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A Radiographic Analysis of Variance in Lower Incisor Enamel Thickness

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A RADIOGRAPHIC ANALYSIS OF VARIANCE IN LOWER INCISOR ENAMEL

THICKNESS

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

by

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Abstract

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Major Director: Steven J. Lindauer, D.M.D., M.D.Sc.
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The purpose of this study was to help predict the enamel thickness of mandibular incisors. At least two direct digital periapical radiographs were made for each of the 80 subjects. Radiographs were scaled to control for magnification errors using dental study models and computer software. Mesiodistal incisor width and mesial and distal enamel thicknesses were measured. Lateral incisors were determined to be wider than central incisors and distal enamel thicknesses were larger than mesial enamel thicknesses on average. The African American group demonstrated wider incisors and enamel thicknesses than the Caucasian group on average. Enamel thickness positively correlated with tooth width for all incisors. No statistically significant differences were detected between male and female groups. Some conclusions relating to enamel thickness can be made based on race, incisor position, and incisor width, but correlations were not considered strong enough to accurately determine enamel width, without the aid of radiographs.

CHAPTER 1 Introduction

An ideal occlusion is dependent on several factors including arch shape, tooth position and tooth size. A proper proportion of total mesiodistal maxillary tooth width to total mesiodistal mandibular tooth width must be present when all of the teeth in the dentition are appropriately positioned and inclined. Often, orthodontic patients do not possess the correct proportion of maxillary tooth size to mandibular tooth size needed to attain an ideal occlusion. According to Bolton,[1,2] in an ideal occlusion, the sum of the mesiodistal widths of the mandibular incisors and canines should be 77.2 ± 1.65% of the sum of the mesiodistal widths of the maxillary incisors and canines. Deviation from this proportion is considered to be a tooth size discrepancy. The effects of deviation from this ideal proportion were reported as early as 1923 by Young.[3] Proffit[4] stated this type of discrepancy exists in approximately 5% of the general population. Others have claimed that between 22% and 30.6% of orthodontic patients possess a significant tooth size discrepancy.[5,6]

Scientists have investigated possible causes of tooth size discrepancies. The size and shape of teeth are closely correlated with craniofacial evolution. Anthropologists believe trends showing alterations of tooth size and form are due to a change in selection forces including modifications of the diet and lessened use of the teeth as tools.[7] Many possible etiologies for tooth size discrepancies have been proposed. According to Proffit,[4] tooth size discrepancies are most often due to an inadequate mesiodistal width of one or both of the maxillary lateral incisors. Restorations placed on the lateral surfaces of teeth can alter their mesiodistal width which could cause, or possibly improve, a tooth size discrepancy.

An asymmetry between contralateral teeth is often a sign of a possible tooth size discrepancy. Ballard[8] reported 90% of orthodontic patients possessed a mesiodistal crown discrepancy of at least 0.25 mm between at least one pair of contralateral teeth within an arch, while 80% showed at least one discrepancy of 0.5 mm or more. Potter[9] deduced that contralateral teeth are under identical genetic control with respect to their size and that there is no genetic basis for asymmetries between contralateral teeth. These asymmetries, therefore, are considered attributable to environmental disturbances during tooth development.

Crosby and Alexander[6] showed no difference in the incidence of tooth size discrepancies between treated orthodontic patients with Angle Class I, Class II, division 1, Class II, division 2 malocclusions or patients with Class II malocclusions treated by surgical means. In general, tooth size discrepancies may develop as a result of genetic, environmental, and/or iatrogenic factors.

Compensations need to be made when a tooth size discrepancy exists. Tuverson[10] asserted there are various ways to handle a tooth size discrepancy due to maxillary tooth size deficiency or mandibular tooth size excess. Possible treatments include leaving space in the maxillary arch, restoring maxillary teeth to increase mesiodistal width, extraction of the maxillary lateral incisors with positioning of the canines in the lateral spaces (canine substitution), increasing the lingual and distal axial inclination of the maxillary anterior teeth, extraction of a mandibular incisor, or mesiodistal crown reduction of the mandibular incisors. This reduction is often referred to as stripping, reproximation, or interproximal reduction (IPR).

IPR is the removal and reshaping of enamel from the contact point(s) of adjacent anterior teeth. The use of IPR was reported as early as 1954 by Lusterman[11] in the treatment of a patient with an Angle Class II, division 2 malocclusion with mandibular incisors that were "excessively wide" mesiodistally.

IPR has been advocated for purposes other than the alteration of a tooth size discrepancy. Peck and Peck[12] recommended the use if IPR as a means of altering the shape of lower incisors to enhance alignment stability. Aasen and Espeland[13] suggested that over-correction of rotated incisors early in treatment and systematic IPR during and after orthodontic treatment may increase lower incisor stability. Chenin et al[14] stated that when using a series of removable appliances, like with the Invisalign® system, crowding can be resolved primarily with IPR or lower incisor extraction to avoid excessive advancement of the incisors.

A practitioner planning to perform IPR as part of treatment needs to know how much enamel is safe to remove with minimal or no negative side effects. Hudson[15] estimated that up to half of the enamel thickness could be safely removed. This 50% estimate is cited repeatedly in the dental literature. It has been reported by multiple authors[5,6,10,16-20] that up to 50% of the enamel thickness from any one interproximal area of a tooth has been safely removed with no signs of problematic sequella.

It is important to know the total thickness of enamel present on a tooth's surface before deciding how much enamel can be removed safely. Overall tooth thicknesses have been measured by geneticists, anthropologists, and dentists.[9,21,22] Studies have evaluated enamel thicknesses in sectioned teeth, but only averages within various groups were reported.[23-26] Moss and Moss-Salentijn[27] examined enamel thickness differences between genders while Stroud et al[28] reported differences based on ethnic origin. Harris and Hicks[29] measured mesial and distal enamel thicknesses of maxillary incisors and compared thicknesses of enamel between sexes. No studies examined the relationship between overall mesiodistal tooth thickness and enamel thickness on an individual-tooth basis.

The purpose of this study was to gather information that could be used to help predict more accurately the enamel thickness of mandibular incisors. Specifically, enamel thicknesses were compared between mandibular lateral and central incisors, between males and females, and between African American and Caucasian groups. The relationship between tooth width and enamel thickness was also determined. The goal was to aid practitioners considering IPR as a mechanism to reduce mandibular incisor tooth mass to reduce crowding or to resolve anterior tooth size discrepancies.

The null hypotheses were:

- There are no differences in enamel thickness between mandibular central and lateral incisors or between mesial and distal tooth surfaces within individuals.

- There are no differences in lower incisor enamel thickness at the interproximal contact points between sexes or between African Americans and Caucasians.
- There is no relationship between mesiodistal tooth width and enamel thickness of mandibular incisors.

CHAPTER 2 Materials and Methods

Approval to conduct this study was obtained from the Institutional Review Board at Virginia Commonwealth University.

This prospective study included 80 people recruited at Virginia Commonwealth University School of Dentistry with no history of IPR who agreed to participate. Only individuals with well-aligned incisors and no history of previous IPR were eligible to participate. Aligned incisors were required so that radiographs of mandibular incisors could be obtained showing no overlap of adjacent teeth. Well-aligned incisors with spacing present were acceptable. 40 African-American and 40 Caucasian subjects agreed to participate. There were 20 males and 20 females of each race.

Individuals who had mandibular incisors with interproximal restorations or noticeable signs of wear were excluded. Females who were pregnant or believed they might possibly be pregnant were also excluded. People were excluded if they were of Asian, Hispanic, or Native Indian origin due to the small number of these subjects available. Those individuals who had special needs, were cognitively impaired, or were not in good general health were excluded.

A dental stone study model of the mandibular arch was made from an alginate impression for every subject. At least two digital periapical radiographs for each subject were made. One periapical was of the right mandibular incisors and one was of the left mandibular incisors. Occasionally, additional periapical radiographs were made if any of the enamel surfaces to be evaluated were not clearly visible due to overlap. The same individual made all of the radiographs to ensure radiographic quality and paralleling techniques were consistent for all subjects.

Dental cast measurements of mesiodistal tooth thickness were made using a sharpened digital Boley gauge that allowed for measurements to 0.001 mm. When measuring casts and radiographs, the examiner was blinded to the group to which the records belonged. Dental cast measurements were matched to the corresponding periapical radiographs and assigned a random number. The width of each mandibular incisor was measured from the mesial contact point to the distal contact point.

Measurements from the radiographs were made using Design CAD Pro 3000 software (Upperspace Corp., Pryor, OK) that allowed for measurements to 0.001 mm. Each radiograph, once loaded in the program, was enlarged to fill a flat-screen 19-inch Dell computer monitor (UltraSharp, Dell Computer Corp., Austin, TX). The mesiodistal width of each incisor on the screen was then calibrated to the corresponding mesiodistal measurement made from the dental casts to correct for radiographic magnification. Once calibrated, measurements of the thicknesses of the mesial and distal enamel layers were made. Enamel thickness measurements were made from the mesial and distal contact points on the shortest line possible to the dentinoenamel junction (DEJ) (Fig. 1). When periapical radiographs were enlarged to fill the screen of the computer monitor, the DEJ appeared as a zone rather than a distinct line. Measurements were made to the area of this zone closest to the enamel surface in order to produce a measurement representing the thinnest layer of enamel between the contact area and the dentin.

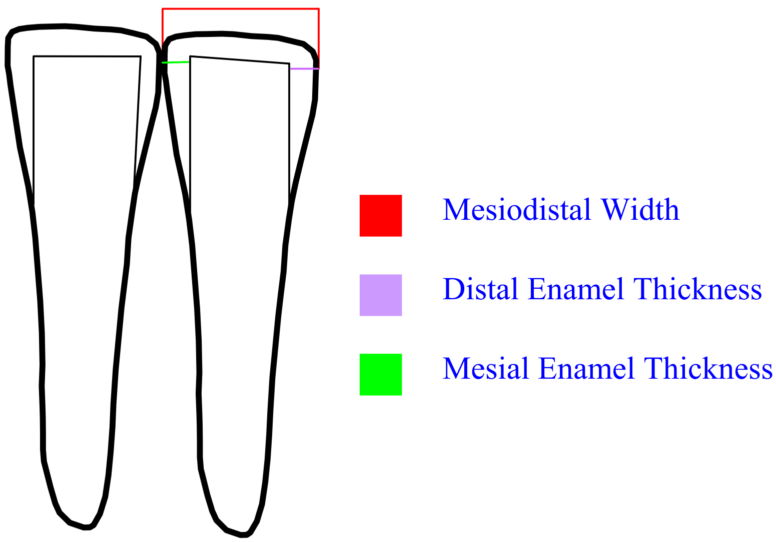

Figure 1. Schematic representation of measurements made from the mandibular left central incisor.

Paired t-tests were used to determine differences in tooth width and mesial and distal enamel thicknesses between right and left incisors and between central and lateral incisors. 2-way MANOVA was used to detect differences in tooth width and mesial and distal enamel thicknesses between males and females and between African American and Caucasian subjects. Correlation analysis was used to determine significant relationships between tooth width and mesial and distal enamel thicknesses. The level of significance for all tests was set at $P \leq .05$.

CHAPTER 3 Results

No statistically significant differences were detected between the repeated sets of measurements for 10 subjects made at separate time points. The correlation between the sets was high for tooth thickness ($r = .99$), mesial enamel thickness ($r = .95$), and distal enamel thickness ($r = .98$). Average differences between repeated measures were less than 0.01 mm.

Table I shows the average values for tooth width and enamel thickness for all subjects. No significant differences were detected between the right and left central incisor widths ($P = .63$) or between the right and left lateral incisor widths ($P = .46$). There were also no statistically significant differences between the enamel thicknesses of contralateral teeth except for the mesial enamel thickness between the right and left lateral incisors. The average mesial enamel thickness for the right lateral incisors was 0.79 ± 0.11 mm while the average mesial enamel thickness of the left lateral incisors was 0.81 ± 0.11 mm. This 0.02 mm average difference was found to be statistically significant ($P = .01$).

On average, lateral incisors were found to be significantly wider than central incisors by 0.52 mm ± 0.27 ($P < .0001$). The distal enamel thickness was significantly thicker than the mesial enamel thickness for central and lateral incisors ($P < .0001$ for each group). Each of the mesial and distal enamel surfaces were found to be significantly thicker in the lateral incisors when compared to the corresponding surfaces in the central incisors ($P < .0001$). When all of the incisors were compared, the distal enamel was 0.10 ± 0.09 mm thicker than the mesial enamel on average ($P < .0001$).

Table I. Average values for tooth width and enamel thickness for all subjects

Tooth	Width*	Mesial enamel thickness†	Distal enamel thickness‡
Right central incisor	5.45 ± 0.36 mm	0.72 ± 0.10 mm	0.77 ± 0.11 mm§
Left central incisor	5.45 ± 0.36 mm	0.71 ± 0.10 mm	0.77 ± 0.11 mm§
Right lateral incisor	5.96 ± 0.42 mm	0.79 ± 0.11 mm	0.95 ± 0.13 mm§
Left lateral incisor	5.98 ± 0.43 mm	0.81 ± 0.11 mm‖	0.96 ± 0.14 mm§

* Lateral incisors wider than central incisors ($P < .0001$)
† Lateral incisor mesial enamel thicker than central incisor mesial enamel ($P < .0001$)
‡ Lateral incisor distal enamel thicker than central incisor distal enamel ($P < .0001$)
§ Incisor distal enamel thicker than mesial enamel ($P < .0001$)
‖ Left lateral mesial enamel thicker than right lateral mesial enamel ($P = .01$)

Table II shows the tooth widths and enamel thicknesses for males and females. No significant differences were detected between males and females when evaluating tooth widths, mesial enamel thicknesses, or distal enamel thicknesses.

Table II. Average values for tooth width and enamel thickness for males and females (no statistically significant differences)

Tooth/surface		Males	Females	Range
Right central:	Width	5.46 ± 0.34 mm	5.43 ± 0.39 mm	4.54 - 6.19 mm
	Mesial enamel	0.73 ± 0.09 mm	0.70 ± 0.11 mm	0.46 - 0.94 mm
	Distal enamel	0.78 ± 0.10 mm	0.76 ± 0.12 mm	0.46 - 0.99 mm
Left central:	Width	5.45 ± 0.40 mm	5.46 ± 0.32 mm	4.44 - 6.16 mm
	Mesial enamel	0.72 ± 0.09 mm	0.71 ± 0.11 mm	0.44 - 0.91 mm
	Distal enamel	0.78 ± 0.10 mm	0.76 ± 0.13 mm	0.45 - 1.11 mm
Right lateral:	Width	5.96 ± 0.43 mm	5.97 ± 0.42 mm	4.89 - 6.93 mm
	Mesial enamel	0.80 ± 0.10 mm	0.78 ± 0.12 mm	0.47 - 1.07 mm
	Distal enamel	0.95 ± 0.12 mm	0.94 ± 0.15 mm	0.62 - 1.25 mm
Left lateral:	Width	5.95 ± 0.42 mm	6.00 ± 0.45 mm	5.09 - 6.89 mm
	Mesial enamel	0.82 ± 0.11 mm	0.81 ± 0.12 mm	0.50 - 1.11 mm
	Distal enamel	0.96 ± 0.13 mm	0.96 ± 0.16 mm	0.65 - 1.28 mm

Table III shows the tooth widths and enamel thicknesses for African American and Caucasian subjects. The African American group had significantly wider central and lateral incisors ($P < .0005$), and all enamel surfaces for this group were found to be significantly thicker ($P < .0001$) than the corresponding widths and thicknesses in the Caucasian group.

Table III. Average values for tooth width and enamel thickness for African American and Caucasian subjects

Tooth/surface		African American	Caucasian	P
Right central:	Width	5.55 ± 0.39 mm	5.34 ± 0.30 mm	P = 0.008
	Mesial enamel	0.76 ± 0.08 mm	0.67 ± 0.09 mm	P < 0.0001
	Distal enamel	0.83 ± 0.09 mm	0.71 ± 0.09 mm	P < 0.0001
Left central:	Width	5.58 ± 0.35 mm	5.33 ± 0.33 mm	P = 0.002
	Mesial enamel	0.84 ± 0.09 mm	0.70 ± 0.09 mm	P < 0.0001
	Distal enamel	0.77 ± 0.08 mm	0.66 ± 0.09 mm	P < 0.0001
Right lateral:	Width	6.07 ± 0.44 mm	5.85 ± 0.38 mm	P = 0.023
	Mesial enamel	0.85 ± 0.09 mm	0.74 ± 0.09 mm	P < 0.0001
	Distal enamel	1.03 ± 0.11 mm	0.87 ± 0.11 mm	P < 0.0001
Left lateral:	Width	6.08 ± 0.44 mm	5.87 ± 0.41 mm	P = 0.025
	Mesial enamel	0.87 ± 0.10 mm	0.76 ± 0.11 mm	P < 0.0001
	Distal enamel	1.04 ± 0.12 mm	0.88 ± 0.12 mm	P < 0.0001

Table IV shows the correlation between tooth width and enamel thickness for African American and Caucasian subjects. Enamel thickness was found to be related to tooth width for all incisors ($P < .01$). The mesial enamel of the right lateral incisors in the African American group was the only surface that showed no significant relationship to tooth width ($P = .11$).

Table IV. Relationship between tooth width and enamel thickness

Tooth/surface		African American	Caucasian	All Subjects
Right central:	Mesial	r = .57*	r = .56*	r = .61*
	Distal	r = .46*	r = .55*	r = .56*
Left central:	Mesial	r = .55*	r = .60*	r = .63*
	Distal	r = .41*	r = .62*	r = .59*
Right lateral:	Mesial	r = .25	r = .52*	r = .45*
	Distal	r = .57*	r = .63*	r = .62*
Left lateral:	Mesial	r = .39*	r = .57*	r = .53*
	Distal	r = .62*	r = .66*	r = .65*

* Tooth width significantly correlated to enamel thickness ($P \leq .01$)

CHAPTER 4 Discussion

IPR is a mechanism used by many practitioners as a way to reduce incisor crowding, resolve anterior tooth size discrepancies, or possibly improve stability.[30] The thickness of enamel of an incisor at the contact area is believed to be related to the amount of enamel that can be safely removed without deleterious sequella. The aim of this study was to determine the amount of enamel present at the contact points on the proximal surfaces of mandibular incisors.

Results from a recent study brought into question the ability for dentists to determine enamel thickness of teeth from radiographs. Grine et al[31] measured the enamel thickness of posterior teeth from periapical radiographs and compared them to measurements of the same teeth once they were sectioned. A general overestimation of measurements made from the radiographs and a large variability in error was detected. They stated that enamel thickness studies that employ radiographs need to be viewed with circumspection.

Mandibular incisors have a thinner labiogingival thickness than posterior teeth, and the dentinoenamel junction of incisors may be easier to correctly identify due to the decreased superimposition of tooth material seen with these thinner teeth. In the current study, magnification error was controlled by calibrating the dental casts and radiographs using tooth width measurements from study casts.

There were no differences detected when the right and left incisor widths and enamel thicknesses were compared with the exception of the mesial enamel surface of the left lateral incisor. The mesial enamel of the left lateral incisor was found to be 0.02 mm thicker than the right lateral mesial enamel. This small difference was found to be statistically significant but is probably not clinically important. Ballard[8] found that 90% of people have at least one set of contralateral teeth with a width discrepancy of at least 0.25 mm. Lateral incisors were about 0.5 mm thicker than central incisors on average, and this difference was statistically significant ($P < .0001$). Lateral incisors also had thicker enamel thicknesses than the central incisors on average. The distal enamel surfaces of the central incisors were about 0.05 mm thicker than the mesial enamel surfaces on average ($P < .0001$), and the distal enamel surfaces of the lateral incisors were about 0.15 mm thicker than the mesial enamel surfaces of the same teeth ($P < .0001$). Though the difference between mesial and distal enamel thickness was small for the central incisors, the difference for the lateral incisors may be large enough to affect the planned amount of enamel reduction.

No statistically significant differences were detected between the incisors of males and females. Stroud et al[32] examined the width and enamel thickness of posterior teeth and also found no differences in enamel thickness between sexes. They did, however, find that the overall width of the posterior teeth was greater in males than in females. They stated that differences in these tooth widths were attributable to wider dentin components. The findings from the current study suggest there is no reason to expect the lower incisor enamel thicknesses in males to be different than the enamel thicknesses in females.

The central incisors in the African American group were about 0.23 mm wider than in the Caucasian group, and the lateral incisors in the African American group were about 0.21 mm wider than in the Caucasian group on average. The mesial enamel thicknesses of the incisors in the African American group were about 0.10 mm thicker than in the Caucasian group, and the distal enamel thicknesses of the incisors in the African American group were about 0.15 mm thicker than in the Caucasian group. Individual measurements and P-values are shown in Table III. This suggests a practitioner may be able to consider slightly more enamel reduction in African American as compared to Caucasian patients.

A correlation was found between tooth width and enamel thickness. Wider incisors generally had thicker enamel surfaces than narrower incisors.

Care needs to be taken when determining how much enamel is available when planning treatment including IPR. All of the groups showed large ranges in enamel thickness. Enamel thicknesses ranged between 0.44 mm and 1.12 mm for the Caucasian group and between 0.58 mm and 1.28 mm for the African American group in this population. Some subjects had more than twice the thickness of enamel for any of the enamel surfaces than other subjects within the same group. Many individuals showed variation of over 0.33 mm in enamel thickness between proximal surfaces in their mandibular incisors. This wide variation in enamel thicknesses among individuals and within individuals demands careful treatment planning with respect to the use of IPR. Some conclusions regarding enamel thickness can be drawn related to differences based on race and tooth width, but correlations were not strong enough to plan IPR without the aid of radiographs. Adjustments for magnification need to be made when measuring the enamel thickness from a radiograph. The calibration of measurements made from periapical radiographs through the use of dental casts measurements, possibly in conjunction with readily available computer software, provide a simple method for reducing the magnification error associated with measurements made directly from periapical radiographs. Accurately determining the amount of enamel present at the proximal contact points of incisors allows a practitioner to use IPR to its greatest potential while minimizing the chance of deleterious side effects.

CHAPTER 5 Conclusion

This study examined the relationship between mandibular incisor proximal enamel thickness and tooth position, race, gender, and overall tooth width. Significant differences were found related to tooth surface, race, and incisor type. Lateral incisors generally had greater proximal enamel thicknesses than central incisors. The distal enamel thickness of an individual mandibular incisor was generally thicker than its mesial enamel thickness. African Americans generally had thicker enamel than Caucasians. Overall tooth width was positively correlated with mesial and distal enamel thickness. No statistically significant differences were detected, however, between males and females. A method for determining enamel thickness of incisors using dental cast measurements to calibrate measurements made from radiographs was presented. This information may be useful to practitioners planning to use IPR as part of dental treatment.

Literature Cited

Literature Cited

1. Bolton WA. The clinical application of a tooth-size analysis. Am J Orthod 1962;48:504-29.
2. Bolton WA. Disharmony in tooth size and its relation to the analysis and treatment of malocclusion. Angle Orthod 1958;28:113-30.
3. Young JL. Rational treatment of infraclusion. Internat J Orthod 1923;9:886-909.
4. Proffit WR, Fields HW. Contemporary Orthodontics. St. Louis: Mosby; 2000. p. 170.
5. Freeman JE, Maskeroni AJ, Lorton L. Frequency of Bolton tooth-size discrepancies among orthodontic patients. Am J Orthod Dentofacial Orthop 1996;110:24-7.
6. Crosby DR, Alexander CG. The occurrence of tooth size discrepancies among different malocclusion groups. Am J Orthod Dentofacial Orthop 1996;95:457-61.
7. Dahlberg AA. Dental evolution and culture. Hum Bio 1963;35:237.

8. Ballard ML. Asymmetry in tooth size: a factor in the etiology, diagnosis and treatment of malocclusion. Angle Orthod 1944;14:67-71.
9. Potter RH. The genetics of tooth size. In: GH Prescott, RE Steward, editors. Oral Facial Genetics. St. Louis: Mosby; 1976. p. 105-23.
10. Tuverson DL. Anterior interocclusion relations. Part I. Am J Orthod 1980;78:360-70.
11. Lusterman EA. Treatment of a class II, division 2 malocclusion involving mesiodistal reduction of mandibular anterior teeth. Am J Orthod 1954;40:44-50.
12. Peck H, Peck S. An index for assessing tooth shape deviations as applied to the mandibular incisors. Am J Orthod 1972;61:384-401.
13. Aasen TO, Espeland L. An approach to maintain orthodontic alignment of lower incisors without the use of retainers. Eur J Orthod 2005;27:209-14.
14. Chenin DA, Trosien AH, Fong PF, Miller RA, Lee RS. Orthodontic treatment with a series of removable appliances. J Am Dent Assoc 2003;134:1233-40.
15. Hudson AL. A study of the effects of mesiodistal reduction of mandibular anterior teeth. Am J Orthod 1956;42:615-24.
16. Betteridge MA. The effects of interdental stripping on the labial segments evaluated one year out of retention. Br J Orthod 1981;8:193-7.
17. Tuverson DL. Anterior interocclusion relations. Part II. Am J Orthod 1980;78:371-93.

18. Boese LR. Fiberotomy and reproximation without lower retention, nine years in retrospect: Part I. Angle Orthod 1980;50:88-97.

19. Sheridan JJ. Air-rotor stripping. J Clin Orthod 1985;19:43-59.

20. El-Mangoury NH, Moussa MM, Mostafa YA, Girgis AS. In-vitro remineralization after air-rotor stripping. J Clin Orthod 1991;25:74-8.

21. Mayhall J, Kanazawa E. Three-dimensional analysis of the maxillary first molar crowns of Canadian Inuit. Am J Phys Anthrop 1977;78:73-8.

22. Kieser JA. Human adult odontometrics: the study of variation in adult tooth size. Cambridge: Cambridge Univ Press; 1990.

23. Gillings BR, Bunocore M. An investigation of enamel thickness in human lower incisor teeth. J Dent Res 1961;40:105-18.

24. Gillings BR. and Bunocore M. Thickness of enamel at the base of pits and fissures in human molars and bicuspids. J Dent Res 1961;40:119-33.

25. Shillingsburg Jr HT,Grace CS. Thickness of enamel and dentine. J So Calif Dental Assoc 1973;41:33-52.

26. Fejerskov OO, Melsen B, Karring, T. Morphometric analysis of occlusal fissures in human premolars. Scand J Dent Res 1973;81:505-10.

27. Moss ML, Moss-Salentijn L. Analysis of developmental processes possibly related to human dental sexual dimorphism in permanent deciduous canines. Am J Phys Anthrop 1977;46:407-14.

28. Stroud JL, Buschang PH, Goaz PW. Sexual dimorphism in mesiodistal dentine and enamel thickness. Dentomaxillofac Radiol 1994;23:169-71.

29. Harris EF, Hicks JD. A radiographic assessment of enamel thickness in human maxillary incisors. Archives of Oral Biology 1989;43:825-31.

30. Peck S, Peck H. Crown dimensions and mandibular incisor alignment. Am J Orthod Dentofacial Orthop 1972;42:148-53.

31. Grine FE, Stevens NJ, Jungers WL. An evaluation of dental radiograph accuracy in the measurement of enamel thickness. Archives of Oral Biology 2001.

32. Stroud JL, English J, Buschang PH. Enamel thickness of the posterior dentition: its implications for nonextraction treatment. Angle Orthod 1998;68:141-6.

APPENDIX A

Raw Data

Patient #	Age (months)	Gender	Race	Tooth	Mesial enamel thickness	Distal enamel thickness	Cast width
CM 1	151	M	C	RL	0.829	0.981	5.86
				RC	0.542	0.602	5.08
				LC	0.522	0.587	5.01
				LL	0.847	0.924	6.02
CM 2	195	M	C	RL	0.638	0.676	5.93
				RC	0.618	0.719	5.56
				LC	0.61	0.722	5.54
				LL	0.621	0.738	5.75
CM 3	189	M	C	RL	0.767	0.909	5.45
				RC	0.626	0.757	5.23
				LC	0.601	0.761	5.25
				LL	0.689	0.861	5.51
CM 4	180	M	C	RL	0.879	0.995	6.12
				RC	0.674	0.738	5.45
				LC	0.702	0.733	5.56
				LL	0.894	1	5.92
CM 5	162	M	C	RL	0.621	0.772	5.44
				RC	0.638	0.588	5.24
				LC	0.538	0.524	5.24
				LL	0.525	0.751	5.33
CM 6	177	M	C	RL	0.611	0.909	5.6
				RC	0.602	0.714	5.23
				LC	0.6	0.702	5.23
				LL	0.605	0.749	5.6
CM 7	186	M	C	RL	0.841	0.916	5.91
				RC	0.737	0.804	5.19
				LC	0.764	0.814	5.48
				LL	0.846	0.91	5.71

CM 8	212	M	C	RL	0.782	0.817	5.88
				RC	0.676	0.7	5.29
				LC	0.676	0.696	5.3
				LL	0.78	0.783	5.91
CM 9	198	M	C	RL	0.668	0.891	6.07
				RC	0.67	0.676	5.74
				LC	0.691	0.67	5.73
				LL	0.714	0.869	6.09
CM 10	188	M	C	RL	0.741	0.988	6.27
				RC	0.695	0.741	5.62
				LC	0.612	0.658	5.58
				LL	0.875	1.052	6.25
CM 11	684	M	C	RL	0.836	0.927	5.99
				RC	0.815	0.844	5.41
				LC	0.798	0.822	5.17
				LL	1.13	0.931	6.07
CM 12	348	M	C	RL	0.902	0.912	6.22
				RC	0.859	0.861	5.62
				LC	0.808	0.821	5.6
				LL	0.909	0.901	6.2
CM 13	119	M	C	RL	0.809	0.911	5.42
				RC	0.753	0.786	5.11
				LC	0.743	0.771	4.89
				LL	0.811	0.926	5.24
CM 14	364	M	C	RL	0.87	0.96	6.11
				RC	0.75	0.792	5.3
				LC	0.708	0.738	5.71
				LL	0.858	0.974	6.05
CM 15	370	M	C	RL	0.665	0.693	5.36
				RC	0.564	0.577	5.16
				LC	0.562	0.571	5.08
				LL	0.655	0.707	5.24
CM16	339	M	C	RL	0.779	0.857	5.86
				RC	0.662	0.727	5.5
				LC	0.668	0.792	5.54
				LL	0.822	0.908	5.96
CM 17	199	M	C	RL	0.716	0.964	6.14
				RC	0.779	0.788	5.4
				LC	0.761	0.783	5.41
				LL	0.91	0.99	6.22
CM 18	351	M	C	RL	0.835	0.876	6.4
				RC	0.738	0.765	5.7
				LC	0.696	0.78	5.66
				LL	0.806	0.917	6.43
CM 19	345	M	C	RL	0.707	0.901	5.67
				RC	0.688	0.766	5.3
				LC	0.684	0.726	4.97

				LL	0.701	0.899	5.63
CM 20	170	M	C	RL	0.743	0.935	6.55
				RC	0.711	0.768	5.43
				LC	0.715	0.77	5.45
				LL	0.965	0.946	6.65
CF 1	163	F	C	RL	0.85	0.962	6.07
				RC	0.699	0.739	5.58
				LC	0.681	0.696	5.6
				LL	0.829	0.888	5.87
CF 2	198	F	C	RL	0.634	0.739	5.27
				RC	0.507	0.571	4.9
				LC	0.502	0.575	4.84
				LL	0.711	0.855	5.39
CF 3	157	F	C	RL	0.465	0.624	5.17
				RC	0.46	0.461	4.65
				LC	0.44	0.451	4.44
				LL	0.499	0.649	5.6
CF 4	176	F	C	RL	0.807	0.891	5.6
				RC	0.686	0.696	5.36
				LC	0.687	0.702	5.37
				LL	0.863	0.98	5.81
CF 5	162	F	C	RL	0.58	0.68	5.26
				RC	0.507	0.543	4.69
				LC	0.551	0.547	4.76
				LL	0.576	0.677	5.22
CF 6	206	F	C	RL	0.706	1.097	6.39
				RC	0.651	0.771	5.1
				LC	0.743	0.779	5.36
				LL	0.759	1.032	6.32
CF 7	182	F	C	RL	0.757	0.981	6.34
				RC	0.686	0.691	5.77
				LC	0.846	0.862	6.07
				LL	0.787	1.085	6.38
CF 8	167	F	C	RL	0.692	0.773	6.01
				RC	0.599	0.612	5.6
				LC	0.602	0.66	5.65
				LL	0.689	0.774	6.12
CF 9	170	F	C	RL	0.703	0.872	6.03
				RC	0.706	0.77	5.88
				LC	0.714	0.772	5.83
				LL	0.771	0.831	6.08
CF 10	208	F	C	RL	0.744	0.971	6.19
				RC	0.608	0.626	5.41
				LC	0.619	0.659	5.63
				LL	0.755	0.975	6.2
CF 11	299	F	C	RL	0.742	0.869	6.12
				RC	0.687	0.739	5.62

				LC	0.691	0.815	5.73
				LL	0.759	0.906	6.22
CF 12	217	F	C	RL	0.706	0.761	5.9
				RC	0.6	0.618	5.19
				LC	0.619	0.622	5.23
				LL	0.711	0.77	5.9
CF 13	298	F	C	RL	0.721	0.783	5.8
				RC	0.706	0.712	5.11
				LC	0.706	0.764	5.12
				LL	0.791	0.988	6.04
CF 14	316	F	C	RL	0.84	0.991	5.64
				RC	0.575	0.748	4.97
				LC	0.665	0.747	5.13
				LL	0.803	0.83	5.54
CF 15	416	F	C	RL	0.716	0.797	5.95
				RC	0.659	0.687	5.41
				LC	0.655	0.691	5.37
				LL	0.732	0.777	5.85
CF 16	198	F	C	RL	0.636	0.732	5.54
				RC	0.611	0.652	5.24
				LC	0.6	0.642	5.18
				LL	0.642	0.742	5.53
CF 17	188	F	C	RL	0.69	0.733	5.34
				RC	0.625	0.65	5.29
				LC	0.62	0.643	5.19
				LL	0.699	0.735	5.38
CF 18	184	F	C	RL	0.801	0.989	6.54
				RC	0.786	0.804	5.82
				LC	0.782	0.809	5.7
				LL	0.821	1.12	6.8
CF 19	169	F	C	RL	0.648	0.864	5.23
				RC	0.624	0.648	4.78
				LC	0.611	0.63	4.76
				LL	0.664	0.781	5.09
CF 20	201	F	C	RL	0.759	0.842	5.5
				RC	0.715	0.752	5.26
				LC	0.695	0.629	5.34
				LL	0.912	1.02	5.58
AAM 1	140	M	AA	RL	0.704	0.858	5.32
				RC	0.599	0.799	4.92
				LC	0.603	0.812	4.95
				LL	0.742	0.903	5.66
AAM 2	185	M	AA	RL	0.736	0.796	4.89
				RC	0.577	0.612	4.54
				LC	0.611	0.721	4.98
				LL	0.744	0.845	5.14
AAM 3	158	M	AA	RL	0.869	1.008	5.68

				RC	0.799	0.843	5.28
				LC	0.803	0.798	5.3
				LL	0.938	1.125	5.71
AAM 4	159	M	AA	RL	0.794	1.098	6.11
				RC	0.718	0.791	5.67
				LC	0.747	0.855	5.8
				LL	0.801	1.186	6.26
AAM 5	161	M	AA	RL	0.841	0.972	5.64
				RC	0.815	0.908	5.15
				LC	0.828	0.924	5.3
				LL	0.824	0.992	5.83
AAM 6	225	M	AA	RL	0.901	1.053	6.51
				RC	0.727	0.814	5.83
				LC	0.745	0.812	5.81
				LL	0.894	0.989	6.33
AAM 7	470	M	AA	RL	0.888	1.01	6.03
				RC	0.778	0.84	5.8
				LC	0.788	0.82	5.85
				LL	0.909	1.119	6.37
AAM 8	189	M	AA	RL	0.876	1.008	6.2
				RC	0.79	0.88	6.12
				LC	0.79	0.904	6.16
				LL	0.892	1.072	6.39
AAM 9	182	M	AA	RL	0.896	0.963	5.71
				RC	0.764	0.897	5.11
				LC	0.764	0.854	5.11
				LL	0.854	1	5.67
AAM 10	230	M	AA	RL	0.823	1.254	6.14
				RC	0.724	0.779	5.73
				LC	0.722	0.781	5.74
				LL	0.833	1.25	6.25
AAM 11	176	M	AA	RL	0.838	1.139	6.77
				RC	0.812	0.907	5.71
				LC	0.851	0.912	5.78
				LL	0.902	1.152	6.81
AAM 12	137	M	AA	RL	0.907	0.965	5.85
				RC	0.78	0.883	5.63
				LC	0.772	0.882	5.62
				LL	0.903	0.963	5.87
AAM 13	146	M	AA	RL	0.881	1.081	6.47
				RC	0.84	0.899	5.84
				LC	0.846	0.901	5.87
				LL	0.884	0.896	5.76
AAM 14	294	M	AA	RL	0.875	1.029	6.2
				RC	0.825	0.875	6.19
				LC	0.815	0.821	5.84
				LL	0.904	0.98	6.11

AAM 15	157	M	AA	RL	0.933	0.981	5.34
				RC	0.743	0.936	5.23
				LC	0.755	0.933	5.24
				LL	0.939	0.985	5.35
AAM 16	202	M	AA	RL	0.855	1.224	6.27
				RC	0.821	0.95	5.8
				LC	0.829	0.952	5.83
				LL	0.851	1.13	6.13
AAM 17	167	M	AA	RL	0.679	0.963	6.39
				RC	0.671	0.737	5.79
				LC	0.698	0.731	5.76
				LL	0.671	0.958	6.32
AAM 18	181	M	AA	RL	1.073	1.113	6.41
				RC	0.819	0.907	5.67
				LC	0.817	0.899	5.57
				LL	1.1	1.191	6.77
AAM 19	119	M	AA	RL	0.663	0.888	6.02
				RC	0.635	0.636	5.54
				LC	0.638	0.641	5.64
				LL	0.685	0.901	6.22
AAM 20	129	M	AA	RL	0.8	0.943	5.47
				RC	0.727	0.755	4.99
				LC	0.722	0.735	4.95
				LL	0.811	0.947	5.41
AAF 1	665	F	AA	RL	0.683	1.097	6.02
				RC	0.674	0.746	5.17
				LC	0.638	0.788	5.11
				LL	0.748	1.018	5.84
AAF 2	216	F	AA	RL	0.854	1.158	6.03
				RC	0.777	0.84	5.66
				LC	0.696	0.807	5.62
				LL	0.907	1.123	6.2
AAF 3	198	F	AA	RL	0.853	0.967	6.01
				RC	0.75	0.804	5.8
				LC	0.806	0.798	5.92
				LL	0.877	1.035	6.16
AAF 4	444	F	AA	RL	0.988	1.054	6.81
				RC	0.942	0.952	6.04
				LC	0.906	0.882	6.12
				LL	0.903	1.032	6.79
AAF 5	638	F	AA	RL	0.878	0.982	6.35
				RC	0.817	0.925	6.17
				LC	0.825	0.914	6.14
				LL	0.899	1.003	6.41
AAF 6	192	F	AA	RL	1.022	1.198	6.1
				RC	0.925	0.992	5.9
				LC	0.909	1.111	5.77

				LL	1.111	1.281	6.33
AAF 7	532	F	AA	RL	0.994	1.128	6.04
				RC	0.818	0.839	5.44
				LC	0.808	0.864	5.69
				LL	1.013	1.228	6.21
AAF 8	201	F	AA	RL	0.877	1.045	6.12
				RC	0.844	0.901	5.42
				LC	0.858	0.938	5.74
				LL	0.923	1.149	6.02
AAF 9	157	F	AA	RL	0.884	1.121	6.11
				RC	0.834	0.899	5.51
				LC	0.86	0.94	5.77
				LL	0.987	1.151	6.22
AAF 10	237	F	AA	RL	0.898	1.175	6.55
				RC	0.788	0.913	5.71
				LC	0.776	0.862	5.65
				LL	0.891	1.178	6.48
AAF 11	208	F	AA	RL	0.881	0.904	6.01
				RC	0.786	0.856	5.75
				LC	0.764	0.77	5.53
				LL	0.852	1.197	6.24
AAF 12	172	F	AA	RL	0.87	1.036	6.56
				RC	0.81	0.832	5.89
				LC	0.775	0.876	6.01
				LL	0.891	1.001	6.5
AAF 13	332	F	AA	RL	0.705	0.843	5.42
				RC	0.595	0.692	5.11
				LC	0.578	0.628	4.89
				LL	0.681	0.841	5.24
AAF 14	220	F	AA	RL	0.814	1.117	6.21
				RC	0.698	0.837	5.89
				LC	0.691	0.829	5.87
				LL	0.899	1.135	6.51
AAF 15	534	F	AA	RL	0.89	0.979	6.02
				RC	0.82	0.831	5.31
				LC	0.881	0.879	5.33
				LL	0.879	0.965	5.93
AAF 16	167	F	AA	RL	0.742	1.004	6.27
				RC	0.691	0.722	5.03
				LC	0.771	0.78	5.28
				LL	0.791	0.998	6.24
AAF 17	164	F	AA	RL	0.877	0.997	5.85
				RC	0.74	0.88	5.22
				LC	0.802	0.825	5.17
				LL	0.905	1.046	5.78
AAF 18	164	F	AA	RL	0.77	0.924	5.72
				RC	0.738	0.77	5.16

				LC	0.743	0.817	5.32
				LL	0.767	0.899	5.62
AAF 19	182	F	AA	RL	0.811	1.062	6.79
				RC	0.8	0.811	6.13
				LC	0.791	0.789	5.82
				LL	0.825	1.111	6.89
AAF20	309	F	AA	RL	0.735	0.891	5.74
				RC	0.65	0.69	5.27
				LC	0.645	0.681	5.23
				LL	0.795	0.776	5.39

VITA

Dr. Nathan E. Hall was born in Waterloo, Iowa on November 16th, 1975. He attended Luther College in Decorah, Iowa where he earned a Bachelor of Arts degree in Biology in 1998. He subsequently entered the University of Iowa College of Dentistry. He spent three months of his final year of dental school training at the University of Nijmegen College of Dentistry in Nijmegen, The Netherlands. He returned to the University of Iowa and was awarded his Doctor of Dental Surgery degree in 2002. The following year was spent teaching and practicing general dentistry as a Fellow Associate at the University of Iowa College of Dentistry in the Admissions, Oral Diagnosis, and Emergency departments. He then entered the Virginia Commonwealth University graduate orthodontics program and is anticipating receiving a Master of Science degree in 2005. He plans to enter a private orthodontic practice in Iowa City, Iowa upon graduation.