, the individual random variability at baseline was quite large. There was no significant sexual dimorphism in the linear measurements or in the annual increases as fixed effects in the model.

During the observation period, increases in palatal vault height were significant in all regions. The growth pattern seemed to differ between genders even though it was not significant. More elaborate methodology is necessary to gain a better understanding of 3D palatal growth.

Introduction

The human dentition and surrounding dentoalveolar processes undergo continuous and complicated alterations as they grow; being a part of the craniofacial complex, and are influenced by changes in different parts of the skull (Thilander, 1995). Orthodontists can benefit from understanding these changes during every stage of human development (Arslan et al., 2007). The growth of the palate has also been of interest in orthodontic literature because palatal dimensions often need to be altered during orthodontic or orthognathic surgical treatment (Ciusa et al., 2007).

Quantitative and qualitative studies of craniofacial morphology in individual patients have been performed in order to determine the effect of therapy and to aid comprehensive facial dysmorphology diagnosis (Ciusa et al., 2007; de Freitas et al., 2001; Ferrario et al., 2001; Heiser et al., 2004b; Heiser et al., 2004a; Primožič et al., 2012; Revelo and Fishman, 1994; Thilander, 2009; Tsai and Tan, 2004). The results of the aforementioned studies become more meaningful and useful when a comparison with normal reference subjects is available (Ciusa et al., 2007). However, most of the studies regarding palatal dimension assessments have focused on craniofacial syndromes (Hermann et al., 2003, Panchón-Ruiz et al., 2000, Suri et al., 2010).

Therefore, such investigations have not produced a consistent view of palatal height and width in healthy children. Performing investigations concerning interceptive treatment effects, the influence of growth should be as small as possible. However, information about the development of the palate in normal subjects, especially palatal height, is scarce (Ciusa et al., 2007).

One of the reasons for that might be attributed to the difficulty in describing the three dimensional (3D) palatal growth in nature (Cha et al., 2007). The maturation of the midpalatal suture at different developmental stages has been histologically examined using autopsy specimens (Melsen, 1975; Melsen and Melsen, 1982; Revelo and Fishman, 1994). Implant studies have also been used to determine the growth pattern of the hard palate on cephalograms (Björk, 1966; Björk and Skieller, 1974; Björk and Skieller, 1977). Although both present clear-cut evidence of growth, they are not only invasive, but also have two-dimensional limitations. The direct measurement of casts has also been used for evaluating the width and length of the palate. For height and volume determination, special techniques were used that included a specialized compass (de Freitas et al., 2001), plastic sheet with a hole (Thilander, 2009), photographs of sectioned casts (Tsai and Tan, 2004),
computerized 3D instruments (Ciusa et al., 2007, Ferrario et al., 2001), and silicon impressions (Bourdiol et al., 2010, Heiser et al., 2004b; Heiser et al., 2004c). Although reliable, these methods are very time-consuming and labor intensive (Primožič et al., 2012). In addition, it is difficult to three dimensionally depict the entire area of the palate due to methodological limitations.

To overcome these problems, Primožič et al., (2012) recently reported on the longitudinal changes from primary to mixed dentition using 3D laser scanners. They determined the volume and surface area of the palatine vault in growing patients, a novel approach for evaluating palatine growth. Technology including 3D scanners and reconstructed virtual models has been widely used in dentistry for various applications (Ahn et al., 2012; Kim et al., 2012; Park et al., 2011; Park et al., 2007; Veli et al., 2011).

Studies of 3D reconstructions have resulted in accurate and reliable techniques for restorative procedures and for facial analyses to aid clinicians in planning more effective treatments. In addition, the use of these 3D reconstructions and specialized software allows for measurements that would be impossible or extremely difficult using conventional means.

Taking advantage of the 3D reconstructed virtual model, we designed a study to investigate the changes occurring in the palatine vault along the growth. The aim of this study was to evaluate 3D longitudinal changes in the palatal vault from 6 to 14 years of age. The pattern of individual variation in the longitudinal changes was also examined using a mixed effect analysis method.

Materials and methods

The materials consisted of dental casts from 50 Korean children (25 boys and 25 girls) followed up from 6 to 14 years of age. From 1995 to 2003, complete dental cast sets were prepared biennially. These subjects were judged to have clinically good rather than ideal occlusion with a class I molar relationship at 14 years of age. Casts with missing teeth other than the third molars, those with greater than 3 mm of arch length discrepancy, and subjects who did not have full sets were all excluded from the study. All of the subjects and their parents or guardians provided written informed consent, and the Institutional Review Board for the Protection of Human Subjects reviewed and approved the research protocol (S-D2010014).

All selected casts were scanned with a 3D scanner (optoTOP-HF; Breckmann GMBH, Meersburg, Germany) and virtual 3D models were prepared according to the previous study (Park et al., 2012). For reproducibility, the reference points were created on the virtual casts in consensus by two observers. Measurements were taken three separate times by a single observer over a 3 week period.

Prior to the measurement, the most cervical points of the palatal dentogingival junction were defined as the intersections of the palatal gingival margin and the point of maximum convexity of the teeth. For the measurements of palatal vault height, a new reference plane was established for each virtual cast from the most cervical points of the dentogingival junction of all erupted teeth, which is similar to the gingival plane used in the Primožič et al.’s study (2012). The plane was constructed using the least-square algorithm. The foots of perpendicular from the most cervical points of the teeth were identified on the reference plane. Four new reference vectors were created by connecting the foots of perpendicular of the most cervical points of the bilateral deciduous or permanent canines, bilateral palatal cusp tips of the permanent premolars, and bilateral mesiolingual cusp tips of the deciduous molars and permanent first molars according to the patient’s eruption state. The vectors were then divided into four equal sections and all 12 of the dividing points (three points per each vector: right quarisectional point, center point, and left quadrisectional point) were registered. Finally, the palatal height was measured from these 12 dividing points to the deepest point of the palate. For convenience, the palatal heights from these dividing points were denoted as 3C, 4C, 5C, 6C (from the center points); 3R, 4R, 5R, 6R (from the right quadrisectional points); and 3L, 4L, 5L, 6L (from the left quadrisectional points) (Figure 1 and 2).

For the measurements of the palatal vault height in regions other than those mentioned above, landmarks of the palatal rugae were created based on the previous study (Kim et al., 2012), because they are relatively stable and readily recognized without confusion. The medial and lateral points of the individual rugae were created only on the three most anterior rugae. From these landmarks, the nearest distance to the reference plane was recorded as the palatal vault height. They were denoted as such, R1L for the height measured from the lateral end point of the right first rugae and L3M for the height measured from the medial end point of the left first rugae (Figure 2).

In addition, the following four distances were measured on the virtual casts to determine the linear width changes of the palatal vault; the distances between bilateral most cervical points of the palatal dentogingival junctions of the canines and premolars and palatal sulci of the deciduous and permanent molars. They were denoted as 3W, 4W, 5W, and 6W. The measuring procedures are depicted in detail in Figure 1 and 2.

To test the reliability, ten 3D scans were randomly selected and measured again on separate days 2 months after the initial measurement. Descriptive statistics for the measurement changes were calculated biennially. Individual subjects provided multiple repeated observations for linear measurements. Since the serial measurements were correlated with each other for individual subjects, a mixed model was applied. The analysis model for the data was written as $y_{ij} = \mu + \beta_1 \text{sex}_i + \beta_2 \text{age}_i + \beta_3 \text{sex}_i \times \text{age}_i + \text{b}_1 + \text{b}_2 \times \text{age}_i + e_{ij}$, where $\mu$ is the total mean, $\beta_1$ is the gender effect, $\beta_2$ is the age effect, $\beta_3$ is the interaction effect between gender.
and age, and $b_i$ ($i = 1, 2, \ldots, 50$) is the random effect by individual subjects.

In addition to observation of serial changes, the periodic changes from 6 to 10 years and those from 10 to 14 years were compared with paired $t$-test since the latter period generally includes the pubertal growth peak. Statistical analyses were performed using the language R and a $P$-value less than 0.05 was predetermined to be statistically significant.

**Results**

The intraexaminer reliability coefficients ranged 0.989–0.997. In terms of root mean squares, the random errors of estimation were lower than 0.05 mm linear measurements and there were no statistically significant differences between the test-retest measurements for any of the variables.

Means, standard deviations, and the average one-year difference during the observation period for all
measurements are summarized in Table 1. Increases in the average value of all variables were observed with age. The average 1 year increase ranged from minimum 0.10 mm (4W) to maximum 0.50 mm (6R). The ratio of the average 1 year change to the initial value at age 6 years ranged from the minimum 0.35 per cent (4W) to maximum 53.23 per cent (LL1). These ratios were quite different according to the variable characteristics. In other words, the variables denoting arch width (3W, 4W, 5W, and 6W) exhibited a smaller ratio than the variables corresponding to palatal height. In addition, the height variables representing the lateral part of the palate showed a larger ratio than the height variables corresponding to the medial part of the palate. There was no significant sexual dimorphism in the linear measurements or in the annual increases as fixed effects in the model. Although some trends where a regional and timing difference in the increase in measurements existed between genders, they were not statistically significant. As fixed effects, the annual increases were statistically significant for all variables and the initial value at 6 years was statistically significant for all variables except for RL2 and LL2 (Supplementary Table 1).

One of the advantages of performing a mixed effect analysis is that it enables the determination of individual random variability. With regard to the effect of individual random variability, individual variation was greater than the annual change over time (Table 2). The ratio of the initial individual variability at age 6 to the annual increases ranged from 4.15 in LL1 to 19.10 in 4W. In contrast to the ratio of the average one-year change to the initial value mentioned in Table 1, the height variables representing the lateral part of the palate had smaller ratios than the height variables corresponding to the medial part of the palate.

Table 1 Descriptive statistics.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Age</th>
<th>Average 1 year change*</th>
<th>Ratio**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Variables of width</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3W</td>
<td>25.64 (1.69)</td>
<td>26.73 (1.80)</td>
<td>27.04 (1.98)</td>
</tr>
<tr>
<td>4W</td>
<td>28.27 (1.55)</td>
<td>28.93 (1.81)</td>
<td>28.63 (1.84)</td>
</tr>
<tr>
<td>5W</td>
<td>32.84 (1.97)</td>
<td>33.94 (1.88)</td>
<td>34.27 (2.12)</td>
</tr>
<tr>
<td>6W</td>
<td>33.93 (1.83)</td>
<td>34.68 (1.98)</td>
<td>35.39 (2.16)</td>
</tr>
<tr>
<td>Palatal heights measured from quadrisectional points on gingival plane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3R</td>
<td>1.63 (0.62)</td>
<td>2.00 (0.66)</td>
<td>2.20 (0.82)</td>
</tr>
<tr>
<td>3M</td>
<td>3.47 (1.05)</td>
<td>3.98 (1.12)</td>
<td>4.25 (1.26)</td>
</tr>
<tr>
<td>3L</td>
<td>1.59 (0.52)</td>
<td>1.96 (0.69)</td>
<td>2.19 (0.78)</td>
</tr>
<tr>
<td>4R</td>
<td>5.56 (1.22)</td>
<td>6.19 (1.41)</td>
<td>6.54 (1.23)</td>
</tr>
<tr>
<td>4M</td>
<td>8.24 (1.38)</td>
<td>8.58 (1.31)</td>
<td>8.93 (1.28)</td>
</tr>
<tr>
<td>4L</td>
<td>5.38 (1.44)</td>
<td>5.87 (1.34)</td>
<td>6.16 (1.33)</td>
</tr>
<tr>
<td>5R</td>
<td>8.54 (1.46)</td>
<td>8.99 (1.22)</td>
<td>9.63 (1.38)</td>
</tr>
<tr>
<td>5M</td>
<td>11.19 (1.24)</td>
<td>11.55 (1.31)</td>
<td>12.17 (1.31)</td>
</tr>
<tr>
<td>5L</td>
<td>8.05 (1.21)</td>
<td>8.58 (1.42)</td>
<td>8.96 (1.39)</td>
</tr>
<tr>
<td>6R</td>
<td>7.73 (1.20)</td>
<td>8.59 (1.22)</td>
<td>9.52 (1.27)</td>
</tr>
<tr>
<td>6M</td>
<td>10.32 (1.45)</td>
<td>11.00 (1.36)</td>
<td>11.79 (1.35)</td>
</tr>
<tr>
<td>6L</td>
<td>7.54 (1.19)</td>
<td>8.35 (1.13)</td>
<td>9.04 (1.13)</td>
</tr>
<tr>
<td>Palatal heights measured from gingival plane to palatine ruga</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RL1</td>
<td>0.50 (0.70)</td>
<td>0.80 (0.74)</td>
<td>1.13 (0.84)</td>
</tr>
<tr>
<td>RL2</td>
<td>1.08 (0.86)</td>
<td>1.37 (0.88)</td>
<td>1.69 (1.03)</td>
</tr>
<tr>
<td>RL3</td>
<td>1.77 (1.25)</td>
<td>2.05 (1.52)</td>
<td>2.46 (1.64)</td>
</tr>
<tr>
<td>RM1</td>
<td>4.14 (1.32)</td>
<td>4.67 (1.31)</td>
<td>5.03 (1.35)</td>
</tr>
<tr>
<td>RM2</td>
<td>5.72 (1.84)</td>
<td>6.17 (1.95)</td>
<td>6.65 (1.99)</td>
</tr>
<tr>
<td>RM3</td>
<td>7.81 (1.66)</td>
<td>8.35 (1.77)</td>
<td>8.91 (1.77)</td>
</tr>
<tr>
<td>LM1</td>
<td>4.77 (1.22)</td>
<td>5.24 (1.25)</td>
<td>5.73 (1.30)</td>
</tr>
<tr>
<td>LM2</td>
<td>6.46 (1.68)</td>
<td>7.05 (1.70)</td>
<td>7.49 (1.65)</td>
</tr>
<tr>
<td>LM3</td>
<td>8.33 (1.73)</td>
<td>8.91 (1.73)</td>
<td>9.38 (1.70)</td>
</tr>
<tr>
<td>LL1</td>
<td>0.34 (0.61)</td>
<td>0.66 (0.64)</td>
<td>1.04 (0.70)</td>
</tr>
<tr>
<td>LL2</td>
<td>1.00 (0.69)</td>
<td>1.30 (0.80)</td>
<td>1.67 (0.89)</td>
</tr>
<tr>
<td>LL3</td>
<td>1.63 (1.22)</td>
<td>2.01 (1.39)</td>
<td>2.40 (1.56)</td>
</tr>
</tbody>
</table>

All variables were measured in millimeters.
Mean and standard deviation in the parenthesis.
*Average 1 year change in the mean of changes of eight years.
**Ratio is defined as the ratio of the average 1 year change to the initial value of age at six; all variables showed statistically significant change over time ($p < 0.05$).
Means, standard deviations, and the comparisons of periodic increments between the former 4 years and the latter 4 years for all measurements are summarized in Supplementary Table 2. In male and total subjects 4M, 5R, 5M, 5L, 6R, 6M and 6L showed significantly greater increments in latter period than former period. In contrast, only 6R and 6M showed significantly greater increments in latter period than former period. Regarding the variables related to the palatine rugae, generally the height measured from medial points of rugae showed significant different increments between former and latter periods.

### Discussion

Craniofacial structures are composed of a very balanced system in which there are mutual influences between the components (Heiser et al., 2004b). The growth and change of the palatal vault is also influenced by surrounding structures, even though they are dominated by genetic programming (Jimenez et al., 2012). For example, the changes in tooth position or tongue posture resulting from either growth or orthodontic therapy may lead to changes in the palatal dimension and form (Heiser et al., 2004c). In order to achieve optimum and stable results, information on the growth of the palatine vault in normal patients is essential in treatment planning for orthodontic patients who require a dimensional change in the maxilla.

There have been several studies describing the longitudinal changes of the palatine vault using various techniques (Ciusa et al., 2007; Heiser et al., 2004a; Heiser et al., 2004b; Thilander, 2009; Tsai and Tan, 2004). The information is highly valued, however, somewhat limited owing to several reasons. First and most important, it is difficult to gather eligible samples for longitudinal studies. Second and as mentioned above, conventional methods of measurements are only able to describe 2D changes such as the midsagittal view on cephalography and the limited transverse plane in sectioned casts or impressions. The third and most unresolved reason involves the 3D measurements of the palatine vault that have yet to be standardized. For example, there is no consensus about the plane from which palatal height should be measured. Several authors included the teeth and therefore the occlusal plane (Heiser et al., 2004b; Thilander, 2009). However, in order to determine the true palatal height, we excluded tooth height and used the gingival plane with all of the most cervical points of the dentogingival junction rather than three occlusal points of selected teeth following Primožič et al.’s method (2012). In fact, the establishment of a reliable reference plane is still an unsolved problem of contemporary biometric studies even though it has been discussed in many dental and anthropologic articles (Ahn et al., 2012).

In addition, even if the 3D measurements are available, the clear-cut depiction of growth change in the palate vault is very difficult since the growth change in the palatine vault is a 3D phenomenon. For example, Primožič et al. (2012) and Heiser et al. (2004b) reported changes in the volume or surface area of the palatine vault as growth changes. Although the gradual expansion of the palatal vault was understandable during the observation period, it could be mistaken as uniform ballooning despite the regional differences in palatal growth. Furthermore, the volume and area are difficult to grasp in contrast to the distance or length.

With these circumstances in mind, we attempted to depict the growth changes in the palatine vault two-dimensionally from frontal and lateral perspectives while taking advantage of 3D technology for measurements in order to gain a better understanding. Summary diagrams of average palatal height according to age and gender are presented in Figure 3, 4 and Supplementary Figures. These diagrams tell us that the growth pattern of the palatal vault differs slightly between girls and boys according to the region and period.
However, these differences were not significant throughout the entire observation period. In other words, there were no differences between genders with regard to baseline values or annual increases. This may be due to the chronological difference in growth between genders, such as age at takeoff or age at peak height. Unfortunately, these diagrams also have limitations in that they only overall average values rather than individual variations.

The comparisons of periodic changes between during the former 4 years and during the latter 4 years were performed...
to get some information related to the pubertal growth maximum. According to these comparisons, the palatal height of the posterior region generally showed greater increase in the latter periods than in the former periods. This trend was more evident in male and total subjects than in female subject.

In order to elucidate the individual subject’s random effect as well as fixed effects, we performed a mixed effect analysis that was not used in previous studies. This analysis revealed that the variation due to differences in growth rate among the subjects was $1/4$ or even $1/19$ as variable as the baseline values and average growth rate. The mixed effect analysis has another advantage in that some missing measurements do not result in the exclusion of all data for an individual subject (Kim et al., 2012). This is ideal for this study since the longitudinal data from

Figure 5 An example of superimposition using 12 palatal rugae endpoints by least square algorithm. Superimposition of 6 and 8 years of age (top left), 8 and 10 (top right), of 10 and 12 (middle left), of 12 and 14 (middle right), and of all ages (bottom).
the present study had several missing values in situations where the permanent teeth did not erupt while deciduous teeth exfoliate.

The difference among the ratios of the average two-year change to the initial value at age 6 can be explained to be largely influenced by the initial values given in Table 1. However, it can be deduced that there were large growth changes in the region where a large ratio was observed such as at the lateral part of the palate. Based on these results, it can be inferred that the growth of alveolar bone accounted for much of the increase in the palatal vault. These results were further supported by the height measured from the palatine rugae end points. The stability of the palatine rugae as reference points were evaluated in the previous study (Kim et al., 2012). Although the initial values of palatal height from the rugae end points exhibited some amount of individual random variability, they showed a relatively small amount of random variability with respect to the annual increase. In this respect, the large ratio for the height measured from the lateral end point of the palatine rugae reflects the adjacent alveolar bone’s vertical growth. If we include the height of the surrounding teeth and sum the amount of passive eruption, then the increase in the palatal space may become greater. Superimposition of the virtual model chronologically showed this trend (Figure 5).

To gain a more detailed and clear-cut understanding of palatine vault growth, a consensus should be established with regard to the standardization of the 3D measuring protocol in the first place. The present study suggested one possible methodology, but more elaborate approaches should be developed. Even though the palatine rugae have been suggested as stable references and showed some promise in short term observations (Kim et al., 2012), the problem in establishing reliable reference structure and plane in palatal regions are not solved clearly. The use of metallic implants (Björk and Skieller, 1974) cannot be chosen currently for observing the growth of healthy patients. However, it can provide absolutely stable references and be a realistic possibility for observing the orthodontic patients who needs the orthodontic implants.

Another issue to be addressed is that the measurements using state-of-the-art technology itself should not be the ultimate goal as mentioned above, rather an effective and intuitive explanation should be focused upon. Due to the small sample size, we were unable to consider the differences that might exist between facial types or ethnic populations. Pertinent studies on palatal growth according to facial type would be very meaningful in explaining human growth. However, the issue of gathering and adequate samples should be addressed beforehand.

Conclusions

1. This longitudinal study presented one method of describing palatine vault growth using 3D virtual models and specialized software. The palatal heights were measured from a total of 12 quadrisectional points between the most ginvial points of the palatal dentogingival junction of the canine to the first molar. In addition, the palatal heights were measured from a total of 12 lateral and medial endpoints of the palatine rugae.

2. There were significant annual increases in all variables related to palatal height. However, the individual random variability of the baseline values was quite large. There was no significant sexual dimorphism in the linear measurements or in the annual increases as fixed effects in the model, even though the growth pattern seemed to differ between genders.

3. Palatal height increases at the lateral part of the palate around the alveolar bone were observed. These increases were thought to account for much of increase in palatal height.

4. To gain a better understanding of palatal growth, a well-designed longitudinal study is necessary with a consensus on the appropriate measuring methodology and reference plane.

Supplementary material

Supplementary material is available at European Journal of Orthodontics online.

Funding

Bumsuk Academic Research Fund in 2011.

References


Melsen B, Melsen F 1982 The postnatal development of the palatomaxillary region studied on human autopsy material. American Journal of Orthodontics 82: e329–e342


Park D E et al. 2012 Different mandibular first molar shapes according to groove and cusp configuration in relation to suggested bracket position. European Journal of Orthodontics 35: 730–736


