European Journal of Orthodontics 33 (2011) 9–14
doi:10.1093/ejo/cjp157
Advance Access Publication 19 March 2010

Variation of the intermaxillary tooth-size relationship in normal occlusion

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SUMMARY The purpose of this study was to explore the intermaxillary tooth-size relationship that is attributed to normal occlusion using multivariate cluster analysis, while simultaneously incorporating the full dentition as a data set. From the central incisor to the second molar, the tooth sizes of 307 subjects (188 males and 119 females; mean age ± standard deviation, 19.9 ± 3.3 years) with normal occlusion were investigated. Tooth-size data were analysed separately for the maxilla and the mandible. When clustering, the partitioning around medoids (PAM) algorithm was performed with the transformed data based on principal component analysis (PCA). After the subjects were classified into four groups, the cluster memberships were cross-classified, and the distribution pattern and intermaxillary tooth-size relationships were explored.

Bolton tooth ratio showed a relatively wide range, and this was indicative of the variability in tooth size in subjects with a normal occlusion. However, the patterns of the intermaxillary tooth-size relationship were similar for males and females, and this result was concordant with the findings of the classic Bolton analysis. Using the multivariate approach to analyse the tooth-size data set of an individual patient and then comparing the results with the normal occlusion cluster has possible clinical applications in determining the amount and location of tooth-size control in orthodontics.

Introduction

The orthodontic literature is replete with studies reporting intermaxillary tooth-size ratios in various ethnic groups and comparing different malocclusion categories (Bolton, 1958, 1962; Lavelle, 1972; Crosby and Alexander, 1989; Nie and Lin, 1999; Smith *et al.*, 2000; Araujo and Souki, 2003; Uysal *et al.*, 2005; Basaran *et al.*, 2006). An abundance of studies attests to the importance of intermaxillary tooth-size relationship as an essential orthodontic diagnostic tool. It is also important to determine the amount and location of a tooth-size control in the finishing stage because patients with intermaxillary tooth-size discrepancies require either removal or addition of tooth structure to open or close spaces in the opposite arch.

Given that there are wide ranges of tooth sizes on which to achieve an excellent occlusion, there are many criteria to determine the difference between normal and significant discrepancies in tooth-size ratios. A large number of orthodontic patients have a significant Bolton tooth-size discrepancy (Crosby and Alexander, 1989; Freeman *et al.*, 1996; Uysal and Sari, 2005). Although some guidelines exist to determine tooth-size discrepancy, such as 2 mm out of normal or an aberration over 2 standard deviations (SD), these are more or less arbitrary (Halazonetis, 1996). A significant discrepancy was once defined as a value outside of 0.5 mm, 2 mm, 1 or 2 SD (Crosby and Alexander, 1989; Freeman *et al.*, 1996; Rudolph *et al.*, 1998; Smith *et al.*, 2000; Araujo and Souki, 2003; Kayalioglu *et al.*, 2005; Uysal and Sari, 2005; Uysal *et al.*, 2005). The majority of these criteria, such as 2 SD, are equivalent to the 95 per cent confidence interval of the mean. It is inadequate to use these definitions to identify normal versus abnormal. Moreover, when the intermaxillary tooth-size ratios are not normally distributed but skewed, the use of mean and 2 SD units to indicate normal is inappropriate (Freeman *et al.*, 1996; Uysal and Sari, 2005).

Even after an abnormal ratio has been detected, the problematic tooth must be localized and adjusted. This decision has largely depended on the experience of the clinician. A more scientific way to identify a normal versus an abnormal ratio and to localize the problematic tooth is needed. Recently, the use of computer programs for dental cast analysis has increased. Sound scientific algorithms are a prerequisite for computer-aided diagnosis. Consequently, it is necessary to develop a method to help determine whether or not the tooth-size ratio is normal, as well as to identify the problematic tooth and its size, subject to the condition of normal variability. Multivariate cluster analysis is a relatively new method in biomedical science and can interpret an entire set of data while preserving information about individual tooth-size measurements.

The purpose of this study was to explore and to visualize the intermaxillary tooth-size relationship that is attributed to normal occlusion by using multivariate cluster analysis while simultaneously dealing with measurements of the full dentition as a data set. Clinical applications of the results are also discussed.

Materials and methods

The data sets of tooth-size measurements were obtained from 307 Korean young adults (188 males and 119 females; mean age ± SD, 19.9 ± 3.3 years) with a natural normal occlusion. The term tooth size referred specifically to the mesiodistal diameter of a tooth, and it was measured with digital callipers (Model No. H530-20, Hanco Corp., Seoul, South Korea), accurate to 0.01 mm from the central incisors to the second molars (Moorrees *et al.*, 1957).

The subject collection was a part of the Korean Standard Occlusion Study that has been ongoing since 1997. The selection criteria for these normal occlusion subjects were as follows: Class I molar and canine relationship with normal occlusal interdigitation, fully erupted permanent dentition except for the third molars, normal overjet and overbite (2–4 mm), minimal crowding (less than 2 mm) and spacing (less than 1 mm), and no history of previous orthodontic or prosthodontic treatment. In addition, subjects with proximal caries or fillings that affected the mesiodistal tooth size, gross restorations, significant attrition, congenital defects, or deformed teeth were excluded. The absence of tooth anomalies in structure and development was also considered.

From the central incisor to the second molar, the tooth sizes of the 307 subjects with normal occlusion were described separately for males and females. Groups of tooth-size data were analysed separately for the maxilla and the mandible. Since tooth sizes were measured for 14 dimensions in the maxilla and the mandible, respectively, the principal component analysis (PCA) was used for the clustering method. PCA includes a mathematical process to reduce a number of correlated variables into a smaller number of variables called 'principal components' (Jolliffe, 2002). Using scree plots, two principal components were determined to account for about 70 per cent of the sample variability in both maxillary and mandibular tooth sizes. The partitioning around medoids (PAM) method was then used to cluster tooth sizes for each group. Medoid is the most centrally located point in the given data set so that its average dissimilarity to all the objects is minimal in the cluster. Thus, PAM is more robust than other clustering methods and accepts a wide range of variability without removal of any data (Kaufman and Rousseeuw, 1990). In addition, PAM with silhouette provides information about the appropriate number of clusters to use for the analysis (Rousseeuw, 1987).

After being divided into groups for the maxilla and the mandible, all subjects were assigned to a cross-classification table composed of maxillary and mandibular clusters. The characteristics of intermaxillary tooth-size ratios were analysed, and the preponderance of elements in the cross-classification table was also examined to explore the extent to which each contributed to normal occlusion. The independence between clusters in the maxilla and the mandible for each gender was evaluated based on the Cochran–Mantel–Haenszel test. The Bolton ratios were further estimated within the maxillary and the mandibular clusters. The mean Bolton ratio was calculated as the anterior (AR) and overall ratios (OR). For each ratio, the difference between the mean Bolton ratios was tested using the analysis of variance model. All reported *P*-values were based on two-sided levels of significance.

Results

After cluster analysis using the PAM method, two clusters for males and females were identified. Table 1 provides an average PAM silhouette width to select the number of clusters, where high average width represents good clustering. As a result, two clusters appeared to be an appropriate number for tooth-size data in the maxilla and in the mandible for each gender category.

Table 2 shows the cross-classification frequency of the maxillary and mandibular tooth-size clusters that were placed into two groups. The association between maxillary and mandibular tooth size was examined in the two groups. For the association analysis, gender was considered as a confounding (or control) variable; it might influence characteristics such as facial size, which may result in heterogeneity between genders in terms of the association between the maxillary and mandibular cluster. Thus, gender was controlled as a possible confounding effect. With the Cochran–Mantel–Haenszel statistic equal to 124.3, the approximate *P*-value was found to be less than 0.0001. Thus, there was extremely strong evidence that maxillary and mandibular tooth sizes were not independent.

Table 1 Average silhouette width according to the number of clusters in the maxilla and mandible arranged by gender.

	Number of clusters	Average silhouette width	
		Males	Females
Maxilla	2	0.393	0.391
	3	0.326	0.376
	4	0.356	0.368
Mandible	2	0.421	0.431
	3	0.391	0.340
	4	0.316	0.300

Because a cluster size of two had the highest average width, two clusters in the maxilla and mandible were identified.

Table 2 Cross-classification frequency (per cent) of maxillary and mandibular tooth sizes, which are clustered into two groups for study subjects with a normal occlusion.

Gender	Mandibular tooth size		*N* (%)	Relative odds
	Smaller group	Larger group	Total	
Males				
Maxillary tooth size	91 (48.4)	13 (6.9)	104 (55.3)	25.7 (11.8–56.0)*
Smaller group	18 (9.6)	66 (35.1)	84 (44.7)	
Larger group				
Total	109 (58.0)	79 (42.0)	188 (100)	
Females				
Maxillary tooth size	46 (38.6)	12 (10.1)	58 (48.7)	15.7 (6.4–38.3)*
Smaller group	12 (10.1)	49 (41.2)	61 (51.3)	
Larger group				
Total	58 (48.7)	61 (51.3)	119 (100)	

A mathematical process of partioning around medoids analysis was used to divide the subjects into two groups. When the sizes of the teeth were included in the equation and the value was smaller than a coefficient, the subject was classified into the smaller group. On the other hand, if the value was larger than a coefficient in the equation, the subject was classified into the larger group.
*95% confidence interval.

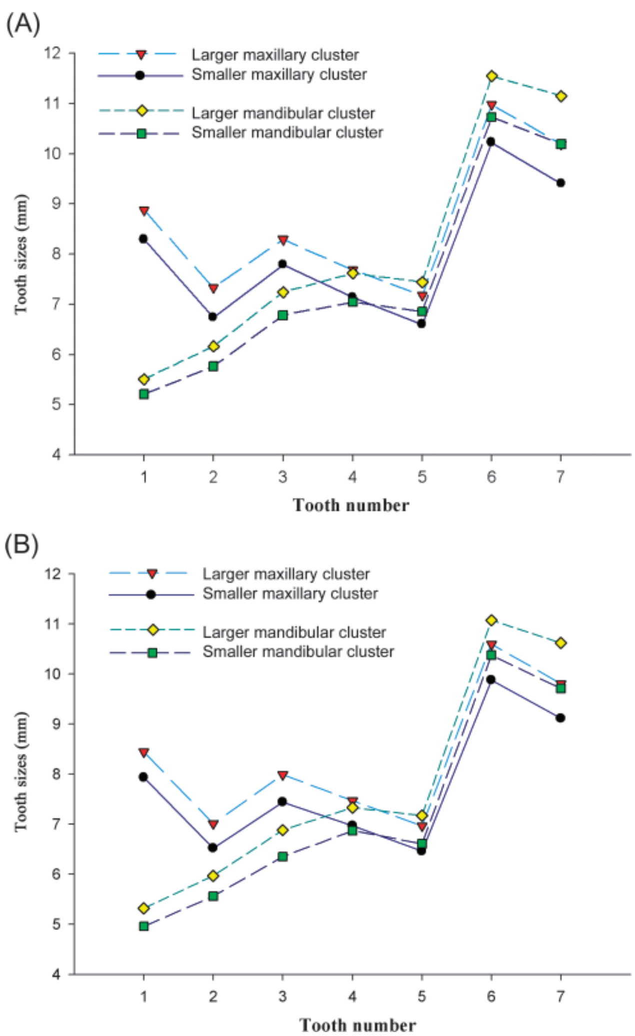

Figure 1 Mean tooth size versus tooth number in males (A) and females (B) with both maxillary and mandibular groups having similar characteristics. The parallel pattern of line drawings suggests that the proportionality of tooth sizes is a decisive factor in normal occlusion.

The associations between maxillary and the mandibular tooth sizes were quite strong for both females and males. To determine if the association was the same for each gender, a Breslow-Day test was performed, and the test statistic was $\chi^2 = 0.666$ with 1 degree of freedom ($P = 0.414$). Thus, the null hypothesis of the homogeneous association between maxillary and mandibular tooth sizes was rejected. The Cochran Mantel–Haenszel estimate of the common conditional odds ratio (20.7) strongly implied that subjects with smaller maxillary tooth sizes tended to have smaller mandibular tooth sizes.

When the mean tooth sizes versus tooth number for males (Figure 1A) and females (Figure 1B) in both the maxillary and the mandibular groups with similar characteristics were depicted, parallel patterns were observed. This suggested that the proportionality of tooth sizes was a decisive factor in achieving a normal occlusion.

With marked inter-individual differences in the tooth size from normal occlusion subjects, the mean Bolton ratios depending on the maxillary and mandibular clusters appeared to be significantly different ($P < 0.001$; Table 3).

Discussion

Although orthodontists have made considerable use of the intermaxillary tooth-size ratio reference first published 50 years ago (Bolton, 1958, 1962), the results of comparisons of intermaxillary tooth-size relationship among malocclusion categories and different ethnic populations are controversial. Some investigators found that normal tooth-size ratios are gender and population specific, and different among malocclusion categories, while others disagreed (Lavelle, 1972; Crosby and Alexander, 1989; Nie and Lin, 1999; Smith *et al.*, 2000; Alkofide and Hashim, 2002; Araujo and Souki, 2003; Al-Tamimi and Hashim, 2005; Basaran *et al.*, 2006). While differences in the samples and methods of the

Table 3 Mean Bolton tooth ratio ± standard deviations for the cluster memberships classified in Table 2.

	Mandibular clusters		Total
	Smaller group	Larger group	
Anterior 3:3 ratio			
Males*			
Maxillary clusters			
Smaller group	77.8 ± 2.4	79.4 ± 1.2	78.0 ± 2.4
Larger group	75.3 ± 2.0	77.2 ± 2.3	76.8 ± 2.4
Total	77.4 ± 2.5	77.6 ± 2.3	77.5 ± 2.5
Females*			
Maxillary clusters			
Smaller group	77.5 ± 2.3	77.0 ± 2.7	77.4 ± 2.3
Larger group	80.8 ± 3.9	77.1 ± 2.0	77.8 ± 2.9
Total	78.2 ± 2.9	77.1 ± 2.2	77.6 ± 2.6
Overall 6:6 ratio			
Males*			
Maxillary clusters			
Smaller group	90.6 ± 1.6	92.6 ± 0.9	90.9 ± 1.7
Larger group	88.3 ± 1.7	90.4 ± 1.8	90.0 ± 2.0
Total	90.2 ± 1.9	90.8 ± 1.8	90.5 ± 1.9
Females*			
Maxillary clusters			
Smaller group	90.3 ± 1.6	88.2 ± 1.3	89.8 ± 1.8
Larger group	93.6 ± 1.8	90.1 ± 1.6	90.8 ± 2.1
Total	91.0 ± 2.1	89.7 ± 1.7	90.3 ± 2.0

*Test for mean Bolton ratio difference among the four groups from the maxillary and mandibular clusters showed significant differences ($P < 0.001$).

various studies could account for dissimilar findings, an adequate explanation for the disparate results was not found.

Normative data have large normal variations. Therefore, an assessment of individual variability using only the mean (standard) data is unreasonable (Lee *et al.*, 2007). A low or high value may not necessarily reflect a true discrepancy. Similarly, an ideal value of 77.2 per cent may not guarantee ideal occlusion (Bolton, 1962; Halazonetis, 1996). As Bolton (1958) stated, there are relatively wide ranges of anterior ratio (AR, 87.5–94.8) and OR (74.5–80.4); this implies a wide range of normal variability within excellent occlusion subjects. Implicit in the rationale for using Bolton tooth analysis is the assumption that a normal Bolton tooth ratio is a prerequisite for adequate anterior overbite and posterior tooth interdigitation. However, Bolton's standards were expressed as means and SDs rather than as ranges and so were used to predict the congruity between the two dental arches.

The ranges of AR (69.6–90.7) and OR (85.3–97.0) in the present study showed even wider variability than those of Bolton (1958). In reporting the heterogeneity inherently present in normal occlusion subjects, it seems that the normal variability within an individual with a normal occlusion might be even greater than the differences between ethnicity, gender and malocclusion groups. However, most investigations in this area have dealt with the normal intermaxillary tooth-size ratio using a somewhat absolute or fixed concept of means and SDs, which might be more or less not concordant with Bolton's original idea. Therefore, it may be better to interpret AR or OR with pattern analysis rather than with fixed (mean and deviation) values.

There were three distinct features of the present study that differed from Bolton's analysis. First, in contrast to the conventional Bolton tooth analysis that evaluated how closely the tooth sizes of a patient approach those predicted by a reported mathematical formula, the present method emphasizes the variability of normal occlusion and individualized analysis for an individual malocclusion patient to achieve a normal occlusal relationship. Second, the 307 subjects had an untreated normal occlusion, whereas most of Bolton's sample (44/55) had been treated orthodontically. Compared with Bolton's study, the present investigation had a larger sample size and comprised only untreated subjects with a normal occlusion. These two factors may result in a wide range of variability. Additionally, racial characteristics may contribute to this variability. Third, the mesiodistal widths of the second molar were incorporated into the multivariate analysis, a variable that was excluded by most previous studies. When comparing tooth size, the most commonly used method is univariate statistical inferences. Although a spreadsheet-style model analysis was introduced to provide a quick and easy way to assess tooth-size ratios, in order to obtain an overall picture, all the variables for each individual should be combined and subjected to multivariate cluster analysis (Halazonetis, 1996). Lee *et al.* (2007) showed the variability problems of tooth size in normal occlusion with seven clusters in males and four clusters in females. However, their study was not successful in solving the important clinical problems, such as estimating tooth sizes forming a normal occlusion (viz. Bolton tooth analysis) or estimating tooth sizes for unerupted teeth (mixed dentition analysis). It was conjectured that this may be a statistical noise component resulting from the rather delicate model-based multivariate-clustering method. Since the multivariate-clustering method is rather sensitive with outliers, although it is efficient without them, a simpler and more robust clustering method, the PAM method, was used. Similarly, PCA was applied in this research to reduce dimensionality. As a result, more reasonable results than previously were obtained and the clusters can be divided by two for each maxilla and mandible in males and females. Two groups make it easier to assign each subject into the groups, which make it easier to use clinically.

As a result of cross-classification (Table 2), the diagonal elements showed more frequent distribution than the off-diagonal elements. This illuminates two important clinical scenarios. First, normal occlusion could be achieved with various tooth-size combinations. Second, since the diagonal elements had overwhelming frequencies, specific associations and principles could be found to achieve normal occlusion. With graphic drawings of clusters (Figures 1 and 2), the parallelism of those lines is readily observable, which was supportive of the current diagnostic approach, i.e. the importance of the intermaxillary tooth-size ratio (Bolton's ideal). At first, the aim of this study was to develop a tool that would be more accurate than the widely used Bolton analysis to achieve excellent occlusion with the multivariate approach. Though the method of analysis was different, this study seems to support and justify the validity of the traditional format of classic Bolton analysis.

Exact localization of tooth-size discrepancies is the standard diagnostic criteria of orthodontic treatment. Although the ideal method would be the use of a diagnostic set-up model that simulates the post-treatment occlusion, this procedure is practically difficult (Bolton, 1962; Halazonetis, 1996). Instead, procedures that can localize teeth that require adjustment using the tooth-size ratio would be helpful both clinically and for ease of application. Sometimes, when the ratio is high, it means that the maxillary tooth sizes are small, but it also implies that the mandibular teeth are large. By allocating the tooth-size data set of an individual patient and comparing the pattern with the normal occlusion cluster, further applications in determining the amount and localization of tooth-size control seem possible. The conventional method of dental cast analysis using a polygonal (wiggle) chart may give a false impression. For example, setting the inside of the polygon as normal and the outside as abnormal ignores the wide variability of normal occlusion (Figure 2A). In this respect, a method to diagnose intermaxillary tooth-size discrepancy by comparing the pattern of tooth sizes graphically with those of normal occlusion clusters may be more appropriate (Figure 2B). This method might help in deciding whether tooth-size adjustments in the anterior segment need to be made and which tooth should be controlled on an individual basis. It does not emphasize the normal ratio itself; rather, it focuses more on the tooth that is an outlier in the normal tooth-size pattern. For instance, if a line connecting a certain tooth severely violates parallelism from the normal pattern line drawing (Figure 2B), the tooth might be a possible cause of tooth-size discrepancy. Sometimes, the insignificant tooth-size discrepancy using the method of this study was viewed as significant when using Bolton's analysis. An example in Figure 2 contrasts the conventional Bolton tooth analysis to the method of this study. By employing the Bolton's AR formula and subtracting the solution from the existing tooth sizes, if a satisfactory anterior relationship is to be achieved, the mandibular segment would need to be reduced by approximately 5.0 mm or the maxillary segment would need to be increased by about 6.5 mm. On the other hand, as shown in Figure 2B, the lines connecting the individual tooth sizes of a patient severely deviated from those of the smaller mandibular tooth-size group. The mandibular incisors seem to be the teeth responsible for the tooth-size discrepancy. The amount of tooth-size alteration necessary would only require a reduction of approximately 1.0 mm of mesiodistal width for both the mandibular central and lateral incisors. Although 1 mm from each incisor gives a total of 4 mm, which might be slightly less than 5 mm with the conventional method and clinically equivalent, it is still advantageous to determine the problematic tooth.

Obviously, this method cannot be used without pointing out some limitations. Intermaxillary tooth-size analysis

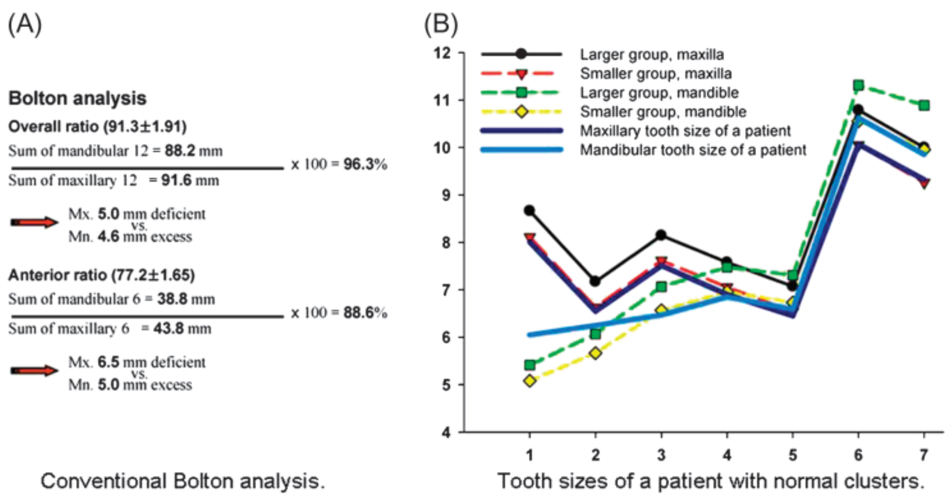

Figure 2 When Bolton analysis was applied, this patient required a reduction of 5.0 mm in the mandibular segment or an increase of 6.5 mm in the maxillary segment (A). When the tooth size was plotted and compared with the normal occlusion clusters (B), this patient was placed into smaller tooth-size group, and the mandibular incisors were indicated as the problem teeth. The required amount of tooth-size alteration would be only an approximately 1.0 mm reduction of the mesiodistal width for both the mandibular central and lateral incisors.

should not overlook the influence of overbite, the length of the central incisors and the cusp height to the AR or the influence of the anterior arch form and incisal edge thickness (Bolton, 1958; Halazonetis, 1996; Rudolph *et al.*, 1998; Braun *et al.*, 1999). The amount of crowding, skeletal pattern and the correct axial inclination of the incisors and canines should also be carefully considered (Shellhart *et al.*, 1995; Halazonetis, 1996). There is a possibility that these factors have had a greater role than intermaxillary tooth-size relationship in forming normal occlusion. This could be one of the reasons why the mean Bolton ratio of normal occlusion subjects was shown as a variable range.

Conclusions

The results of this study seem to justify the validity of the classic Bolton tooth analysis that emphasizes that excellent occlusion depends on a harmonious intermaxillary tooth-size relationship. The findings also showed that the Bolton tooth ratio has a relatively wide range indicative of the variability of tooth size in normal occlusion subjects. The clinical application of a multivariate cluster analysis is of help in determining the amount and location of the tooth-size discrepancy.

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