[UCI]I804:24011-200000265218

2016년 2월 석사학위논문 Spee 만곡 레벨링에 따라 증가되는 하악 치열궁 길이의 디지털 모형을 이용한 분석 조 용 화

2016년 2월

석사학위 논문

Spee 만곡 레벨링에 따라 증가되는 하악 치열궁 길이의 디지털 모형을 이용한 분석

조선대학교 대학원

치의학과

조 용 화

Spee 만곡 레벨링에 따라 증가되는 하악 치열궁 길이의 디지털 모형을 이용한 분석

Addtional arch length required for leveling the curve of Spee evaluated using digital model setups

2016년 2월 25일

조 선 대 학 교 대 학 원

치 의 학 과

조 용 화

Spee 만곡 레벨링에 따라 증가되는 하악 치열궁 길이의 디지털 모형을 이용한 분석

지도교수 임 성 훈

이 논문을 치의학 석사학위신청 논문으로 제출함

2015년 10월

조선대학교 대학원

치 의 학 과

조 용 화

조용화의 석사학위 논문을 인준함

위원장 조선대학교 교 수 이 상 호 (인)

위 원 조선대학교 교 수 임 성 훈 (인)

위 원 조선대학교 조교수 강 성 남 (인)

2015년 11월

조 선 대 학 교 대 학 원

목 차

표 목 차

도 목 차

ABSTRACT

Spee 만곡 레벨링에 따라 증가되는 하악 치열궁 길이의 디지털 모형을 이용한 분석

Yong-hwa Cho
Advisor : Prof. Sung-hoon Lim, DDS, MSD, PhD.
Department of Dentistry,
Graduate School of Chosun University

Objective: 본 연구는 Spee만곡 레벨링에 따라 증가되는 하악 치열궁 길이(AALL)를 평가함에 있어 cusp tips와 proximal maximum convexities 중 더 적절한 측정 기준점을 3차원 디지털 셋업 모형을 이용해 알아보고자 하였다.

Methods: Typodont teeth와 3D software를 이용하여 0부터 4.7mm의 Spee만곡 깊이를 갖는 16개의 디지털 셋업 모형을 제작하였다. AALL을 계산하기 위해 cusp tips와 proximal maximum convexities를 기준점으로 각각 2차원과 3차원 치열궁 길이를 측정하였고, 레벨링시 증가되는 하악 치열궁 길이(AALL)는 3차원적 치열궁 길이에서 교합평면에 투영된 2차원적 치열궁 길이를 공제하여 평가하였으며, 두 기준점 사이의 측정값은 paired *t*-test로 비교분석하였다.

Results: 3차원적 치열궁 길이는 Spee만곡이 깊어져도 동일하게 유지되어야 함에도 불구하고 Spee만곡이 0mm에서 4.7mm으로 점차 깊어질 때 cusp tips를 기준으로 하여 측정한 3차원적 치열궁 길이가 3.8mm 감소한 반면 proximal maximum convexities를 기준으로 측정한 3차원적 치열궁 길이는 0.4mm 감소하였다. AALL은 3차원적 치열궁 길이에서 2차원적 치열궁 길이를 공제하여 평가하므로 cusp tips를 기준점으로 사용한 AALL은 proximal maximum convexities를 기준점으로 사용한 AALL 보다 작게 계산된다.

Conclusion: AALL은 cusp tips를 기준으로 측정하였을 때 왜곡되어 측정되므로 proximal maximum convexities를 기준점으로 사용하여야 AALL을 더 정확히 측정할 수 있다.

I. Introduction

The curve of Spee (COS) is an important characteristic of the mandibular arch.[1] Most dentists believe that the COS comprises the occlusal surfaces of molars and incisal edges.[2] The COS is flatter in primary dentition than in permanent dentition, and develops with the eruption of the mandibular permanent first molars and permanent incisors.[3] Once established, the COS remains relatively stable.[4,5] The rationale behind the traditional concept of leveling the COS is somewhat obscure.[6] Andrews[7] suggested that the COS should be leveled to a flat plane in order to facilitate construction of an optimal occlusion. He also suggested that a flat plane should be a treatment goal as a form of overtreatment.[7] Correction of the deep overbite often involves leveling of the COS,[8] and this leveling is an everyday practice in orthodontic clinics.[9] Leveling of the COS is associated with an increase in the arch length.[8-14] As the COS deepens, the amount of additional arch length required for leveling the COS (AALL) increases. Since leveling of the COS requires additional arch length, the COS can be viewed as a crowding or arch-length discrepancy that is expressed in the vertical aspect. Therefore, evaluating the AALL is as important as evaluating arch-length discrepancy when there is a deep COS.[9] However, the amount of AALL is not easily predicted. A popular rule of thumb for estimating the AALL is that 1mm of arch length is needed to level each millimeter of the COS depth when the depth of the COS is the average depth on the right and left sides.[10,11] This popular theory is thought to be based on the study of Baldridge,[12] who used setups of patients' malocclusion models with varying COS depths to develop an equation for estimating the AALL. Germane et al[9] also reported an equation for estimating the AALL from a mathematical model.

Most recently, Braun et al[13] used a coordinate-measuring machine to record the three-dimensional (3D) coordinates of cusp tips and incisal edges of malocclusion models, and then calculated the AALL by subtracting the planar projection of the total arch circumference from the total arch circumference (Table 1). The total

arch circumference is measured by summing the distances between the cusp tips,[13] and can be described as a 3D arch circumference. The planar projection of the total arch circumference can be thought of as the planar projection of the 3D arch circumference onto the occlusal plane, and can be described as a 2-dimensional (2D) arch circumference. Therefore, the AALL can be measured by subtracting the 2D arch circumference from the 3D arch circumference.

In addition, the AALL can be measured for an individual tooth by subtracting the 2D tooth width from the 3D tooth width. The 3D tooth width is the conventional tooth width measured between the mesial and distal maximum convexities, and the 2D tooth width is a projection of the 3D tooth width onto the occlusal plane. This individual tooth AALL means that space is needed to upright the occlusal surface of a tooth parallel to the occlusal plane. Additional arch length is required for uprighting of teeth tipped mesiodistally along the COS, but is not required for pure extrusion or intrusion of teeth maintaining the mesiodistal tooth axis. The AALL of an arch can also be measured by subtracting the sum of the 2D tooth widths from the sum of the 3D tooth widths or by summing individual tooth AALLs.

When estimating the AALL, the question is raised as to which reference points should be used for the measurements of arch circumference. Braun et al[13] measured the 3D arch circumference by summing the distances between the distobuccal cusp tip of the second molar, the mesiobuccal cusp tip of the first molar, the buccal cusp tips of the premolars, the cusp tip of the canine, and the center points of each incisal edge. This may lead to underestimation of the 3D arch circumference in the molar region because the curve formed by the occlusal surfaces of the molars is deeper than the line connecting the distobuccal cusp tip of the second molar, the mesiobuccal cusp tip of the first molar, and the buccal cusp tip of the second premolar. When using a coordinate-measuring machine equipped with a mechanical probe, the position of the contact point or the proximal maximum convexity cannot be contacted by the mechanical probe. This could explain why Braun et al[13] used the cusp tips as measurement points.

A software tool that calculates the 2D arch circumference and 2D tooth width

can be added easily to digital model analysis programs, which means that the AALL can be estimated more easily and accurately by subtracting the 2D arch circumference from the 3D arch circumference or by subtracting the sum of the 2D tooth widths from the sum of the 3D tooth widths in each case, rather than estimating the AALL using the various equations suggested by different authors.[9-14] In this case, using the proximal maximum convexities for calculating AALL can be more convenient than using landmarks such as cusp tips because identification of the proximal maximum convexities is also required for tooth-size measurements and calculation of the required space and arch-length discrepancy.

The purpose of this study was to compare the AALL measured from the cusp tips (AALLct) and that measured from the proximal maximum convexities (AALLpmc) so as to determine the most suitable reference points for calculation of AALL.

II. Materials and methods

A set of mandibular teeth of a typodont (PE-ANA001, Nishin, Tokyo, Japan) was scanned using a 3D scanner. With these digital models of teeth,16 digital setup models having a COS depth ranging from 0 to 4.7mm were fabricated using 3D software (Geomagic Design X 2014, 3D Systems, Rock Hill, SC). The definitions of the terms used in this present study are listed in Table 1 (also see Figure 1A).

Braun et al[13] used the sum of the right- and left-side COS depths. In the present study, the COS depth was defined as the average of the right- and left-side depths, because the average value is more frequently used than the sum of the right-and left-side COS depths. In the present study, the average depths of the right- and left-side COS of the setup models ranged from 0 to 4.7mm, with a mean±SD value of 2.6±1.5mm (Table 2).

In each setup, even marginal ridge relationships between adjacent teeth were maintained. The interproximal contacts were made to occur at the adjacent proximal maximum convexities, which were determined from a plane perpendicular to the occlusal plane and also perpendicular to the line of occlusion (Figure 1B). These contacts were checked with a clipping view to minimize overlapping of the proximal surfaces (Figure 2A). A constant arch form was maintained by setting the intercanine and intermolar widths at 27and 46mm, respectively (Figure 2B). The AALL was calculated by subtracting the 2D arch circumference from the 3D arch circumference (Table 1, Figures 3 and 4).

While the distances between cusp tips cannot be described as the tooth width, the distances between adjacent cusp tips or adjacent proximal maximum convexities were defined as a tooth width for ease of understanding (Table 1). The contribution of the uprighting of each tooth on the AALL was evaluated by calculating the individual tooth AALL by subtracting the 2D tooth width from the 3D tooth width. These values were measured for each setup, and mean values were calculated after averaging the right- and left-side measurements.

The Shapiro-Wilk test confirmed that the measurements from the cusp tips and measurements from the proximal maximum convexities were consistent with a normal distribution. Therefore, the paired t-test was used to test the difference between these two measurements. In addition, linear regression equations were obtained for both measurements. Determination of reference points and measurements of ten setup models were repeated by the first author with three-month interval. Then, the method errors were calculated with Dahlberg's Formula.15 Method errors of both 2D and 3D measurements of the distances between cusp tips were equally 0.151 mm, and method errors of 3D and 2D measurements of the distances between proximal maximum convexities were 0.115 mm, and 0.030 mm, respectively. The threshold for statistical significance was set at $P<0.05$. All statistical evaluations were conducted using SPSS (version 20; IBM, Armonk, NY).

III. Results

As the average of the right-and left-side COS depths increased from 0 to 4.7mm, the 2D arch circumference decreased by 6.0mm in the cusp-tip measurements and by 3.4mm in the proximal maximum-convexity measurements (Tables 2 and 3, Figure 5). Simultaneously, the 3D arch circumference decreased by 3.8mm in the cusp-tip measurements and by 0.4mm in the proximal maximum-convexity measurements. These changes resulted in a 2.3-mm increase in the AALLct and a 3.0-mm increase in the AALLpmc as the COS depth deepened from 0 to 4.7mm. Paired t-test revealed a significant difference between AALLct and AALLpmc (P=0.002).

The cusp tip placed deepest from the occlusal plane was the mesiobuccal cusp tip of the mandibular first molar. Examination of the mean values of the individual tooth AALL disclosed that the value was highest between the first and second molars for the cusp-tip measurements (0.27mm), and in the mandibular second molar for the proximal maximum-convexity measurements (0.32mm Figure 6).

The following regression equations were obtained:

$Y=0.48\chi - 0.31$ (R^2=0.94) for the cusp tip measurements

$Y=0.62\chi - 0.38$ (R^2=0.88) for the proximal maximum-convexity measurements

where Y (mm) is the AALL and χ (mm) is the average of the right- and left-side COS depths (Figure 7).

IV. Discussion

The 3D arch circumference represents the arch length after complete leveling of the COS. Therefore, the 3D arch circumference should be constant regardless of the COS depth. However, the 3D arch circumference decreased by 3.8mm in the cusp-tip measurements because the distances between the adjacent cusp tips decreased as the COS deepened from 0 to 4.7mm. This means that the AALLct would be underestimated. In contrast, the 3D arch circumference measured from the proximal maximum convexity decreased by only 0.4mm as the COS deepened from 0 to 4.7mm.

When the COS deepens, the interproximal contact points move slightly toward the occlusal direction, thereby reducing the distances between the contact points. This might have caused a 0.4-mm reduction of the 3D arch circumference in the proximal maximum-convexity measurements. This result indicates that the proximal maximum convexity is more appropriate than the cusp tip as a reference point for estimation of the AALL.

There was also a greater reduction in 2D arch circumference with the cusp-tip measurements. Therefore, the greatest difference in the AALL (3D arch circumference minus 2D arch circumference) was only 0.7mm smaller with the AALLct when the COS depth was 4.7mm.

In the present study, the deepest point from the occlusal plane was the mesiobuccal cusp tip of the mandibular first molar. This finding is in accordance with that of a previous study[16] in which malocclusion models were surveyed to evaluate the COS. The mean value of individual tooth AALLs was lowest in the mandibular second premolar and central incisor areas, and highest in the mandibular second molar area. The lowest value for 3D tooth width minus 2D tooth width being at the mandibular second premolar is attributable to it being near the center of the COS and having a smaller mesiodistal width than the mandibular first molar. The greatest increase of the COS was reported as occurring with the eruption of the mandibular second molars.[3] The value of 3D

tooth width minus 2D tooth width of the mandibular second molar accounted for about half of the AALL. If the mandibular second molar could be uprighted with the center of rotation near its center of resistance, then this uprighting of the mandibular second molar would cause minimal flaring of the mandibular incisors during leveling of the COS. Extraction of third molars would be helpful to make room for distal uprighting of the mandibular second molars and to facilitate uprighting of the mandibular second molar with the accelerated regional phenomenon.[17,18]

Braun et al[13] reported a relationship of $Y=0.2462\chi-0.1723$, where Y is the arch circumference differential in millimeters, which is the same as the AALL in the present study, and χ is the sum of the right- and left-side depths of the COS in millimeters. When χ is defined as the average of the right- and left-side COS depths, as in the present study, this regression equation can be converted to $Y=0.4924\chi-0.1723$. The popular rule of thumb for estimating the AALL is $Y=\chi$.[10,11] In the present study, the linear regression equation of $Y=0.479\chi-0.31$was obtained from cusp-tip measurements.

This similarity between the cusp-tip measurements in the study of Braun et al.[13] and in the present study is attributable to use of the same reference points. When the COS depth is 4.7mm, the equations from cusp-tip measurements in the present study and the equation of Braun et al[13] would predict only 61% (1.95/3.2) and 67% (2.14/3.2) of the AALLpmc, respectively.

Braun et al[13] suggested that the increase in arch length after leveling is due mainly to flaring of the incisors during leveling with a continuous wire and the geometric requirement of AALL being smaller than was previously thought (Figure 8).[13,19] This suggestion emphasizes the importance of flaring caused by the biomechanics of leveling using a continuous arch wire. Although this suggestion is valid, the geometric requirement of the AALL is not negligible given the larger AALL estimated from the proximal maximum-convexity measurements.

If the available space is measured using a brass wire bent to follow both the line of occlusion and also the COS in the vertical aspect, this available space would constitute a 3D available space. Digital model analysis programs usually

measure the available space by drawing a 3D spline curve over the arch and inserting control points as needed to conform to the COS, and these control points are automatically placed onto the mesh surface. This measurement of available space is also a 3D available space. In these cases, measurement of arch-length discrepancy reflects the space deficiency or redundancy in aligning teeth into the arch with the COS bent into the brass wire or the spline curve that was used for measurement of available space. Thus, the AALL can be estimated by subtracting the 2D available space that is the projection of the 3D available space (length of spline curve or brass wire) onto the occlusal plane. This 2D available space can also be measured by bending a flat brass wire over a transparent acrylic or glass plate placed over the occlusal surface of a model. If a brass wire or a digital spline curve for measuring the available space was not bent to conform to the COS and kept flat in the vertical aspect, this measurement can be viewed as a 2D available space. Arch-length discrepancy and the AALL can be calculated simultaneously simply by subtracting the required space from the 2D available space. When this measurement of arch-length discrepancy is used, neither AALL estimation nor measurement of the COS depth are needed.

It would be desirable to add a tool to the digital model analysis programs for estimating the AALL automatically by subtracting the 2D arch circumference from the 3D arch circumference. This could be easily implemented by transforming the 3D coordinates of the reference points into 2D coordinates by removing the coordinate values representing vertical height (usually z values) when the occlusal plane is parallel to the base plane (usually xy plane). This method will estimate the AALL more accurately than using a regression equation. Similar method can be used to calculate individual tooth AALLs and this can gives information about which tooth requires the largest space for leveling, and this information would help the planning of leveling method.

The most ideal way of estimating AALL and arch length discrepancy can be using model setups. However, model setups require considerable work. This can be overcome when a software tool for automatic alignment of dentition is developed in the future. Until then, calculation of AALLpmc can be useful. The

limitation of the present study is that the simulation was done with a typodont model. It is difficult to use patient's malocclusion models because there always some crowding in most cases with deep COS. Further studies using patient's malocclusion models are needed.

V. Conclusion

Sixteen 3D digital model setups were constructed with various degrees of COS while maintaining even marginal ridge relationships between the adjacent teeth to compare AALLct and AALLpmc. Although the 3D arch circumference should not decrease as the COS deepens, it was found to decrease by 3.8mm in the cusp-tip measurements and by 0.4mm in the proximal maximum-convexity measurements as the COS deepened from 0 to 4.7mm. The AALLct significantly underestimated the AALL than AALLpmc (P=0.002). Therefore, the use of AALLpmc is recommended than the use of AALLct or the use of a equation estimating AALL.

References

1. Spee FG, Beidenbach MA, HotzM, Hitchcock HP. The gliding path of the mandible along the skull. J Am Dent Assoc 1980;100:670 - 5.

2. Hitchcock HP. The curve of Spee in Stone Age man. Am J Orthod 1983;84:248 - 53.

3. Marshall SD, Caspersen M, Hardinger RR, Franciscus RG, Aquilino SA, Southard TE. Development of the curve of Spee. Am J Orthod Dentofacial Orthop 2008;134:344 - 52.

4. Carter GA, McNamara JA Jr. Longitudinal dental arch changes in adults. Am J Orthod Dentofacial Orthop 1998;114:88 - 99.

5. Bishara SE, Jakobsen JR, Treder JE, StasiMJ. Changes in the maxillary and mandibular tooth size-arch length relationship from early adolescence to early adulthood. Am J Orthod Dentofacial Orthop 1989;95:46 - 59.

6. Burstone JC, Marcotte MR. Problem Solving in Orthodontics: Goal-Oriented Treatment Strategies. Chicago: Quintessence 2000. p. 181 - 3.

7. Andrews LF. The six keys to normal occlusion. Am J Orthod 1972;62:296 - 309.

8. AlQabandi AK, Sadowsky C, BeGole EA. A comparison of the effects of rectangular and round arch wires in leveling the curve of Spee. Am J Orthod Dentofacial Orthop 1999;116:522 - 9.

9. Germane N, Staggers JA, Rubenstein L, Revere JT. Arch length consideration due to the curve of Spee: a mathematical model. Am J Orthod Dentofacial Orthop 1992;102:251 - 5.

10. Proffit WR, Epker BN. Treatment planning for dentofacial deformities. In: Bell WH, Proffit WR, White RP, editors. Surgical Correction of Dentofacial Deformities. Philadelphia: WB Saunders 1980. p. 167.

11. Proffit WR, Ackerman J. Diagnosis and treatment planning in orthodontics. In: Graber M, editor. Orthodontics: Current Principals and Techniques. St Louis: CV Mosby 1986. p. 62 - 7.

12. Baldridge DW. Leveling the curve of Spee: its effect on the mandibular arch length. J Pract Orthod 1969;3:26 - 41.

13. Braun S, Hnat WP, Johnson BE. The curve of Spee revisited. Am J Orthod Dentofacial Orthop 1996;110:206 - 10.

14. Garcia R. Leveling the curve of Spee: a new prediction formula. J Charles H Tweed Int Found 1985;13:65 - 72.

15. Dahlberg G. Statistical methods for medical and biological students. London: George Allen & Unwin Ltd.; 1940. pp. 122-132.

16. Cheon SH, Park YH, Paik KS, Ahn SJ, Hayashi K, Yi WJ, et al. Relationship between the curve of Spee and dentofacial morphology evaluated with a 3-dimensional reconstruction method in Korean adults. Am J Orthod Dentofacial Orthop 2008;133:640.e7 - 14.

17. Frost HA. The biology of fracture healing. An overview for clinicians. Part 1. Clin Orthop Relat Res 1989;248:283 - 93.

18. Yaffe A, Fine N, Binderman I. Regional accelerated phenomenon in the mandible following mucoperiosteal flap surgery. J Periodontol 1994;65:79 - 83.

19. Woods NI. A reassessment of space requirements for lower archleveling. J Clin Orthod 1986;20:770 - 8.

Tables

Table 1. Definitions of the terms used in the present study.

Term	Definition of present study	Term (definition) used by Braun et al[13]
Occlusal plane	A plane passing through the distobuccal cusp tips of mandibular second molars and the midpoint between incisal edges of right and left mandibular central incisors (Fig. 1A)	Same as in the present study
Depth of COS	Average of the right and left greatest distances between occlusal plane and buccal cusp tip measured perpendicular to the occlusal plane	Sum of the right and left greatest distances between occlusal plane and buccal cusp tip measured perpendicular to the occlusal plane
3D tooth width	Distance between adjacent reference points such as cusp tips or proximal maximum convexities	Not used
2D tooth width	Distance measured on the projection of the 3D tooth width onto the occlusal plane	Not used
Individual tooth AALL	3D tooth width minus 2D tooth width	Not used
3D arch circumference	Sum of the 3D tooth widths	Total arch circumference (sum of the distances between cusp tips)
2D arch circumference	Sum of the 2D tooth widths	Planar projection of the total arch circumference
AALL	3D arch circumference minus 2D arch circumference	Arch circumference differential (total arch circumference minus planar projection of the total arch circumference)
AALLct	AALL measured from cusp tips	Same as above
AALLpmc	AALL measured from proximal maximum convexities	Not used

Table 2. Changes in arch circumferences and AALL according to increases in the COS depth using the cusp tips as reference points.

Model number	Average COS depth (mm)*	3D arch circumference (mm)	2D arch circumference (mm)	AALLct (mm)
1	0.0	108.5	108.5	0.0
2	0.4	108.4	108.3	0.1
3	0.9	108.1	108.0	0.2
4	1.4	107.9	107.6	0.3
5	1.7	107.7	107.3	0.4
6	1.9	107.6	107.1	0.4
7	2.1	107.1	106.6	0.5
8	2.7	106.7	106.0	0.8
9	2.8	106.7	105.8	0.9
10	3.3	106.3	105.1	1.2
11	3.4	106.1	104.8	1.2
12	3.6	105.7	104.3	1.4
13	3.9	105.5	104.0	1.5
14	4.2	105.4	103.7	1.8
15	4.6	104.9	102.8	2.1
16	4.7	104.7	102.5	2.3
Maximum difference	4.7	3.8	6.0	2.3

* Average of right- and left-side COS depths

** AALL : the amount of additional arch length required for leveling the COS

Table 3. Changes in arch circumferences and AALL according to increases in COS depth using the proximal maximum convexities as reference points.

Model number	Average COS depth (mm)*	3D arch circumference (mm)	2D arch circumference (mm)	AALLpmc (mm)
1	0.0	112.7	112.5	0.2
2	0.4	112.7	112.5	0.2
3	0.9	112.6	112.4	0.2
4	1.4	112.6	112.3	0.4
5	1.7	112.6	112.1	0.4
6	1.9	112.6	112.1	0.6
7	2.1	112.6	111.9	0.6
8	2.7	112.4	111.5	0.9
9	2.8	112.4	111.4	1.0
10	3.3	112.4	111.0	1.3
11	3.4	112.3	110.9	1.4
12	3.6	112.4	110.7	1.7
13	3.9	112.5	110.3	2.2
14	4.2	112.5	110.1	2.4
15	4.6	112.3	109.5	2.8
16	4.7	112.3	109.1	3.2
Maximum difference	4.7	0.4	3.4	3.0

* Average of right- and left-side COS depths

** AALL : the amount of additional arch length required for leveling the COS

Figures

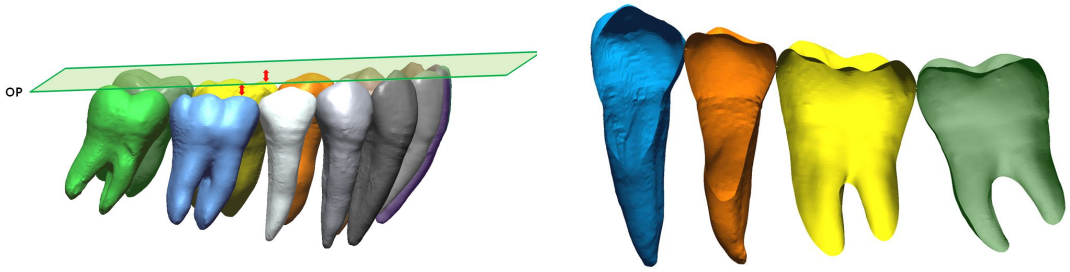

Figure 1. A, The occlusal plane was determined using the distobuccal cusp tips of the mandibular second molars and the midpoint between the incisal edges of the mandibular right and left central incisors. The depth of the COS (indicated by double-headed arrows) was determined by calculating the average of the right and left maximum distances between the deepest cusp tips and the occlusal plane; B, During each setup, even marginal ridge relationships were maintained to form curved-ribbon-shaped, continuous occlusal surfaces.

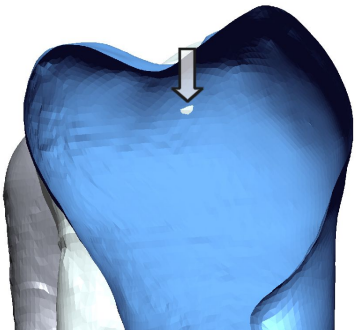

Figure 2A.

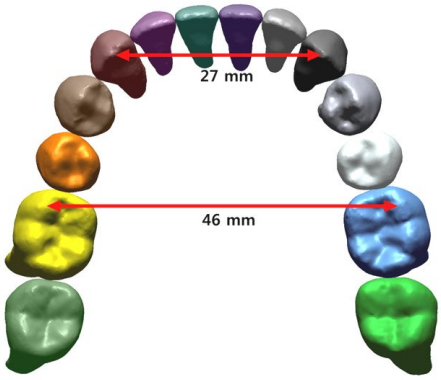

Figure 2B.

Figure 2. Using a clipping tool, the interproximal contact areas were visualized and adjusted to minimize overlapping of the interproximal surfaces of the adjacent teeth. A, The arrow indicates the point contact made between the lower right first and second molars; B, The intercanine and intermolar widths (indicated by double-headed arrows) were maintained constant (at 27 and 46 mm, respectively) in each setup.

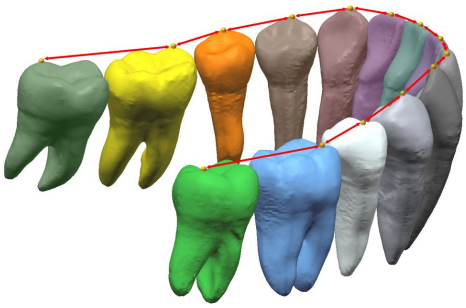

Figure 3A.

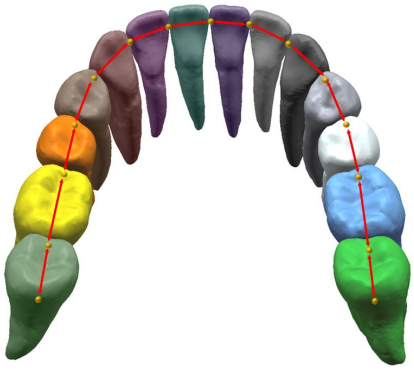

Figure 3B.

Figure 3. The 3D arch circumference is calculated as the sum of the 3D tooth widths, corresponding to the distances between adjacent reference points, shown as orange dots in A and B. A, 3D tooth widths measured using the cusp tip as a reference; B, 3D tooth widths measured using the proximal maximum convexity as a reference.

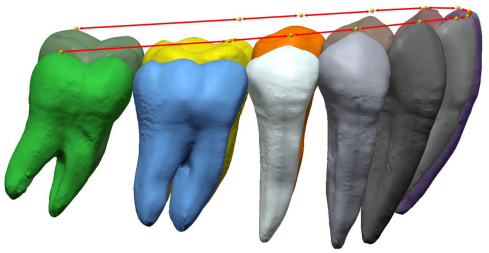

Figure 4A.

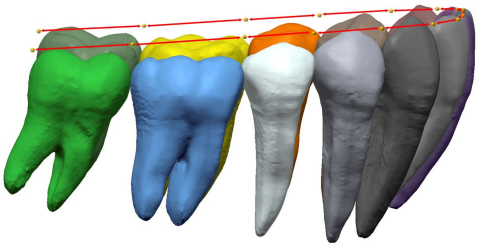

Figure 4B.

Figure 4. The 2D arch circumference is calculated as the sum of the 2D tooth widths, which are the projections of the 3D tooth widths onto the occlusal plane. A, 2D tooth widths measured using the cusp tip as a reference; B, 2D tooth widths measured using the proximal maximum convexity as a reference.

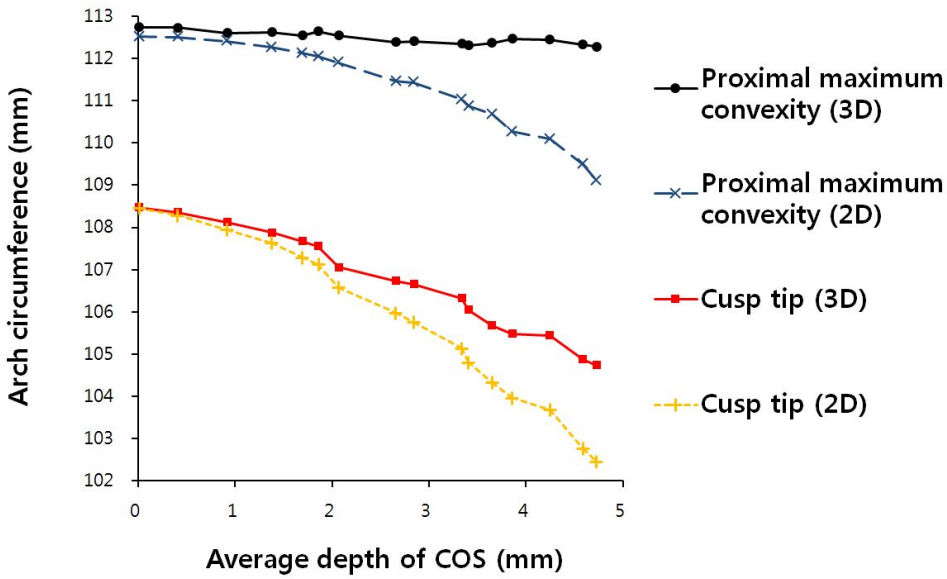

Figure 5. Changes in 3D and 2D arch circumferences according to the use of cusp tips and proximal maximum convexities as references. The 3D arch circumference decreased by 3.8 mm in the cusp-tip measurements and by 0.4 mm in the proximal convexity measurements as COS increased from 0 to 4.7 mm. The gap between the 3D arch circumference and the 2D arch circumference is the AALL. Data are mean and SD values.

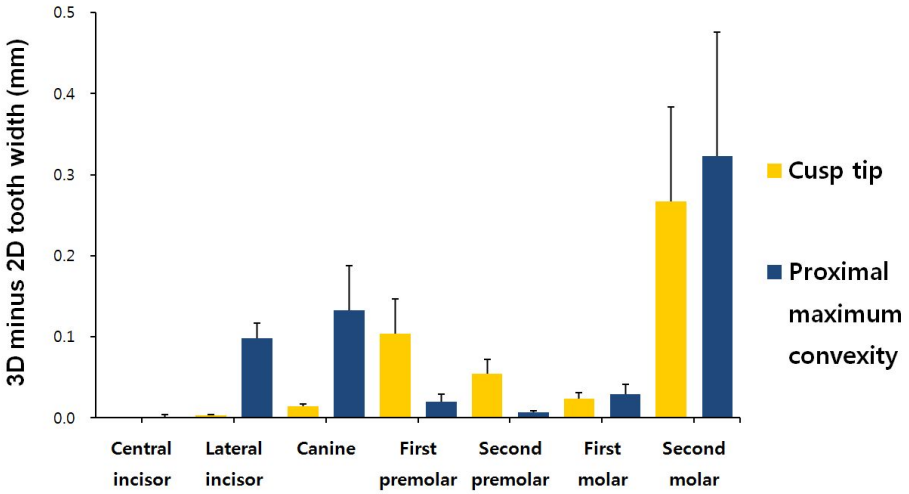

Figure 6. Measurements of 3D tooth width minus 2D tooth width for each tooth. In the cusp-tip measurements, the widths were measured between the cusp tips of the adjacent teeth, while in the proximal maximum-convexity measurements they were measured between the mesial and distal maximum convexities. Mean values of 16 setup models are shown.

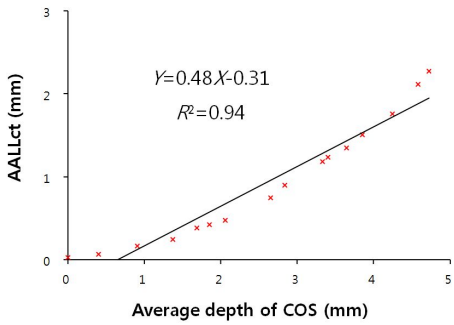

Figure 7A.

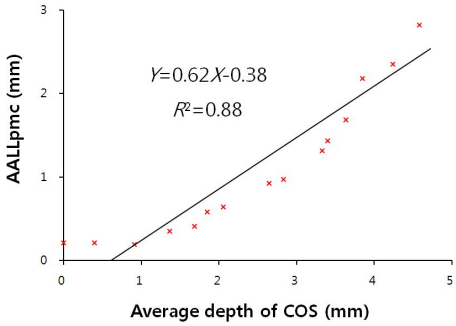

Figure 7B.

Figure 7. Scatter diagram of AALL versus COS depth. A, AALLct; B, AALLpmc.

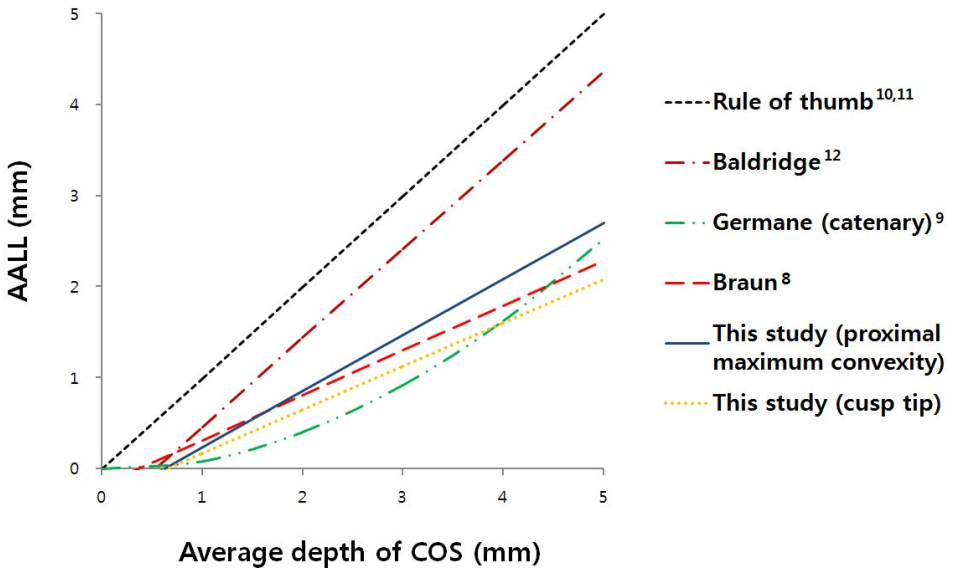

Figure 8. Comparison of estimations of AALL in various studies.