University of Alberta

The Bolton Analysis Revisited

by

Lillian Amanda Bailey ©

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Abstract

The purpose of this research was to validate the Bolton Analysis, and to investigate potential relationships between the Anterior Bolton Analysis and arch form.

Eighty-eight nonorthodontically treated optimal occlusions were identified and measured for individual tooth width and arch measurements. In this study the Anterior Bolton Ratio of 76.71% was just less than Bolton's Anterior Index of 77.2% and the Overall Bolton Ratio of 91.10% was close to Bolton's Overall Index of 91.3%. Males and females had similar Bolton ratios. The variations in arch form proportion found in the naturally occurring optimal occlusions in this sample did not result in significant differences in the Anterior Bolton ratio.

A second study compared the pretreatment to the post treatment Anterior and Overall Bolton Ratios in each of 90 orthodontic cases. The results showed no significant differences in the majority of cases. The results of both investigations validated Bolton's original findings.

Never doubt that a small group of thoughtful, committed citizens can change the world. Indeed it's the only thing that ever has.

Margaret Mead

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Introduction and Literature Review

Chapter One Introduction and Literature Review

1.1 Introduction

Orthodontic diagnosis and treatment planning involve the collection and review of a comprehensive database. An orthodontic database is formed by: interviewing the patient and family; clinical evaluation of extraoral and intraoral findings; and analysis of diagnostic records which include photographs, radiographs and casts of dental structures. Dental cast or model analysis generally involves evaluation of a) symmetry, b) arch size and arch form c) alignment crowding or spacing, and d) tooth size analysis.[1]

For good occlusion, the teeth must be proportional in size. If teeth are mismatched, with unusually large teeth in one arch compared to the other, then an ideal occlusion cannot be attained. Disproportion in the sizes of teeth between the maxillary and mandibular arches is not uncommon.[2-6] This has been defined as tooth size discrepancy.[6]

In 1952, Dr. Wayne A. Bolton developed a tooth size analysis that is commonly used today and it is generally referred to as the "Bolton Analysis". [7] Bolton's Tooth Size Analysis is based on measurement of the mesiodistal widths of permanent teeth (Appendix A). Bolton compared the sum of the widths of lower teeth to the sum of the widths of upper teeth in a sample of excellent occlusions. From this sample, Bolton determined two clinically significant ratios which compare the sizes of the upper to the lower permanent teeth. The first ratio, derived from the Overall Bolton Analysis, involves measures from first molar to first molar inclusively. He found a ratio of 91.3% ± 0.26 when the overall measurement of the 12 lower teeth was divided by the 12 upper teeth. The second ratio, derived from the Anterior Bolton Analysis, involves width measurements from canine to canine inclusively. A ratio of 77.2% ± 0.22 was determined by the comparison of the six lower anterior teeth to the six upper anterior teeth (Appendix B). According to Bolton, an anterior mean ratio of 77.2% provides a satisfactory anterior relationship if the angulation of the incisors is correct and if the labiolingual thickness of the incisal edges is not excessive.[8,9] An overall mean ratio of 91.3% results in a good posterior occlusion.[8,9]

Dental arch form is determined by the relative positioning of the teeth, alveolar bone and denture base within the jaw.[10] Genetic, developmental, functional, environmental factors, and orthodontic treatment have an influence on arch form. Both arch form, and tooth shape and size, vary among individuals.[11-14] When upper and lower jaws have complementary dimensions of both arch form and tooth structure a potentially harmonious occlusion may exist.[10,12]

A variety of descriptions have been used to qualify and quantify arch form and a great deal of study has been devoted to arch form.[15,16] The degree of curvature is most evident in the anterior of the dental arch,[10,17,18] however a review of the literature revealed few articles that specifically dealt with arch form in relation to the Anterior Bolton Analysis.[19-21]

The objectives of this study are threefold: first, to determine the validity of the Bolton Tooth Size Analysis on a sample of untreated optimal occlusion cases (Paper One); second, to compare the results of the Bolton tooth size discrepancy analysis on pre and post treatment casts of the same patients and thereby evaluate the usefulness of the analysis as a diagnostic aid (Paper Two); and third, to evaluate the effects that anterior arch form may have on inter arch tooth size proportions (Paper Three).

1.2 Statement of the Problem

Bolton's Analysis has been used as a diagnostic tool for over 35 years to identify potential tooth size discrepancies that may create occlusal disharmony. A discrepancy in tooth size, which may be localized in either the anterior or posterior segments of the arch, can be identified by studying both the anterior and overall analyses. The discrepancy can be classified as either a deficiency or an excess of tooth width in the upper or lower arch.

Tooth size discrepancy often influences treatment planning. For example, enlargement of a congenitally small lateral incisor may require preserving or regaining space in order to accommodate a restoration or a crown.[22,23] Extraction decisions may be influenced by the relative tooth size discrepancies identified with the Bolton Analysis.[9,24] In some situations the need for a diagnostic set-up (manipulation of model teeth in a wax base to simulate orthodontic movements) can be determined by the presence or absence of a tooth size discrepancy.[9]

Bolton's original work was conducted on a sample of 55 cases carefully selected for the presence of excellent occlusions, 44 were orthodontically treated cases and 11 were untreated. The values derived from Bolton's work were statistically significant based on the total sample, though the number of naturally occurring excellent occlusions was relatively small. The sample was not broken down by gender. It would be helpful to know if Bolton's results could be replicated in a similar sample of naturally occurring ideal occlusions. It would also be of clinical advantage to know if there are different ratios for males and females.

Tooth width measurements can be made with relative ease on well aligned dentitions like those used in Bolton's original study. However, in orthodontic cases the preexisting malocclusion may alter the relationship of the teeth so that interproximal contact points must be estimated on the preliminary casts.[25] Since a sound treatment plan and a successful treatment outcome depend on accurate diagnostic information, [26] appropriate conclusions on tooth size can be made only if pretreatment measures are very similar to the measures attained after alignment. It would be beneficial to ascertain if the two measures on the same patient were comparable.

Bolton and others have discussed the interactions of overbite, overjet and angulation on the Bolton Analysis.[2,9,27-29] Incisal length and cusp height,[7] arch radius and arch perimeter have also been examined.[20,21,30] The degree of curvature is most evident in the anterior of the dental arch, and the rate of change of curvature of the arch is greatest from canine to canine.[10,17] Interactions of anterior arch form with Bolton's Anterior Analysis have not been fully evaluated.[21] For extremely narrow or broad shaped arch forms the Anterior Bolton Index of 77.2% possibly may not apply.[21]

1.3 Purpose

Purposes of this study were:

1. To determine the validity of the Anterior and Overall Bolton Tooth Size Analyses (Chapter 2),

2. To determine the effects of orthodontic tooth movement on the measurement of the Anterior and Overall Bolton Tooth Size Analyses (Chapter 3), and,

3. To determine whether changes in the Anterior Bolton Analysis ratio result from varying anterior arch form (Chapter 4).

1.4 Research Questions

1. Does analysis of "optimal" occlusions yield a correlation of mandibular to maxillary arch lengths similar to Bolton's Index of 77.2% for the six anterior teeth and Bolton's Overall Index of 91.3%?

2. Do the results of the Bolton Analysis vary between pretreatment and post treatment orthodontic casts in a sample of orthodontic malocclusion cases?

3. Does changing the anterior arch form change the "Index" or mean ratio of the Anterior Bolton Tooth Size Analysis?

1.5 Null Hypotheses

Hypotheses of this study are:

1. Nontreated ideal occlusions when measured have:

   a) an Anterior Bolton ratio that is not significantly different from the Anterior Bolton Analysis mean index of 77.2%,

   b) an Overall Bolton ratio that is not significantly different from the Overall Bolton Analysis mean index of 91.3%.

2. The ratios of the Anterior and Overall Bolton Tooth Size Analyses are not significantly different when measured on pre and post treatment orthodontic casts.

3. Changing the anterior arch form does not change the mean ratio value of the Anterior Bolton Tooth Size Analysis.

1.6 Literature Review

1.6.1 Development of Tooth Size Discrepancy Analysis

Execution of proper treatment relies on an adequate assessment of all the underlying problems inherent in a patient's particular malocclusion. Esthetics and function depend on jaw sizes, bite position and relative tooth sizes. As Ricketts stated, the "study of any aspect of orthodontics involves the problem of variation in the size of structure, variation in the form of parts, and variation in function."[31] The existence of a tooth size discrepancy often influences treatment planning decisions. An assessment of the amount of crowding or spacing of anterior teeth is one of the first steps in orthodontic diagnosis and treatment planning. Objective information on the amount of arch-size-tooth-size discrepancy in the incisor region often tips the balance for or against premolar extraction.[32]

Tooth sizes and their inter arch relationships are fundamental to orthodontic treatment.[26,33] In the early 1900's Angle included eight variables in occlusion: position, interincisal relation, size of teeth, pattern of teeth, length of teeth, length of cusps, width of arch, arch form, and curve of Spee.[12]

G.V. Black[11] published tables of mean sizes of teeth in 1902 based on the measurement of many teeth of each type. In 1944, Ballard measured 500 sets of models to determine the greatest mesiodistal diameter of each permanent tooth on the models.[34] He catalogued discrepancies between teeth on opposite sides of the upper and lower arches and compared mean values of each tooth to those in Black's table. His measurements showed a notably increased range in the sizes of the individual teeth. Ballard's results showed right to left asymmetry of 0.25 mm or more in 90% of the sample. He discussed judicious stripping of proximal surfaces as a practical solution to correct the intra arch disharmony in tooth size.

Ballard in 1956 discussed the "subversive influence" that the relative sizes of the upper and lower six anterior teeth had on the harmony of the occlusion.[3] He studied size relationship between the widths of the six upper and lower anterior teeth in 400 orthodontic cases. He found that more than 50% of the mandibular anterior segments were 2 mm or more larger than required for ideal tooth-to-tooth and arch-to-arch relationships, when compared to a denture tooth manufacturer's ratio of 75%. Ballard also measured 20 orthodontic cases that he considered to be "ideally treated" with very favourable results (it is not clear whether these ideal cases were from within the 400 cases sampled or from a separate sample). The ideal orthodontic cases had harmony in tooth size, cuspal relation, arch form, overbite and overjet. Ten cases had been treated with four premolar extractions, and ten had a full complement of teeth. In this "ideal" sample, the average variation was plus 1.20 mm. This indicated that the ideal cases also had a ratio larger than the denture ratio of 75%, but they did not have relative mandibular excess to the extent that the 400 cases had. Ballard concluded that this variation in tooth size and the relationship of upper and lower anterior segments are of sufficient incidence and magnitude to merit serious consideration in the etiology, diagnosis, and treatment planning of every orthodontic case. However, in this study Ballard compared his natural dentition cases to a supposed "ideal" denture ratio, which was likely too low.[3] The ratio provided by the Trubyte company was one of a few possible denture ratio values. Neff in 1957 noted that he was provided with a figure of 83% by the same company and he also mentioned that the 75% value was an average.[35] Neff stated that finished denture cases ranged from a 75 to 90% ratio with little overbite, but often with an overjet of 1 to 2 mm. It was not possible to calculate "corrected" anterior ratio values from Ballard's study due to the lack of values presented.

Variation in the proportion of the upper and lower anterior teeth make proper alignment with the ideal amount of overbite difficult to obtain.[2] Neff in 1949 proposed a mathematical guide to relate the maxillary and mandibular tooth sizes to overbite. He measured 200 cases and correlated the sum of the mesiodistal widths of the maxillary and mandibular six anterior teeth with the percent of overbite for each individual. Neff calculated the "Anterior Coefficient" by dividing the lower sum into the upper sum, which he found to be 1.20 - 1.22 with an overbite of 20%. Inverting the Neff Anterior Coefficient gives a percent ratio of 82.6%.

Neff stated that when the coefficient was close to 1.20 - 1.22 and when the lower incisors were in an upright position relative to the mandibular plane, the anterior teeth could be made to articulate favourably regardless of tooth size or shape. He published a correlation table relating the "Anterior Coefficient" to the overbite. In it, a coefficient of 1.10 correlated to an overbite of 0%, 1.20 to 20%, 1.40 to 55%, and a coefficient of 1.55+ correlated with 100% overbite.[2]

Bolton developed two analyses whereby the ratio of mandibular to maxillary tooth material was determined.[7] The presence of deficiency or excess for each arch can be identified by applying Bolton's formula to the case under study and comparing the calculated value to Bolton's Index. The amount of the discrepancy is usually determined by using regression tables or lists which predict the amount of tooth material that the corresponding arch should contain.[5]

Bolton observed that the numbers arrived at were useful only as an aid in developing a treatment plan.[9] However, Bolton found that if a significant proportional deviation existed, that is, of more than one standard deviation from the mean ratio, then alteration of mesiodistal tooth dimension in one of the arches had to be considered. This alteration could range from interproximal enamel removal (stripping) to extraction.

Bolton noted that regardless of the mathematical findings, each patient required individual consideration. The Bolton Analysis can be used to indicate what the anterior and posterior inter arch relationship might be at the conclusion of therapy.[24]

In 1957 Neff reported another survey of 300 malocclusions with all the measurements taken intraorally.[35] The results related the ratio in the reverse to his earlier work, computing the mandibular teeth as a percentage of the upper teeth. The anterior ratio mean was 79% and the range was 73 to 85%. Neff reported in this study that tooth size relation of the anterior segments of the dental arches and the degree of overbite did not bear a consistent relationship in malocclusions and orthodontic normals.

Lundstrom[27] measured tooth widths of randomly selected occlusions of which eight were "normal" or without significant deviations. The mean value of 78.5% was reported on 264 casts with a range of 73 to 84.5% for the anterior six teeth (Index I - Lundstrom). The mean value of 92.3% was reported on 63 casts with a range of 88.0 to 97.5% for the incisors to first molars bilaterally (Index S - Lundstrom). Lundstrom reported that no strong correlations could be found between the anterior index and overjet and overbite in 62 cases for which these parameters were available. In 1981 Lundstrom reported his earlier work again and included the results on the normal cases with slight deviations in form (i.e. slight rotations, crowding or spacing) as "excellent cases".[36] In this report the "excellent" cases had a first molar to first molar mean ratio of 91.9% and a range from 87 to 93%. No anterior ratio was provided for this group. In this study Lundstom also reported the 1937 work of Tonn. Lundstrom used Tonn's data on 50 "excellent" cases and calculated a mean incisor ratio of 74.1%, range 67-81% and a mean overall ratio of 92.5% with a range of 87 to 98%.

Stifter[37] carried out a study on the models of 57 dental students and eight Navaho Indians. The 65 case sample was reduced to 58 through elimination of cases with missing teeth, obvious peg laterals or other anomalies. All were normal Class I occlusions cases with acceptable overjet and overbite according to Stifter.

Stifter's results were:

Overall: Normals (34) and Ideals (24) - Mean 91.04%, SD 1.90, Range 87.2 to 94.6%.

Anterior: Normals - Mean 78.59%, SD 2.37, Range 73.5 to 83.3%;

Ideals - Mean 77.55%, SD 2.72, Range 72.5 to 81.7%.

In Stifter's study the ideals came very close to Bolton's anterior relationship, but the normals did not correlate closely with Bolton's anterior value.

A summary of the key articles showing the ratios between the upper and lower teeth is outlined in Table 1.1. A number of published studies use Bolton's Indices as the standard for comparison and the basis for the diagnosis of tooth size discrepancy.

Sperry et al.[26] carried out a Bolton Analysis of 78 cases of Angle Class III malocclusion, 26 cases of Angle Class I malocclusion, and 26 cases of Angle Class II malocclusion. They computed and analyzed the frequency of excess mandibular tooth structure, magnitude of the excess, overall ratios, and anterior segment ratios.

Sperry et al. concluded that: the frequency and magnitude of mandibular tooth-size excess (overall ratio) in the sample was greater in cases of mandibular prognathism than in Angle Class I and Angle Class II cases, and that tooth-size discrepancy analysis should be included as one part of the diagnostic records for mandibular prognathism.

Manke and Miethke[22] sought to find: the average Anterior Bolton ratio for an orthodontic patient sample; how many cases had an oversize of the lower anterior teeth; and, if there were any gender specific differences. Initial models taken of 49 boys and 51 girls were studied from an untreated "orthodontic normal collective". The teeth on the casts were without obvious anomalies in either form or size, and were of their original tooth width.

Manke and Miethke found the average anterior Bolton ratio for boys was 78.60% ± 3.85%; for girls, the mean was 77.87% ± 3.05% and for both genders together, the mean was 78.28% ± 4.29%. They concluded that the comparatively larger mean ratio for the total sample meant that the mandibular anterior teeth were generally slightly wider than Bolton's sample. The standard deviation suggests a larger variation of the sample, a result that the authors thought could be expected from the random selection procedure. Testing the gender specific differences showed that statistically the boys, more often than girls, had anterior Bolton discrepancies with a probability of error $< 5\%$.

McArthur[38,39] published, in a prosthetic dentistry journal, a two-part study of cases where complete maxillary denture and natural mandibular anterior teeth were present. He demonstrated, using several methods, the maxillary six anterior teeth were 1.3 times larger than the mandibular six anterior teeth in a mesiodistal dimension. He determined that this correlation between the size of the mandibular anterior teeth could be used to select the anterior teeth for the denture. In the absence of preextraction records, artificial maxillary anterior teeth could then be selected that were of the approximate size to produce a Class I relationship with the natural canines.

In the first method the Trubyte Bioblend mold chart was used to obtain a ratio of the relative size of mandibular to the maxillary mold for 42 different prosthetic molds. The stated size on a curve for a maxillary mold was divided by the given size for the appropriate mandibular mold. The average of the 42 ratios was 1.31, with a range of 1.24 to 1.37, and there did not appear to be any correlation of the ratio varying directly with denture mold size.

In another method casts from 100 completed adult orthodontic patients were studied: 56 females and 44 males were randomly selected from a pool of completed patients. The arches were measured en mass with a flexible ruler and the results of the calculated mean ratios were 1.298 for both men and women, with a range of 1.20 to 1.39. The average size for the maxillary anterior teeth was 53.7 mm and for mandibular anterior teeth was 41 mm. The average sizes for the 56 women were 52.3 mm for the maxillary anterior teeth and 40.2 mm for the mandibular anterior teeth. The average sizes for the 44 men were 54.6 mm for the maxillary anterior teeth and 41.9 mm for the mandibular arch.

McArthur concluded from these results that a reliable relationship existed between the maxillary anterior teeth and the mandibular anterior teeth measured on a curve. He stated that when mandibular anterior teeth are present, the arch width from distal-of-canine to distal-of-canine can be measured, and this measurement times 1.3 equals the arch width of maxillary anterior teeth required to produce a Class I canine relationship, (1 divided by 1.30 = 76.9%).

Crosby and Alexander[40] reported tooth size analyses performed on the pretreatment models of 109 orthodontic patients with varying malocclusions (Class I; Class II, Division 1 and Division 2; and Class II malocclusions requiring surgery). They analyzed the incidence of mesiodistal tooth size discrepancies in the malocclusion groups and compared the data with Bolton's means and standard deviations. The results showed no difference in the incidence of tooth size discrepancies from one malocclusion group to another. Taken as a whole, the sample showed no significant difference in the mean of the mesiodistal tooth size ratios when compared to Bolton's mean. The study showed an anterior ratio mean of 77.5%, SD 3.4, range 65.3-90.5% and overall ratio mean of 91.4%, SD 2.4, and range 86.6-99.8% for the entire sample of 109 orthodontic cases.

Although Crosby and Alexander[40] found no significant difference in the incidence of tooth size discrepancies among malocclusion groups, they did note a large number of tooth size discrepancies in each group: 16.7% in the Class I group and 23.4% in the Class II, Division 1 had anterior discrepancies that warranted clinical concern. For the overall ratio, 13.35% of the Class II, Division 1 group and 6.8 % in the Class II surgical group had ratios that were greater than 2 SD from Bolton's means. When all patients were grouped together, 22.9% had an anterior ratio with a significant deviation from Bolton's mean. Due to the large percentage of discrepant cases in this orthodontic patient sample it was suggested that Bolton's Tooth Size Analysis be performed before initiation of orthodontic treatment.

Lew and Keng's[29] study established normative data on crown dimensions of the anterior teeth of Chinese subjects. Results showed the odontometric measurements of anterior tooth crown sizes in a Chinese sample of 85 Class I occlusions to be similar to those published in the white population except for larger upper lateral incisors and smaller upper central incisors in the Chinese. They found no other significant differences in the mesiodistal dimensions of other teeth and observed sex differences in tooth sizes only in the maxillary and mandibular canines. The Bolton ratios of Lew and Keng's Chinese sample revealed a Bolton ratio of 77.89% with a SD of 1.62 which compared favourably with Bolton's original findings. In his 1958 paper, Bolton[41] theorized that small interincisal angles and extreme labiolingual thickness tended to disrupt the anterior tooth size ratio. The authors cited several cephalometric studies on Chinese patients that showed bimaxillary protrusion and increased torque angles compared to Caucasians. Lew and Keng were therefore surprised to find a ratio in their sample similar to Bolton's. The interincisal angles, overbite and overjet relationships were statistically different at the $p = 0.01$ level. The increased maxillary protrusion contributed to the decrease in the interincisal angle (161.87 ± 8 degrees) of the Chinese compared to Caucasians. The different incisor inclination would tend to cause a smaller Bolton ratio according to Lew and Keng. This expected smaller ratio could be offset by the smaller overbite and overjet parameters found in this sample. Theoretically a smaller overjet and overbite would correlate with a larger Bolton ratio, Lew and Keng noted. Their results suggest that Bolton's original tables are applicable to the Chinese race and can be used without modification.

Tayer[24] used three diagnostic procedures to assist in making final treatment decisions in four case studies: a Bolton tooth size analysis; a space available/space needed assessment; and a pretreatment diagnostic set-up. The cases required asymmetric dental extractions in order to achieve the desired treatment results. The Bolton analysis used in the diagnostic predictions supported the treatment plans. The completed treatment results closely approximated the original diagnostic predictions.

Freeman et al.[23] analysed the Bolton tooth size discrepancies of 157 patients accepted for treatment in an orthodontic residency program and evaluated for the frequency and the magnitude of deviation from Bolton's mean. They determined the percentage of orthodontic patients who presented with an inter arch tooth size discrepancy likely to affect treatment planning or results. They defined significant discrepancy as a value outside of 2 SD from Bolton's mean. For the overall ratio, they defined a significant discrepancy as a ratio below 87.5% or above 95.1%, and any ratio below 73.9% or above 80.5% as a significant discrepancy for the anterior ratio.

This study reported the following values for the overall: mean 91.4%, SD 2.57, range 82.8-99.4%; and for the anterior ratio 77.85%, SD 3.07, and, range 68.4-87.9%. The mean of the sample was nearly identical to that of Bolton's for both the overall and the anterior ratios. The ranges and standard deviations varied considerably with a large percentage of the orthodontic patients having discrepancies. Of the 157 cases, 21 or 13.4%, had overall ratios outside of 2 SD from Bolton's mean. Forty-eight cases, or 30.6%, had anterior ratios that were outside of 2 SD from Bolton's means. The overall discrepancy was equally likely to be an excess in either jaw, however, the anterior discrepancy was more likely to be a mandibular excess, (19.7% mandibular excess, 10.8% maxillary excess).

1.6.2 Summary of the Studies

Tooth size disproportions between the maxillary and mandibular arch are not uncommon [2,3,5,6,30] and the effects of the disproportion may become especially apparent in the finishing stages of orthodontic treatment.[5,26] Several studies have analysed tooth size discrepancy using inter arch ratios on various numbers and types of cases. Key investigations are: Tonn[36] developed an anterior ratio for the proportions between the incisors only; Neff's "Anterior Coefficient", when inverted, gave a ratio of 82.6%[2] and 79%[35] in a later study on malocclusions; Lundstom[36] used eight excellent occlusions to study the overall ratio only; Stifter[37] conducted part of his study on 24 "ideal" natural occlusions, which was the only additional study besides Bolton's to use ideal cases to quantify the anterior six tooth ratio. Table 1.1 summarizes these investigations.

Several more recent studies have compared the ratios calculated for different malocclusions and various ethnic groups to Bolton's Indices using his ratio values as "golden standards." The previously referenced studies on orthodontic patients by Crosby and Alexander[40] and Freeman et al.[23] each found means similar to Bolton's and significantly larger ranges and standard deviations than Bolton's. Both studies concluded that the high frequency of clinically significant discrepancies within orthodontic patients suggest that a tooth-size analysis should be routinely performed and the findings incorporated into orthodontic treatment planning.

1.6.3 Clinically Significant Tooth Size Discrepancy

A number of authors have noted that in ideal sets of teeth the mesiodistal widths of the upper teeth are proportional with those of the lower jaw,[2,3,41] and that exceeding the Bolton Index values could result in a deviation of the intercuspation or the overbite and overjet relationships,[5,9,22,24,26,30] They have advised correcting larger discrepancies to avoid disturbances in the occlusion.

Various values of inter arch tooth size discrepancies have been considered clinically significant or likely to affect treatment planning or results. Manke and Miethke[22] suggested starting corrections at about 2 to 3 mm of discrepancy, using, for example, extractions, prosthetic preparation of crowns or interproximal reduction. Others have defined a significant discrepancy as a value outside of 2 SD from Bolton's mean.[23,40] Bolton's SD of 1.65 for the anterior ratio, multiplied by two, equals 3.3% and Bolton's SD of 1.91 for the overall, multiplied by two, equals 3.82%. Therefore for the anterior ratio, they defined a significant discrepancy as a ratio below 73.9% or above 80.5%, and any ratio below 87.5% or above 95.1% as a significant discrepancy for the overall ratio. Freeman et al.[23] chose 2 SD to define a significant discrepancy, as approximately 95% of Bolton's cases were within this range. Similarly Thurlow[5] indicated that any combinations of maxillary and mandibular tooth widths that fell within the 2 SD lines, on the regression tables graphically representing Bolton's data, may be considered normal.

Cases with ratios outside 2 SD were selected according to Crosby and Alexander[40] because this represented a 2 to 3 mm discrepancy from the mean of Bolton's study, which was considered great enough to warrant attention in the normal course of orthodontic therapy.

To test the validity of these methods a composite of G.V. Black's[11] and Wheeler's[42] maxillary and mandibular average tooth sizes was created to achieve ratios of 77.2% and 91.3% and subsequently used as a basis to estimate the discrepancies of tooth size in millimeters at ranges of 2 SD. Application of the low and high ranged ratios in place of Bolton's Mean Indices to the composite values yields the following results for the anterior and overall analysis:

Proposed 2 SD Method	Low Range (-2 SD)			High Range (+2 SD)		
for Clinical Significance	Mandibular	Maxillary	Ratio	Mandibular	Maxillary	Ratio
Anterior Analysis (77.2%)	-1.5	+2.0	73.9%	+1.5	-1.8	80.5%
Overall Analysis (91.3%)	-3.6	+4.1	87.5%	+3.5	-3.7	95.1%
Either	deficiency or excess in mm			excess or deficiency in mm		

Using 2 SD above and below Bolton's mean ratio as a method to distinguish clinically discrepant cases gives moderately low values for the anterior analysis and higher values for the overall analysis. The values obtained for the overall analysis are significantly higher (at -3.6 to +3.5 mm for the mandibular arch and -3.7 to +4.1 mm for the maxillary arch) than the discrepancy values indicated in a leading orthodontic reference text. Proffit stated that "a tooth discrepancy less than 1.5 mm is rarely significant, but larger discrepancies create problems" to consider when planning

treatment.[6] Proffit does not indicate whether this minimum value is for the anterior or for the overall analysis or for both.

Bolton found that a proportional deviation of more than one standard deviation from the mean anterior ratio existed in 29 cases within a 100 case sample of his patients. He stated this high percentage of cases reflecting more than one standard deviation indicated a need for diagnostic consideration (1962). It is not clear from his thesis or published articles exactly what discrepancy values he considered clinically significant. Bolton noted that regardless of the mathematical findings, each patient required individual consideration. Applying the 1 SD low and high ranged ratios to the composite values yields one half the values of the 2 SD results as a measure of clinical significant tooth size discrepancy for the anterior and overall analysis. The anterior analysis values are 1 mm or less using this approach and once again the corresponding overall values are remarkably larger. A guide for the evaluation of clinical significance of discrepancy could be developed from an amalgamation of techniques, ultimately using the clinician's impression and a diagnostic setup as the decisive factors.

The following points are offered for consideration when interpreting Bolton ratios. The result obtained in the analysis evaluates a relative discrepancy: one arch may be deficient or the other in excess, but either arch can be chosen as the arch for comparison. The application of the ratios result in reversible but unequal and opposite signed discrepancies. This point is illustrated with two simple examples for the Anterior Analysis using Bolton's Mean Index of 77.2%: a 2 mm mandibular excess correlates to a 2.6 mm maxillary deficiency, and a 1.5 mm mandibular deficiency correlates to a 2.0 mm maxillary excess, (Anterior Bolton 1.29 Mandible / Maxilla = Mandible / 0.772 Maxilla). The disparity between the discrepancy in maxillary or mandibular arches is less significant when interpreting the Overall Analysis since the ratio of 91.3% is closer to a one-to-one proportion of lower to upper tooth size. (Overall Bolton 1.10 Mandible / Maxilla = Mandible / 0.913 Maxilla).

Manke and Miethke[22] concluded that for one fifth of their sample of orthodontic patients there was an oversize of the lower six front teeth that would justify a narrowing of these teeth. They also stated that relative oversize of the upper six front teeth is less common than relative oversize of the lower six front teeth. It is notable that though there is possibly a mandibular excess, the result could instead be interpreted as a relative maxillary deficiency. Comparing the widths of the teeth to average tooth size data would allow appropriate conclusions regarding whether the sample or case in question is excessive in one arch or deficient in the other arch.

1.6.4 Definition of "Normal", "Ideal", "Excellent" and "Optimal" Occlusions

In order to validate Bolton's study, similar ideal occlusion cases were needed. The criteria for the "excellent" occlusions used by Bolton were based in part on reference to Angle's 1907 text. Other sources have discussed normal and ideal occlusion of the teeth as follows:

Stifter[37] related a definition of normal occlusion as "occlusion of the teeth is normal when their manifold functions are efficiently performed and the health of the supporting structures is maintained. The primary functions of the teeth include mastication, esthetics, and functions of speech and deglutition."[37] He also wrote that strict adherence to the concept of ideal occlusion had been severely criticized. Andrews[43] points out that orthodontic treatment results do not always satisfy the occlusal standards of other specialists or generalists. He questions whether orthodontists' goals are different from others in dentistry or whether there are clinical limitations that prevent orthodontists from reaching the goals considered exemplary by others. Graber[4] similarly stated that "for the orthodontist, ideal occlusion is an admirable goal but usually a therapeutic impossibility."

A number of authors have referred to Angle's classification as the best way to understand the exact features of normal occlusion and the types of occlusions.[4,6,37] Angle's key to occlusion was the position of the upper first molar.[12] The upper and lower molars relate such that the mesiobuccal cusp of the upper molar is situated in the buccal grove of the lower molar. Normal occlusion results in the presence of this molar relationship, if the teeth are aligned on a smooth, catenary, curving line of occlusion. Proffit stated that 100 years of experience has proved Angle to be correct except when there are aberrations in the size of teeth.[6]

Lundstrom[27] stated that "By normal or anatomically correct occlusion is meant functionally ideal occlusion". According to Lundstrom the following rules are generally recognized at the adult stage:

1. The teeth (32 in number) form regular arches in both jaws, with contact between them but no crowding, and with defined points in the mesiodistal direction.
2. On biting together the upper teeth meet the lower labially and bucally. In the anterior region there is moderate overbite of between 1 and 3 mm. In the premolar-molar region the upper palatal cusps intercuspate with the lower buccal and lingual cusps. Double antagonism occurs between all teeth except the lower I_1 and the upper M_3, each maxillary tooth occluding with the corresponding and the adjacent mandibular teeth, counting towards the midline.
3. In articulation there is so-called balanced occlusion; that is, in incisal and lateral occlusion there is smooth contact between the arches anteriorly and in both lateral regions.[27]

Lundstrom wrote "since this conception of the norms is the ideal it is hardly to be expected that it will be fully realized in actual cases.... It is impossible to find in the material for any case that fulfills exactly all of the requirements in respect of tooth alignment and occlusion."[27] He found that in most cases closely approaching the ideal there are small deviations in the form of slight rotation of single teeth, slight crowding or spacing. He felt that the boundary was fluid between those cases and those with more pronounced malposition. The percentage of normal cases depends, according to Lundstom, on the degree of malocclusion admissible.[27]

Brodie[44] stated that "each individual is distinct so far as the morphological characteristics of the head are concerned and just as there are no two sets of identical fingerprints... each component part exhibits wide ranges of variation." He felt that one could establish a norm by taking an average of all of the variants and combining them, but having done so, the result was not significant for diagnosis.

Current concepts of ideal occlusion are based to a large extent on the principles and teaching of Andrews.[45] Through his clinical experience and research, he developed the "Six Keys to Occlusion" which are "interdependent elements of the structural system of optimal occlusion". Assessment of optimal occlusion, according to Andrews, is based on the presence of the "Six Keys to Occlusion".[45]

They are:

- Key One: Molar relationship – Class I,
- Key Two: Crown angulation (tip) – mesiodistal tip of the long axis of the crown such that the gingival portion is distal to the incisal portion,
- Key Three: Crown Inclination (torque) – refers to the labiolingual inclination of the long axis of the crown such that the labiolingual position of anteriors is positive for maxillary teeth and slightly negative for mandibular incisors; buccolingual inclination of canines through to second molars is progressively more negative with lingual crown inclination ("Anterior crown inclination is necessary to resist overeruption of the anterior teeth.... Properly inclined anterior crowns contribute to normal overbite and posterior occlusion."[45]),
- Key Four: Absence of tooth rotations,
- Key Five: Tight contacts,
- Key Six: Curve of Spee depth varies from flat to slightly concave.

Andrews established his six keys to occlusion by evaluating the characteristics common to 120 cases, which he described as nonorthodontic normals (N.O.N.). Models selected for his study were of teeth which:

1. had never had orthodontic treatment,
2. were straight and pleasing in appearance,
3. had a bite which generally looked correct, and,
4. in Andrews' judgment would not benefit from orthodontic treatment.[45]

The 120 non-orthodontic normal models studied in his research differed in some respects, but all shared the six characteristics. The absence of any one or more of the six keys results in an occlusion that is proportionately inferior to the naturally optimal sample according to Andrews. *Optimal* is used for correct; normal is used to mean *not abnormal.*[43] The six keys can be used as treatment guidelines.

Andrews stated that most of the population is afflicted with malocclusion and that occlusal deviations are "natural". He distinguished "normal malocclusion" from "abnormal malocclusions" as those individuals that can be treated to optimal standards without compromise or help from surgical specialists.[43]

Standards elucidated by Andrews in the development of the "Straight Wire Appliance" include the principles that most people with malocclusions have normal teeth and jaws, each normal tooth type is similar in shape from one individual to another, and the size of normal crowns has no effect on their optimal angulation or inclination. Crown size discrepancies and peg-shaped maxillary lateral incisors are abnormalities according to Andrews.[43]

1.6.5 Tooth Crown Size Measurement and Error in Tooth Width

Odontometry is the science of measuring the size and proportion of teeth and the mesiodistal diameter is the crown dimension most frequently reported in odontometrics.[46] Numerous interpretations of this dimension appear in the literature. Crown size was defined by Sanin and Savara[47] as the greatest distance between the points of interproximal contact. Moorrees and Reed[48] suggested measuring the mesiodistal crown diameter as the greatest distance between the contact points on the approximal surfaces of a tooth, using a sliding caliper held parallel to the occlusal and labial surfaces. When a tooth was not in alignment Moorrees used as landmarks the points where normal contact with neighboring teeth should occur.[48,49]

Hunter and Priest[50] measured the mesiodistal crown diameter wherever possible, with the points of the dividers or calipers on the normal contact areas. The dividers or calipers were inserted from the labial, with the instrument held at a right angle to the long axis in most cases, or from the occlusal or incisal, with the instrument held in a plane parallel to the long axis of the tooth. In cases of linguoversion, a lingual insertion was used. When teeth were rotated, the normal contact areas were chosen. They noted that since the widest portion of a tooth is usually toward the buccal, it follows that the measurement from contact point to contact point is not necessarily the greatest mesiodistal diameter. However there is only a slight difference when measuring rotated teeth this way according to Hunter and Priest.

Kieser et al. described the mesiodistal crown diameter as the maximum mesiodistal dimension, with the two points of the instrument making contact with the tooth parallel to the occlusal plane.[51] In a discussion on the measurement of mesiodistal dimension Kieser states that the measures taken tangential to the most mesial and distal points of the crown need not correspond to the points of interstitial contact.[52]

Adherence to a consistent definition of the mesiodistal definition is important to precise or repeatable measures.[51] However, even when the same definition of tooth width is used, observers have freedom of interpretation of the definition.[51] Subjective interpretations, inconsistency in applying the definition, and error can account for discrepancies in measures of tooth width. In Beers' terminology, error and discrepancy are used in their technical sense and do not encompass what is commonly called "mistakes" (such as where a reading of 0.87 instead of 0.78 is made).[53]

Technique may depend upon tooth position on the cast. In Hunter and Priest's study, investigators' measurements varied for the cuspids, and variability as a whole was greater for the posterior teeth.[50] Reproducibility of measurements on study casts varied from ± 0.05 to 0.11 mm for the centrals and incisors in Sanin and Savara's study.[47] Moorrees et al.[49] calculated, from a number of double determinations for single permanent mandibular teeth, that the error measurement was 0.09 mm; for the combined mesiodistal crown diameters of ten permanent mandibular teeth, it was 0.41 mm.

Hunter and Priest[50] evaluated the experimental errors and discrepancies involved in the measurement of tooth size in a study comparing two methods, using dividers and calipers, two investigators measured each set of casts twice. The conclusions were: dividers on average gave a significantly larger measurement of tooth size than calipers. A systematic error probably occurred because of the taper on the points of the dividers such that the sides of the points, not the tips, contacted the teeth. The variation in measures around the mean was reduced from first measure to second, suggesting that the measuring technique was perfected to some extent with practice. Both investigators in this study measured with similar accuracy.

Hunter and Priest[50] also evaluated reliability, using the same measuring instrument to compare variances for all teeth individually. They concluded the variability in discrepancies generally increases from central incisor to second molar, although these remained within the acceptable limits of experimental error. Tests of mean differences between investigators and between first and second measures were significant at the 0.1 level only for differences between investigators. Most differences between investigators were less than 0.1 mm in size and did not have practical significance. The total mean difference between investigators was 0.04 mm.

Garn et al.[54] tabulated mesiodistal crown size data for 658 subjects of Northwestern European ancestry living in Ohio. The measurements were made by one person on plaster casts using a ground tip micrometer caliper. Females had smaller teeth for all 28 teeth measured and exhibited greater variability in 16 out of 28 teeth. The mean values for corresponding teeth on opposite sides of the midline were similar, and Garn et al. concluded that combining right and left teeth in population comparisons was justified.

1.6.6 Bolton Analysis Measurement Error

Malposition of the teeth may alter the ability to measure the mesiodistal dimension of tooth width, as a result severely crowded cases may have a significant measurement error factor.[25] Determining the accurate Bolton ratio for a case may be difficult when measurements are made on the malposed pretreatment casts.

Shellhart et al.[25] studied 15 pretreatment cases with 3 mm or more of crowding in at least one arch and concluded that significant measurement error can occur when Bolton Analyses are performed on pretreatment crowded casts. Their study examined measurement error, differences between the two measuring devices, and intra examiner and inter examiner reliability. Four clinicians measured the teeth on 15 sets of casts using the two instruments in two sessions two weeks apart. Both the Anterior and Overall Bolton Analyses were examined.

The average of the largest errors when the Anterior Bolton Analysis was performed with needle point dividers was 2.2 mm. However, the combined average error of two measuring techniques, Boley gauge and dividers, was calculated as 0.71 mm for the Anterior Bolton Analysis and 0.95 mm for the Overall Bolton Analysis from Shellhart et al.'s data. For the majority of the comparisons made, the clinically significant errors were not due to consistent differences in measurement technique between tests done two weeks apart. All analyses demonstrated significant correlation between investigators and there were significant correlations between the two measurements made by the same examiner.

Measurement error in another previously mentioned study of maloccluded cases also showed no significant difference between two sets of measurements made on pretreatment models done by the same examiner.[40] Crosby and Alexander[40] evaluated measurement error in the study of 109 maloccluded cases by having the same examiner measure five sets of pretreatment models twice, on different days. The results showed no significant difference between the two sets of measurements.

1.6.7 Arch Form

1.6.7.1 Characterization of Anterior Arch Form

A variety of descriptions of form have been applied to the dental arch. The anterior curvature was described as circular in early dental literature. Bonwill,[55] in his work on the articulation of the teeth and the movement of the jaws in mastication, outlined a set of geometrical principles which he believed provided the basis for the movement of the jaws and the form of an ideal arch. In 1884 he developed guides for the setting of artificial teeth based on study of human anatomy. Bonwill constructed an articulator upon the basis of a four inch equilateral triangle, which he found to be the average width between the condyles in an examination of skulls. "The other arms of the triangle run from the condyle to the median line of the incisors (and are) also four inches long." Another of Bonwill principles was that "the normal jaw should overjet and have a corresponding underbite" and "in 95% of the cases ... the upper jaw projects over the lower, and the depth of the underbite varies from three-eighths of an inch to a sixteenth." He also felt that the arch should not be "horseshoe shape" as artificial dentures were generally made at the time.[55]

Hawley[56] adapted Bonwill's setup to orthodontics where the arch was based upon and proportional to the widths of the central, lateral and canine. He suggested that in any orthodontic case a circle could be drawn using the combined widths of these three teeth as a radius. The radius was then measured upon the circumference of the circle, its ends marking the distal points of the canines. Connecting lines were constructed and the arch was arranged within an equilateral triangle. "The teeth may be laid off on [the arch diagram], with a pair of dividers from measurements on the plaster cast, thus locating their exact positions...The second molars are turned slightly toward the median line. The lower arch is drawn from measurements of the lower teeth. In case of deformed teeth, as for example peg laterals, the size of the upper arch can be determined from the lower, as it is very unusual to find such a deformity in both arches."

Hawley suggested that "the drawing is kept at hand and at any point in the progress of the work measurements can be taken ... and compared to the case in progress".[57] While Bonwill's arch was described by Hawley as "universally accepted as ideal...."[57] it was not favoured by all dentists.[12,58] In 1917 Williams also described the maxillary anterior teeth as lying on the arc of a circle but in his paper the radius of the circle was determined by the combined mesiodistal diameters of the permanent teeth from the buccal grooves of one first molar to the buccal groves of the other first molar.[17]

Hellman[57] disagreed with the theory that the form assumed by the human dental arch is dependent upon the dimension of certain teeth constituting it. Citing the considerable variation found in numerous skulls he examined, he refuted the use of formula in working toward the natural arch form in malocclusion cases.

Although the Bonwill-Hawley theory has been largely discredited[12,58,59] the arch form is very similar to one of the standard arch form templates (3M Unitek) in use today. A circular anterior arch form was more recently advocated again by Interlandi.[60] Based on the study of nearly 200 cases, Interlandi developed a method for establishing the anterior arch form as a "perfect curve". The radius of the curves varied from 18 to 22 mm. In the technique proposed by Interlandi "Radius Curvature" templates were related to the vestibular surfaces of the lower front teeth, including the canines, and used to choose the best lower incisor curvature for orthodontic treatment.

G.V. Black[11] wrote "The upper teeth are arranged in the form of a semi-ellipse, the long axis passing between the central incisors. In this curve the cuspids stand a little prominent....In different persons there is much variation of the form of the arch within the limits of the normal. Occasionally the bicuspids and molars form a straight line, instead of a curve, and frequently the third molars are a little outside the line of the ellipse....The incisors are arranged with their cutting edges forming a continuous curved line from cuspid to cuspid and this line is continued over the cusps of the cuspids and buccal cusps of the bicuspids and molars. The lower teeth are arranged similarly but on a slightly smaller curve .... in occlusion the buccal cusps of all the upper teeth project a little to the labial of the lower at all points of the arch". See Figure 1.1.

In 1907 Angle[12] described "one true line of occlusion, or the line with which each tooth must be in perfect harmony if in normal occlusion..." as being "more or less of a parabolic curve, [which] varies within the limits of the normal, according to the race type and temperament, etc., of the individual." He wrote further that "it is difficult to determine exactly what the form of this line should be in each given case." Angle characterized Hawley's use of the Bonwill law as ingenious but not accurate in determining the curve of the occlusion. Angle stated that the orthodontist can only relate the teeth normally and correct the general form of the arch and leave the fine adjustments to natural forces.

Izard's[59] 1927 study on skulls with normal arches from the Museum of Natural History in Paris, described the frequency of arch forms distinguished as 75% elliptical, 20% parabolic, and 5% other (square or "U" shaped).

The catenary proposed by MacConaill and Scher[61] as the ideal curve of common occlusion was the curve assumed by a fine chain when suspended by its ends and allowed to hang freely. The curvature of the catenary was not constant – being greatest at its apex and least at its points of suspension. Unlike the parabolic curve, "its arms do not tend to approximate to straight lines; they are always curved, however slightly."[61] MacConaill and Scher observed 25 upper and lower casts and found that the average curve closely fit a catenary curve, having an apical radius of curvature of 1.5 cm with small variation amongst the persons of Northwestern European descent studied. They stated that the catenary was a curve of minimal extraneous force and represented the ideal human dental arcade. The concept of a catenary curve has been satisfactorily applied to embryonic dental arches and to the study of dental arch perimeter in orthodontic therapy.[15,62,63]

Brader[10] hypothesized that the dental arch was made up of teeth in unique positions along a compound curve representing an equilibrium of counterbalancing forces of the oral tissues. Brader cited the study of 25 superior untreated occlusion cases evaluated by computer analysis which showed the ellipse was particularly consistent for describing the facial surfaces of the maxillary teeth. From other investigators' data on resting pressures, Brader developed a formula to explain the average mandibular pressure profile. Brader determined that along the buccolabial curve of the dental arch the pressure P, when multiplied by the radius R, produced a mathematical constant C. According to Brader the equation PR=C reveals an inverse relation between pressure and radius of curvature such that the tighter the curve the greater the pressure per unit area. The oral pressure studies showed higher values at the anterior of the mouth where the radius of the curvature was the smallest. Brader stated that this may explain why the anterior teeth evidence the most crowding and least stability after orthodontic treatment. He proposed the "trifocal ellipse" with three internal foci in a closed compounded elliptical curve to best approximate the curvilinear geometry of the dental arch form. The Brader arch forms are alike in shape and differ in size as dictated by the widths at the second molars. The constricted end of the trifocal ellipse used by Brader generally resulted in a narrowing in the cuspid areas.[58]

The original mandibular intercanine width has been used to determine arch form during treatment.[64] Arch guides or templates and computer assisted programs have also been used to determine the ideal arch form for an individual patient.[10,60,65] White[58] described the Rocky Mountain Data Systems computer derived formula, which relies on measurements taken from cast width and depth measurements. White noted that the Bonwill-Hawley, Brader, Catenary and Computer-derived arch design techniques agreed that the anterior part of the arch was a curve but disagreed as to the shape of that anterior arc. He undertook a study of 24 superior untreated adult occlusions and found that only 8% of the Bonwill-Hawley designs could be considered a good fit, while 40% were moderately good fits and 52% were poor fits. The Brader arch design had 12% good fits, 44% moderately good fits and 44% poor fits. The Rocky Mountain design had 8% good fits and 92% moderately good fits. Asymmetry played a role in the poor fits. White concluded that no universal arch form seemed generally applicable and there were many small individual variations in arch shape.

Many studies have sought to predetermine a geometric arch form on the basis of landmarks recorded on systems of coordinates.[58,65-69] Currier[70] in a study of radiographs of 25 dental casts (the same casts cited by Brader) defined three separate curvatures as the outer, middle and inner curves of the arch. A set of reference lines were established, and relative x and y coordinates were recorded for each of the three curves and analysed by a "modified least squares curve fitting program". Statistical analysis of the data showed that the parabola showed the least variance for the middle curve in the mandible, and the ellipse showed the least variance for the outer (facial) curve in both the mandible and maxilla. Jones and Richmond[16] used a three-dimensional Reflex Plotter linked to a computer to study the validity of the fit of computer generated parabolic curves to dental arches. They found that the parabola fit the middle curve of post treatment mandibular arches the best.

Sanin et al.[66] stated that the fitting of a curve by mathematical function gives the most accurate and reproducible representation of the size and shape of the dental arch. There are many ways to determination of the length of curves using "mathematical functions such as exponential, logarithmic, elliptical, parabolic, hyperbolic, the Fourier series, polynomial, and the transcendental functions."[66] The polynomial functions of the fourth and the sixth degrees are the most described.[66,71] The polynomial function of the sixth degree used in Raberin et al.'s study was stated to be of minimal complexity and enabled them to trace curves through seven cast reference points.[68] According to Lu[69] the fourth degree polynomial is the easiest curve to fit that also adequately describes the dental arch. Felton et al.[72] computer digitized and generated arch forms using a polynomial function of the fourth degree on three samples of mandibular orthodontic casts. No particular arch form predominated in any of the samples. The PAR and Vari-Simplex arch forms approximated 50% of the cases and the remaining 50% displayed a wide variety of arch forms. Customizing arch forms was recommended by the authors because of the great individual variability in arch form.

Braun and Hnat[73] used a Micro-Val Coordinate Measuring Machine (Brown and Sharp) to record coordinates in three dimensions of the cusp tips, interproximal contacts and incisal edges of the anterior teeth on 21 mandibular casts. A planar projection of the anterior segment was obtained by reducing the Z coordinates for each point to zero. The authors applied the analytic equation of a hyperbolic cosine function to describe the relationships between intercanine width, anterior segment depth, anterior arch perimeter and incisor angulation. Braun and Hnat suggest the equation could be used to predict the changes in anterior segment arch depth and incisor angulation that would occur with changes in intercanine width.

1.6.7.2 Sectorial Analysis of the Dental Arch and the Use of Ratios In Arch Analysis

Robnett[18] used three reference measurements of the mandibular arch: canine width, molar width and the sum of the mesiodistal diameters of the anterior teeth to outline a "segment concept of arch pattern design". It was Robnett's opinion that arch shapes are inconsistent combinations of non-linear figures and that components of arch shapes can be recognized as segments. Data from 555 dental patients were used to develop arch patterns which can be individualized to a specific arch form. Three primary lines comprise the segment concept in arch pattern design: arc of anterior segment, premolar line and molar line. Once precisely measured, the arch segments can be uniquely grouped to comprise an individual arch pattern. Canine width is viewed as inviolable and for a given canine measurement a limited cluster of anterior arch lengths and intermolar dimensions would occur. The anterior segment forms a semicircular convexity, "its arc having a chord equal to the canine width and length equal to the sum of the mesiodistal diameters of the anterior teeth".[18] This arc is then joined to the premolar and molar segments, forming a pattern that conforms to the line made connecting the contacts as in an ideal arch – using the molar widths and visualization of the roots centered in the alveolar bone.

Arch width and arch depth have been used to determine an analysis of the dental arch in several investigations. Raberin et al.[68] defined five mandibular dental arch forms in a study of 278 dental casts of untreated French adults with normal occlusions (as defined by a full complement of permanent teeth, Class I occlusion without midline deviation, and a clinically acceptable symmetry of mandibular arch). The dimensions of the dental arches were evaluated with three transverse and three sagittal measurements. The arch breadth was evaluated from: the intercanine width, the intermolar width between the first molars, and the posterior intermolar width between the second molars. The arch length was evaluated in the mid-sagittal plane by: the canine depth, first molar arch length, and the total length measured from the incisal edge to the line joining the distobuccal cusps of the second molars. Five independent ratios were determined by dividing the width of each sector by its length, and by dividing the anterior width by the first molar width plus dividing the anterior length by the first molar length.

The mandibular anterior ratio (L31/L33) characterized the anterior curve according to Raberin et al. and was calculated from the data presented in their paper. When the depth of the anterior arch (measured between the interproximal contact of the central incisors to the line connecting the right and left canine cusp tips) was divided by the intercanine width (measured at the cusp tips) the mean ratio was 0.21 for the entire sample. The ratio of depth over width was 0.217 for females and 0.207 for males. Distributions of the arch forms were not significantly different between male and female subjects. In female subjects all transverse measurements were on average smaller and in the sagittal dimension only the total length was shorter.

Sanin et al.[66] stated that the fitting of a curve by a mathematical function gives the most accurate and reproducible representation of the size and shape of the dental arch. They conducted a study to determine the accuracy of establishing arc length by regression on arch width and arch length (i.e. depth according to definition given).The regression equation derived was arc length = arch width x 0.504 + arch length x 1.525 + 14.856 (in mm). The standard error of the estimate was 1.532 mm.

Sanin et al.'s results showed that two easily obtained linear measurements used in a simple formula gave an estimation of the arc length of the dental arch close to the estimate obtained by the fitting of a fourth degree polynomial. The coefficient of multiple correlation was 0.97 between the independent variables arch width and arch length, and the dependent variable, arc length.

Lavelle[74] compared the results of three simple objective techniques for arch analysis, in an investigation on dental age change using computation of dental arch area, dental arch index and the determination of the length of the outer circumference of the dental arcade as the methods of arch analysis. A series of measurements of dental arch widths and dental arch lengths between teeth were used in all three analysis techniques. Lavelle examined dental arch growth in a cross-sectional study of Caucasoids, Mongoloids, and Negroids using over 2000 sets of casts with intact normal arches – without gross discrepancies or imbrication, and exhibiting parabolic arch forms.

The effect of age on the dental arches from the three groups was computed and assessed by the three methods: Dental Arch Area was derived by summing the areas of trapezoids created by the measurements of arch width and length; Dental Arch Index was determined by the ratio of intercanine width to total summed arch lengths and expressed as a percentage; and, Length of Arc of Dental Arcade was calculated using an approximate formula for the length of the arc of a parabola. The data from this study showed that the computation of dental arch areas and dental arch indices proved sensitive to the age changes in the arch dimensions in the three ethnic groups studied. The arc lengths were approximately 14% greater in the maxillary than in the mandibular arches, in all ethnic groups, throughout all age ranges, in both males and females. The first two methods illustrated marked changes in arch dimensions during growth spurts, and are simply applied and helpful in comparative arch analysis.

1.6.7.3 Arch Form and the Anterior Bolton Analysis

Steyn et al.[19] presented a table to use in predicting changes in anterior arch length based on changes in arch circumference. According to Steyn et al., the formula used by clinicians in constructing Visual Treatment Objectives (VTO), which states that a 1 mm sagittal change will require 2 mm of arch circumference compensation, does not hold true for the anterior teeth. Posterior to the canines this formula is acceptable for the average arch form because the teeth are nearly parallel to one another in the distal segments. Under the assumption that the anterior arch form from canine to canine is parabolic in shape, Steyn et al. adapted a mathematical equation for parabolas and computed the correlation between arch length and arch circumference at various intercanine widths. The authors suggest the tables can be used to construct accurate VTO during treatment planning where anterior crowding or spacing is present, and to predict the approximate arch length change needed to correct a Bolton discrepancy.

Halazonetis[21] assumed a circular shape for the anterior arch segment from canine to canine and developed a speadsheet program to examine the effects of the mandibular arch radius and the difference between the upper and lower arch radii on the Anterior Bolton Index. The quantitative assessment of the labiolingual thickness of the incisor teeth and the curvature of the anterior arch segment were evaluated through changing values in a speadsheet model. In Halazonetis' computed model small changes in incisor thickness changed the Bolton ratio. By altering the radius and changing from a curved to a flatter anterior segment, as in broad square shaped arches, the Bolton ratio increased in the model. Halazonetis suggested that changing the anterior arch form could change the Anterior Bolton ratio and therefore be useful in treating anterior tooth size discrepancy. A maxillary deficiency could be treated by flattening the anterior curvature, while a maxillary excess could be theoretically treated by increasing the convexity. The anterior curvature changes were applied to both the mandibular and the maxillary arch radii to effect the described changes in the Anterior Bolton ratio. Halazonetis acknowledged that many assumptions were involved in this model and that the results should be viewed with caution until further studies were done. The speadsheet used in his article required manual inputting of the tooth size measurements. The spreadsheet calculation of the Bolton ratio gave the corrected value for both arches but did not calculate the actual discrepancy in tooth sizes for the arches.

Epker and Fish[30] suggested that changing the anterior arch form from a gentle to a tighter curve resulted in a reduced overjet unless the upper arch length was increased to maintain the same canine relationships. Cordato's mathematical model of anterior inter arch relationships supported this premise when hypothetical measurements were used.[20] The anteroposterior differences in arch depth gradually increased as the angles of curvature of both arches increased.[20,75]

1.6.7.4 Gender and Arch Form

In most studies, the arch dimensions depend on the sex of the subjects, with smaller dimensional values in women.[68,74,76] The dental arches of the women in Raberin et al.'s study had smaller transverse measurements, but no significant differences in the distribution of the types of arch forms were found between male and female subject in the study. The females had slightly more convex anterior arch sectors. The canine depth was not significantly related to sex.

1.6.8 Summary of Arch Form and the Anterior Bolton Analysis

A variety of descriptions have been applied to the form of the dental arch. Bonwill[55] outlined a set of geometrical principles which he believed provided the form of an ideal arch. Hawley's early 20th century adaptation of Bonwill's principles used a portion of a circle to position the incisors and based the radius of the anterior curve on the combined mesiodistal widths of the central, lateral, and canine teeth.[56] Various other types of conic sections, such as the ellipse, parabola, trifocal ellipse, and the catenary curve have been used to characterize arch shape.[10,11,12,15,16,61]

Many studies have sought to predetermine a geometric arch form on the basis of landmarks recorded on systems of coordinates.[58,65-67] Other studies have used polynomial functions in the fitting of a curve to give an accurate and reproducible mathematical representation of the size and shape of the dental arch.[69,71]

Measures and ratios of arch dimensions have been used to analyse dental arch form. Two easily obtained linear measurements, arch width and arch length, have been used to provide estimations of arch form.[66] Arch widths and arch lengths have been used in the computation of dental arch area, dental arch index, and length of arc of dental arcade.[74] Dimensional ratios using sagittal and transverse measurements have also been used to determine a sectorial analysis of the dental arch. According to Raberin et al., the ratio of depth of the anterior arch and the intercanine width characterized the anterior curve.[68]

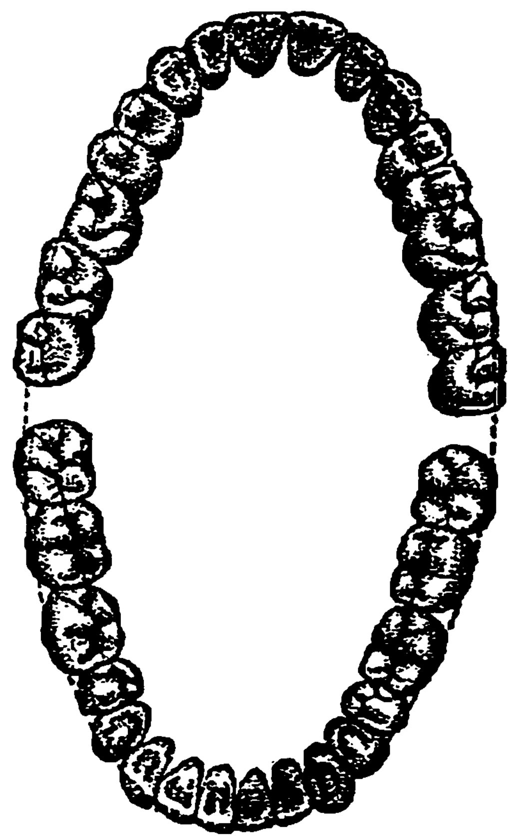
The degree of curvature is most evident in the anterior of the dental arch,[10,17,18] although a review of the literature revealed few articles that specifically dealt with arch form or curvature in relation to the Anterior Bolton Analysis.[19,20,21] The reported investigations have primarily used mathematical equations or theoretical models to develop tables and offer hypothetical findings relating the Anterior Bolton Analysis and the curvature of both maxillary and mandibular arch forms.[19,20,21,30,75] However, definitive studies on the relationship of arch curvature have not been reported.

Table 1.1 Key Investigations Reporting Intra Arch Tooth Size Ratios

Author Year	# Cases	Type of Occlusion	Ratio	Mean (percent ratio)	SD	Range (%)	Description
Tonn* 1937	50	excellent	Md4/Mx4 anterior	74.1	2.4	67-81	incisors only
			Md12/Mx12 overall	92.5	1.8	87-98	
Neff 1949	200	not described	Mx6/Md6	1.20-1.22 inverted 82.6	-	1.17-1.41	"Anterior Coefficient"
Bolton (MSc 1952) Published 1958	55	excellent 44 orthodontic treated (non exo) 11 naturally occurring	Md6/Mx6	77.2	1.65	74.5-80.4	Bolton Anterior Index
			Md12/Mx12	91.3	1.91	87.5-94.8	Bolton Overall Index
Lundstrom 1954 (1981)	264	random occlusions	Md6/Mx6	78.5	2.1	73.0-85.0	Index I
		63 random occlusions	Md12/Mx12	92.3	2.1	88-98	Index S
		8 excellent	Md12/Mx12	91.9	-	87-93	Index S
Ballard 1956	400	general orthodontic cases	Md6/Mx6	compared to denture tooth ratio of 75%: +2 mm Md excess	-	-	
		excellent 20 treated orthodontic cases (10 = 4 bicuspid extraction cases, 10 = non exo)	Md6/Mx6	compared to denture tooth ratio of 75%: +1.2 mm Md excess	-	-	
Neff 1957	300	malocclusions	Md6/Mx6	79.0	-	73.0-85.0	
Stifter 1958	58	ideal and normal	Md12/Mx12	91.04	1.90	87.2-94.6	
		34 normal	Md6/Mx6	78.59	2.37	73.5-83.3	
		24 ideal	Md6/Mx6	77.55	2.72	72.5-81.7	

* reported by Lundstrom, 1981, from Tonn's data

Figure 1.1 Arch Form as Described by G. V. Black*



(* diagram from Black[11], 1902)

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Chapter Two

Research Paper One

Validity of the Bolton Analysis Within a Sample of Non-Orthodontically Treated Optimal Occlusions and Comparison of Low and High Ranked Anterior Bolton Analysis Ratio Cases

Chapter Two Research Paper One

Validity of the Bolton Analysis Within a Sample of Non-Orthodontically Treated Optimal Occlusions and Comparison of Low and High Ranked Anterior Bolton Analysis Ratio Cases

2.1 Introduction

Tooth size disproportions between the maxillary and mandibular arch are not uncommon[1-5] and the effects of the disproportion may become especially apparent in the finishing stages of orthodontic treatment.[3,6] Bolton's Analysis has been used in orthodontic diagnosis for over 35 years to identify tooth size discrepancies that might create occlusal disharmony.

Bolton's original work was conducted on a sample of 55 cases carefully selected for the presence of excellent occlusions, 44 were orthodontically treated cases and 11 were untreated.[7] The total number of subjects with naturally occurring excellent occlusion was relatively small in his study. The sample was not identified by gender.

Several studies have analysed tooth size discrepancy using inter arch ratios on various numbers and types of cases. The key investigations are summarized in Table 2.1. Neff's "Anterior Coefficient" when inverted gave a ratio of 82.6.[1] Lundstom[8] used excellent occlusions to study the posterior ratio only. Stifter[9] conducted part of his study on 24 "ideal" natural occlusions using both the anterior and overall analyses. This was the only study besides Bolton's to use ideal cases to quantify the anterior six tooth ratio. The other studies with larger samples were conducted on random malocclusions. It would be helpful to know if Bolton's Anterior and Overall Analysis results could be replicated in a sample of naturally occurring ideal occlusions. It would also be of clinical benefit to know if there are different ratios for males and females.

Bolton and others have discussed the effects of overbite, overjet, and angulation on the Bolton Analysis.[1,6,10,11] Correlations between Bolton ratio values and inter arch parameters such as overjet, overbite and interincisal angle have not been fully evaluated within a sample of naturally occurring ideal occlusions.

The purposes of this retrospective comparative study are to determine the validity of the Bolton Tooth Size Analysis using a sample of non-orthodontically treated optimal occlusions, and to evaluate cases with low and high ranked Anterior Bolton Analysis ratios for possible correlations with other occlusal parameters.

2.2 Materials and Methods

Sample

The sample for this study consisted of study casts from 88 individuals, 39 males and 41 females, with 8 unlabelled as to gender. The casts were chosen from a larger sample of over 120 cases from the L.F. Andrews Foundation collection of Non-Orthodontic-Normals (N.O.N.), located in San Diego, California.

The following selection criteria were used for the casts included in the sample:

- Naturally occurring, non-orthodontically treated optimal dentitions.
- All permanent teeth present to the first molars.
- Angle Class I molar and canine relationships.

- Optimal intercuspation: "straight and pleasing in appearance, a bite which generally looked correct and would not benefit from orthodontic treatment."[12]
- No spacing or crowding greater than 1 mm in total for either arch.
- No rotation of teeth.
- No apparent loss of tooth contour due to attrition or restorations.
- Casts free of obvious distortion or apparent alterations.

The casts selected for use in this study were defined as "optimal" occlusions.

Cast Analysis

Mitoyoto* electronic digital calipers, coupled with a Mitoyoto UP-1 data relay, were used to transmit cast measurements into a 486 IBM clone PC. The outer edges of the tips of both caliper arms were specially milled to fine needle points, and the digital calipers provided readouts in hundredths of a millimeter. See Appendix C for details on hardware and software.

A data-gathering system was developed utilizing the calipers and computer to aid in record keeping and to replace tables or charts traditionally used in Bolton's Analysis.[3,4] Software was customized to record measurement data and a spreadsheet was designed to subsequently calculate the anterior and overall tooth size discrepancies directly from the tooth width measurements. See Appendix D.

(* Mitoyoto MTI Canada Ltd., Mississauga, Ont., ABS Digimatic Caliper)

Procedure

The upper and lower models were measured on site and the following measurements were obtained for each set of casts:

- Mesiodistal widths were determined for the twelve maxillary and mandibular teeth from the right first permanent molars through the left first permanent molars. The widest portion of each crown was measured with the tips of the calipers held parallel to the incisal edges or occlusal surfaces.[13-17] (Figure 2.1)

- Overjet was obtained by measuring the distance projected parallel to the occlusal plane, between the labial surface of the maxillary central incisors, at midpoint of the incisal edge, to the labial surface of the directly opposing mandibular incisor. The overjet between right and left sides was averaged. (Figure 2.2)

- Overbite was assessed by first measuring the height of the incisal edge at the midpoint of the labial surface of each maxillary central incisor. Second, the incisal edge of the opposing mandibular incisor was measured at the point which corresponded, mesiodistally, to the midpoint of the maxillary central incisor. The average distance between maxillary and mandibular central incisor edges was then calculated and used as the overbite. (Figure 2.3 a, b, c, and d)

The following derived measurements or calculations were obtained:

- Maxillary and Mandibular Incisor Torque values were obtained from Andrews' published data of optimal cast measurements.[18] Andrews measured the angle between a line perpendicular to the occlusal plane and a line tangent to the midpoint of the facial axis of the maxillary or mandibular incisor clinical crowns as viewed "from the mesial or distal perspective, the tangent being equidistant from the gingival and incisal portions of the crown."[18] (Figure 2.4) Seventy-one of the 88 cases in this study were included in the published data. The average of the right and left central incisor measurement was calculated and used as maxillary or mandibular torque for these cases.

- Interincisal Crown Angle was defined as the "combined angle between the occlusal plane and a line tangent to the midpoint of the facial axis of the maxillary and mandibular incisor clinical crowns".[18] To calculate the interincisal crown angle in each case, the maxillary and mandibular central incisor torque values obtained from Andrew's published data[18] were subtracted from 180 degrees. (Figure 2.5)

The landmarks and parameters measured or calculated are listed in Appendix E. The 88 cases selected for the final sample were analysed for inter arch tooth size discrepancy. Anterior and the Overall Bolton Analysis ratios were established in the same manner as described by Bolton for each case in the sample:

The *anterior ratio* was derived by dividing the sum of the mesiodistal widths of the six mandibular anterior teeth, by the sum of the widths of the opposing six maxillary anterior teeth, and multiplying by 100 to obtain a percentage.

The *overall ratio* was obtained by dividing the sum of the mesiodistal widths of the twelve mandibular teeth, by the sum of the widths of the opposing twelve maxillary teeth, and multiplying by 100 to obtain a percentage.[7]

Reliability and Error Determination

Inter Examiner Reliability

Six sets of casts were measured on two occasions, at least one day apart, by four senior orthodontic graduate residents to establish inter examiner reliability in a pilot project. Anterior Bolton ratio measurement reliability was determined for averaged ratings using the Analysis of Variance. The inter examiner reliability index was equivalent to the average correlation between all pairs of raters[19] and the reliability of K = 4 raters was 0.953 for the pilot project. There was a high degree of reliability between the examiners[19] for the Anterior Bolton ratio results.

Intra Examiner Reliability

Measurements on seven sets of casts were taken by one investigator on two occasions, separated by at least one day, and analysed for intra examiner reliability. The repeatability or Reliability Coefficients comparing the first measurement to the second for each individual parameter ranged from 0.938 to 0.998. When analysed in combination the Reliability Coefficient for the Anterior and Overall Bolton values was 0.955 (Appendix F). The standard deviations of the Anterior Bolton ratios taken between time one and two ranged from 0.22 to 1.31% for the seven cases. The standard deviation of the Anterior Bolton ratio averaged over seven cases was 0.67%.

Tooth Size Measurement Error

The average standard deviation for individual tooth size measurements ranged from 0.09 to 0.13 mm for the twelve individual anterior teeth when all examiners' figures were evaluated for tooth size measurement error. The average standard deviation between time one and two for all anterior tooth measures for all four examiners was 0.11 mm. These findings are similar to the error values reported in other studies.[15,20,21]

Statistical Analysis

The means, standard deviations, and ranges were computed for both the Anterior and the Overall Bolton Analysis ratios using SPSS for MS WINDOWS Release 6.1. These values were compared to the Bolton study values using Independent t-Tests to identify statistically significant differences between the two groups studied. The sample was also analysed for differences between genders in both the Anterior and the Overall Bolton Analyses using Independent t-Tests.

In addition the cases in the study were rank ordered according to their calculated anterior Bolton ratios. Those with a low anterior Bolton ratio, relative mandibular deficiency/ maxillary excess, were compared to those ranked as high anterior Bolton ratio cases in order to search for clinically significant differences between groups for a number of measured and calculated parameters. Cases approximately ±1 SD from the sample mean anterior Bolton ratio were selected for comparison. Cases ranked 1 to 16 had low anterior Bolton ratios and cases ranked 73 to 88 had high Bolton ratios. Statistically significant differences were examined between the sixteen lowest and highest anterior Bolton ratio groups for the variables maxillary perimeter, mandibular perimeter, overjet, overbite, incisor torque, and interincisal angle using Independent t-Tests. For all statistical analyses performed the level of significance was set at 5%.

2.3 Results

1. The Anterior Bolton ratio values were approximately normally distributed as displayed in the histogram in Appendix G. Superimposed over the histogram is the normal distribution curve for the mean and variance of the 88 case sample data.
2. Bolton ratios results obtained for the optimal occlusion sample of 88 cases were not significantly different from Bolton's Indices for the Anterior and Overall Bolton Analysis (p-value > 0.05). See Table 2.2 for comparison of ratio values.
3. The mean tooth widths recorded in the present investigation were smaller than Bolton's average tooth sizes. The mandibular incisors, and the second bicuspids and first molars in both arches, were statistically significantly smaller (p-value > 0.05). Tooth width statistics are shown in Table 2.3.
4. Tooth size discrepancy ranged from a mandibular deficiency of 3.72 mm (or a maxillary excess of 4.83 mm) to a mandibular excess of 3.74 mm (or a maxillary deficiency of 4.84 mm). (See Table 2.4)
5. Average incisor overjet was 2.23 mm and ranged from 0.93 to 4.72 mm. (Table 2.4)
6. Average incisor overbite was 2.43 mm and ranged from 0.32 to 5.89 mm. (Table 2.4)
7. Mean interincisal crown angle was 175.26 degrees and ranged from 157.0 to 189.5 degrees. Bolton's value of 177 degrees and definition for this measure was similar.
8. Anterior Bolton Analysis ratio mean was 76.82% for males and 76.42% for females. Overall Bolton Analysis ratio mean was 91.21% for males and 90.81% for females. There was no statistically significant difference in ratios found between males and

females in either analysis when the sample was evaluated using Independent t-Tests (p-value > 0.05). (Table 2.5)

Comparison of the Low Anterior Bolton Ratio group to the High Anterior Bolton Ratio group (Table 2.6 and Table 2.7) gave the following results:

1. The Anterior Bolton Analysis ratio mean was 73.44% for the Low group and 80.23% for the High group with a statistically significant difference, p-value < 0.01.
2. The Overall Bolton Analysis ratio mean was 89.49% for the Low group and 92.79% for the High group with a statistically significant difference, p-value < 0.01.
3. The mandibular six anterior width measurements sums were significantly higher for the High Bolton group than for the Low Bolton group (p-value < 0.01), whereas the maxillary measurements sums were on average similar for both groups.
4. Average overbite was significantly lower in the High Bolton group, at 1.85 mm, as compared to 2.99 mm for the Low Bolton group (p-value < 0.01).
5. Average overjet was significantly lower in the High Bolton group at 1.99 mm compared to 2.81 mm for the Low Bolton group (p-value < 0.01).
6. Interincisal crown angle was 176.82 degrees for the Low Bolton group and 171.89 degrees for the High Bolton group on average (0.05 > p-value > 0.025).

2.4 Discussion

The average individual tooth widths recorded in the present study were all smaller than Bolton's tooth sizes, but the ratios of the perimeter sums were not statistically different from Bolton's Indices. Neither the anterior ratio nor overall ratio was statistically significantly different from Bolton's Index. Independent t-Tests of the mean ratio values obtained in Bolton's and the present study yielded p-values greater than 0.05 for both the Anterior and the Overall Bolton Analysis.

The differences in mean tooth sizes may be in part due to Bolton's use of three-inch needle point dividers to measure the greatest mesiodistal diameter of the teeth. Use of dividers gave, on average, a significantly larger measurement of tooth size than did sliding calipers when evaluated in Hunter and Priest's comparative study on discrepancy in measurement of tooth size.[15]

Tooth size discrepancies were minimal on average for the study sample. The mean anterior ratio value of 76.71% relates to a mandibular deficiency of 0.24 mm or a maxillary excess of 0.33 mm. The ranges for excesses and deficiencies in this study were notable: values ranged from a mandibular deficiency of 3.72 mm (or a maxillary excess of 4.83 mm) to a mandibular excess of 3.74 mm (or a maxillary deficiency of 4.84 mm). The range of values for this parameter were not reported in Bolton's study but the mean value would have been zero when Bolton's "ideal" ratio was calculated.

The average overjet measurement for the present study was greater than the average overjet reported in Bolton's study. However the overjet in Bolton's study was measured to the junction of the incisal and lingual surfaces of the maxillary incisor rather than the labial surface of the maxillary incisor as was measured in the present study.[7] Some of the increased difference in overjet could possibly be explained by the effects of the orthodontic treatment in Bolton's sample since 44 of the total 55 cases in Bolton's sample were treated cases.

Non-Orthodontically treated Normal (N.O.N.) or optimal cases are described by Andrews as individuals with occlusions that do not require or would not benefit from orthodontic treatment18 in his opinion. Presumably these cases were clinically acceptable in esthetics and function. The author's visual examination of the 88 casts used in this study showed acceptable model occlusion when hand articulated. General esthetics and function were difficult to establish for each case since not all casts had complete records such as photos, slides or radiographs and the majority of casts were unmounted. Most of the cases in the sample were from southern California and some cases came from other American cities. All were Caucasian except for one Hispanic case. Bolton's study did not provide ethnic background.

There was a noticeably wider range of Anterior Bolton Analysis ratio values in the present study compared to Bolton's study. The ranges for the Overall Bolton Analysis ratio values were similar between the two studies.

The wide range of Anterior Bolton ratio values found within this sample of optimal occlusions demonstrates that clinically acceptable occlusions exist with Bolton ratios greater than 1 SD from Bolton's Index value of 77.2%. Compensations for the calculated tooth size discrepancies in this sample likely resulted from combinations of minor spacing or crowding as well as from variations of overjet and or overbite that were within normal ranges. The mean values of this study agree with Bolton's Index values. However there were cases that had clinically significant tooth size discrepancies according to Bolton's Analysis. The anterior tooth size discrepancies were not readily apparent, possibly because these naturally occurring optimal cases were not treated to orthodontic ideals in terms of alignment, overjet and overbite.

The low ranked Anterior Bolton ratio group was compared to the high ranked Anterior Bolton ratio group for a number of parameters, see Tables 2.6 and 2.7. The Anterior and the Overall Bolton ratios were significantly different for each group. The Anterior Bolton ratio was 73.44% on average for the Low group and 80.23% on average for the High group. The net difference in mean anterior tooth size discrepancy between the Low and High groups was 3.2 mm for the mandible and 4.1 mm for the maxilla.

The High Bolton group on average had a significantly larger mandibular anterior perimeter relative to the maxillary arch. The maxillary perimeters were not statistically different for the two groups (Tables 2.6 and 2.7). A difference in maxillary rather than mandibular perimeters between High and Low Bolton groups would be anticipated since the maxillary lateral incisors are the most commonly anomalous teeth that cause clinical problems.[4,22,23] Small maxillary laterals would be generally associated with High Bolton, maxillary deficient cases. By screening the sample and selecting cases with only minimal spacing, the obvious small lateral incisor cases would have been excluded from the sample.

The average overjet measurement was 40% higher in the Low Bolton group, at 2.8 mm compared to 2 mm. An increase in overjet can be seen clinically with Low Bolton cases[10] and could be considered an associated compromise in treatment if the relative maxillary excess were not apparent until the finishing stages of treatment.[2,6,24]

The average overbite measurement was 40% higher in the Low Bolton group, at 2.99 mm compared to 1.85 mm. Bolton and Lundstrom were unable to find statistically significant correlations between overbite and the anterior ratio in their investigations.[7,13,25] If the ideal Bolton Index applies to only moderate overjet and overbite cases, an increase in overjet and/or overbite should be associated with mandibular deficient cases.[1,10] The findings of this study comparing Low and High anterior Bolton groups supports associations between relative maxillary excess with increased overjet and overbite, and between relative mandibular excess with decreased overjet and overbite.

The variation in interincisal crown angle between the Low and High Bolton groups was due mainly to a significant difference in the mandibular central incisor torque. The mandibular central incisor torque was minus 4.6 degrees in the Low Bolton group and plus 1 degree in the High Bolton group. The average for the entire 88 case sample was minus 1.86 degrees. The lower incisors were significantly more retroclined (p-value > 0.05) in the Low Bolton group. This may be related to the increase in overjet and overbite also found in this same group (Table 2.6).

The Overall Bolton Analysis mean ratios were significantly different (p-value > 0.05) between the two groups, at 89.49% for the Low group and 92.79% for the High group. The primary reason for the difference in overall ratios between groups was a relative increase in overall mandibular perimeter alone, at 84.2 mm for Low and 87.4 mm for High Bolton groups. The maxillary perimeter lengths were nearly identical (similar to the findings for the Anterior Bolton Analysis), at 94.1 and 94.2 mm (Table 2.6).

The following points need to be considered when interpreting Bolton ratios. The result obtained in a Bolton analysis evaluates a relative discrepancy: one arch may be deficient or the other in excess, but either arch can be chosen as the arch for comparison. The application of the ratios results in reversible, but unequal and opposite signed discrepancies. This point is illustrated with two simple examples for the Anterior Analysis: a 2 mm mandibular excess correlates to a 2.6 mm maxillary deficiency, and a 1.5 mm mandibular deficiency correlates to a 2.0 mm maxillary excess. The disparity between the maxillary and mandibular discrepancies is less significant when interpreting the Overall Analysis since the percent ratio of 91.3% is closer to a-one-to one proportion of lower to upper tooth size.

2.5 Conclusions

The validity of Bolton's Tooth Size Analysis Indices were reconfirmed in this study in a sample of 88 non-orthodontically treated naturally occurring optimal cases. Untreated optimal occlusions can have a wide range of Anterior Bolton Analysis ratio values. Comparison of Low and High ranked Anterior Bolton ratio cases showed a decrease in overjet, overbite and interincisal angle and an increase in mandibular perimeter in the higher ranked Anterior Bolton ratio cases in this study. There were no gender specific differences found in the Anterior or Overall Bolton Analysis ratios in this sample.

The findings of this study indicate that a clinically acceptable result may be possible in cases with minor to moderate tooth size discrepancies without tooth size modification and thus individual assessment should be applied in each orthodontic case.

Table 2.1 Key Investigations Reporting Intra Arch Tooth Size Ratios

Author Year	# Cases	Type of Occlusion	Ratio	Mean (percent ratio)	SD	Range (%)	Description
Neff 1949	200	not described	Mx6/Md6	1.20-1.22 (inverted 82.6)	-	1.17-1.41	"Anterior Coefficient"
Bolton 1958	55	excellent 44 orthodontic treated (non exo) 11 naturally occurring	Md6/Mx6	77.2	1.65	74.5-80.4	Bolton Anterior Index
			Md12/Mx12	91.3	1.91	87.5-94.8	Bolton Overall Index
Lundstrom 1954 (1981)	264	random occlusions	Md6/Mx6	78.5	2.1	73.0-85.0	Index I
		63 random occlusions	Md12/Mx12	92.3	2.1	88-98	Index S
		8 excellent	Md12/Mx12	91.9	-	87-93	Index S
Ballard 1956	400	general orthodontic cases	Md6/Mx6	compared to denture tooth ratio of 75%: +2 mm Md excess	-	-	
		excellent 20 treated orthodontic cases (10 = 4 bicuspid extraction cases, 10 = non exo)	Md6/Mx6	compared to denture tooth ratio of 75%: +1.2 mm Md excess	-	-	
Neff 1957	300	malocclusions	Md6/Mx6	79.0	-	73.0-85.0	
Stifter 1958	58	ideal and normal	Md12/Mx12	91.04	1.90	87.2-94.6	
		34 normal	Md6/Mx6	78.59	2.37	73.5-83.3	
		24 ideal	Md6/Mx6	77.55	2.72	72.5-81.7	

Table 2.2 Comparison of Ratios

	n	Mean	SD	Range	SEM	p value for differences
Bolton's Anterior Index	55	77.2%	1.65	74.5-80.4%	0.22	
Optimal Anterior Ratio	88	76.71%	2.43	70.16-85.12%	0.26	p > 0.05
Bolton's Overall Index	55	91.35%	1.91	87.5-94.8%	0.26	
Optimal Overall Ratio	88	91.10%	1.62	87.78-94.86%	0.17	p > 0.05

Table 2.3 Tooth Size Width Values

	Present Study			Bolton's Data			
	Mean*	SD	CV**	Mean*	SD	CV**	
Maxillary Teeth							p value for differences
Central Incisor	8.74	0.53	6.1	8.82	0.42	4.8	N.S.
Lateral Incisor	6.82	0.55	8.0	6.96	0.48	6.9	N.S.
Canine	7.79	0.42	5.4	7.91	0.46	5.8	N.S.
First Bicuspid	6.94	0.42	6.0	7.04	0.46	6.5	N.S.
Second Bicuspid	6.62	0.43	6.6	6.84	0.39	5.7	p < 0.01
First Molar	10.09	0.52	5.1	10.40	0.58	5.6	p < 0.01
Mandibular Teeth							
Central Incisor	5.27	0.37	7.0	5.42	0.31	5.7	p < 0.01
Lateral Incisor	5.81	0.40	6.9	5.94	0.26	4.4	p < 0.05
Canine	6.81	0.46	6.7	6.93	0.37	5.3	N.S.
First Bicuspid	7.06	0.43	6.2	7.15	0.38	5.3	N.S.
Second Bicuspid	6.98	0.46	6.6	7.27	0.39	5.4	p < 0.01
First Molar	10.87	0.57	5.2	11.14	0.62	5.6	p < 0.01

(* in millimeters)
(** percent)
(N.S. = Not Significant difference p > 0.05)

Table 2.4 Parameter Values

Parameter	Present Study			Bolton's Data		
	Mean	SD	Range	Mean	SD	Range
Anterior Ratio (%)	76.71	2.43	70.2-85.1	77.2	1.65	74.5-80.4
Overall Ratio (%)	91.1	1.62	87.8-94.9	91.3	1.91	87.5-94.8
Ave OJ (mm)	2.23	0.68	0.93-4.72	(0.74 to	mid	incisal edge)
Ave OB (mm)	2.43	1.09	0.32-5.89	31.3%		11.8-53.9%
Interincisal Angle (degrees)	175.26	7.37	157.0-189.5	177	not reported	
Mx6 (mm)	46.70	2.49	42.5-53.5	47.38	not reported	
Md6 (mm)	35.81	2.01	31.6-42.3	36.58	not reported	
Mx12 (mm)	93.98	4.06	85.5-105.3	95.94	not reported	
Md12 (mm)	85.62	3.99	76.2-96.8	87.7	not reported	
Md 6 discrepancy (mm)	-0.24	1.15	-3.72 to 3.74	0	not applicable	
Mx 6 discrepancy (mm)	0.33	1.49	-4.84 to 4.83	0	not applicable	

Table 2.5 Bolton Analysis Values for Males and Females

	Males n=39			Females n=41		
	Mean	SD	Range	Mean	SD	Range
Anterior 6 Ratio Optimals (%)	**76.82**	**2.54**	**70.16-85.22**	**76.42**	**2.42**	**72.61- 82.13**
Sum Md 6 (mm)	36.48	1.88	33.19-39.94	34.88	1.66	31.62-38.71
Sum Mx 6 (mm)	47.52	2.64	46.68-53.52	45.65	1.86	42.51-51.61
Independent t-test Anterior Bolton ratio	**Results between**	**for genders**	**differences not significant**	**$p > 0.05$**		
Overall Ratio Optimals (%)	**91.21**	**1.65**	**88.08-94.86**	**90.81**	**1.57**	**87.78-94.06**
Sum Md 12 (mm)	86.72	3.46	80.69-93.57	84.02	3.86	76.20-92.86
Sum Mx 12 (mm)	95.10	3.95	88.02-103.89	92.51	3.63	85.49-101.76
Independent t-test Overall Bolton ratio	**Results between**	**for genders**	**differences not significant**	**$p > 0.05$**		

Table 2.6 Low and High Bolton Anterior Ratio Groups Compared by t-Test Statistics

Parameter	Average of entire sample of 88 optimal cases	Low 16 Anterior Bolton Group Mean	High 16 Anterior Bolton Group Mean	t - Test statistic	t statistic greater or less than	p value Significant difference Low & High Groups
Anterior Bolton (%)	**76.71**	73.44	80.23	-14.16	2.75	p < 0.01
Sum Mx 6 (mm)	**46.70**	47.27	46.22	1.05		N.S.
Sum Md 6 (mm)	**35.81**	34.70	37.08	-3.15	2.75	p < 0.01
Md 6 discrepancy (mm)	**-0.24**	-1.79	1.40	-13.45	2.75	p < 0.01
Mx 6 discrepancy (mm)	**0.33**	2.33	-1.80	13.45	2.75	p < 0.01
Ave OJ (mm)	**2.23**	2.81	1.99	3.19	2.75	p < 0.01
Ave OB(mm)	**2.43**	2.99	1.85	3.21	2.75	p < 0.01
Interincisal Angle (degrees)**	**175.26**	176.82	171.89	2.30	2.042-2.457	0.05 > p > 0.025
Torque 1 Mx (degrees)*	**6.70**	7.75	7.04	0.55		N.S.
Torque 1 Md*(degrees)*	**-1.96**	-4.57	1.07	-3.54	2.75	p < 0.01
Bolton 12 (%)	**91.10**	89.49	92.79	-8.34	2.75	p < 0.01
Sum Mx 12 (mm)	**93.98**	94.10	94.20	-0.06		N.S.
Sum Md 12 (mm)	**85.62**	84.21	87.40	-2.05	2.042-2.457	0.05 > p > 0.025

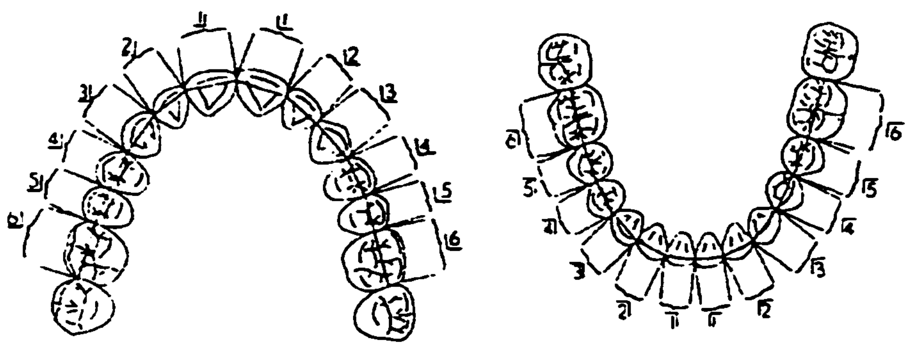
(* directly from, and ** derived from data tables in Andrews LF. Straight Wire: The Concept and Appliance. San Diego, California: L.A. Wells Publisher, 1989.)

(N.S. = Not Significant difference p > 0.05)

Table 2.7 Arch Perimeters for Low and High Anterior Bolton Ratio Groups

	Mandibular perimeter in mm			Maxillary perimeter in mm		
	Mean	SD	Range	Mean	SD	Range
Low Bolton Group	34.70	2.06	31.62-39.33	47.27	3.02	43.27-53.52
High Bolton Group	37.08	2.20	34.35-42.3	46.22	2.60	42.68-52.56

Figure 2.1 Cast Measurements*



Mesiodistal Measures of Tooth Width*

Teeth 1 to 6
All quadrants

(* after Bolton's diagram[7])

Figure 2.2 Overjet

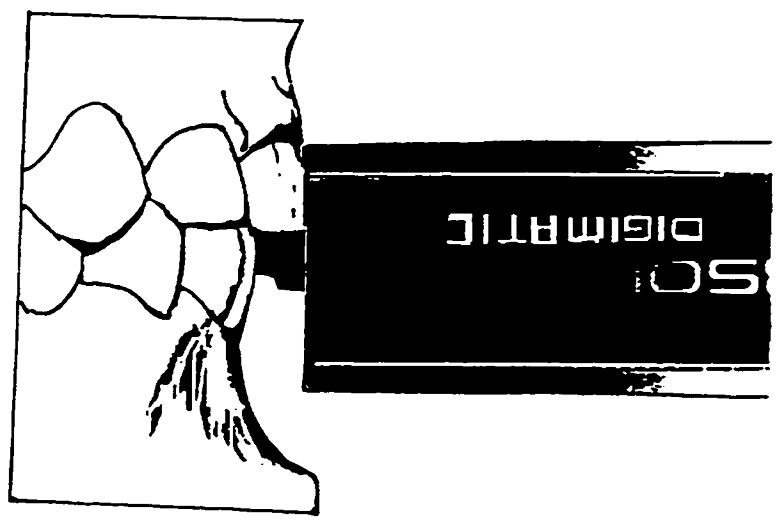


Figure 2.3 Overbite

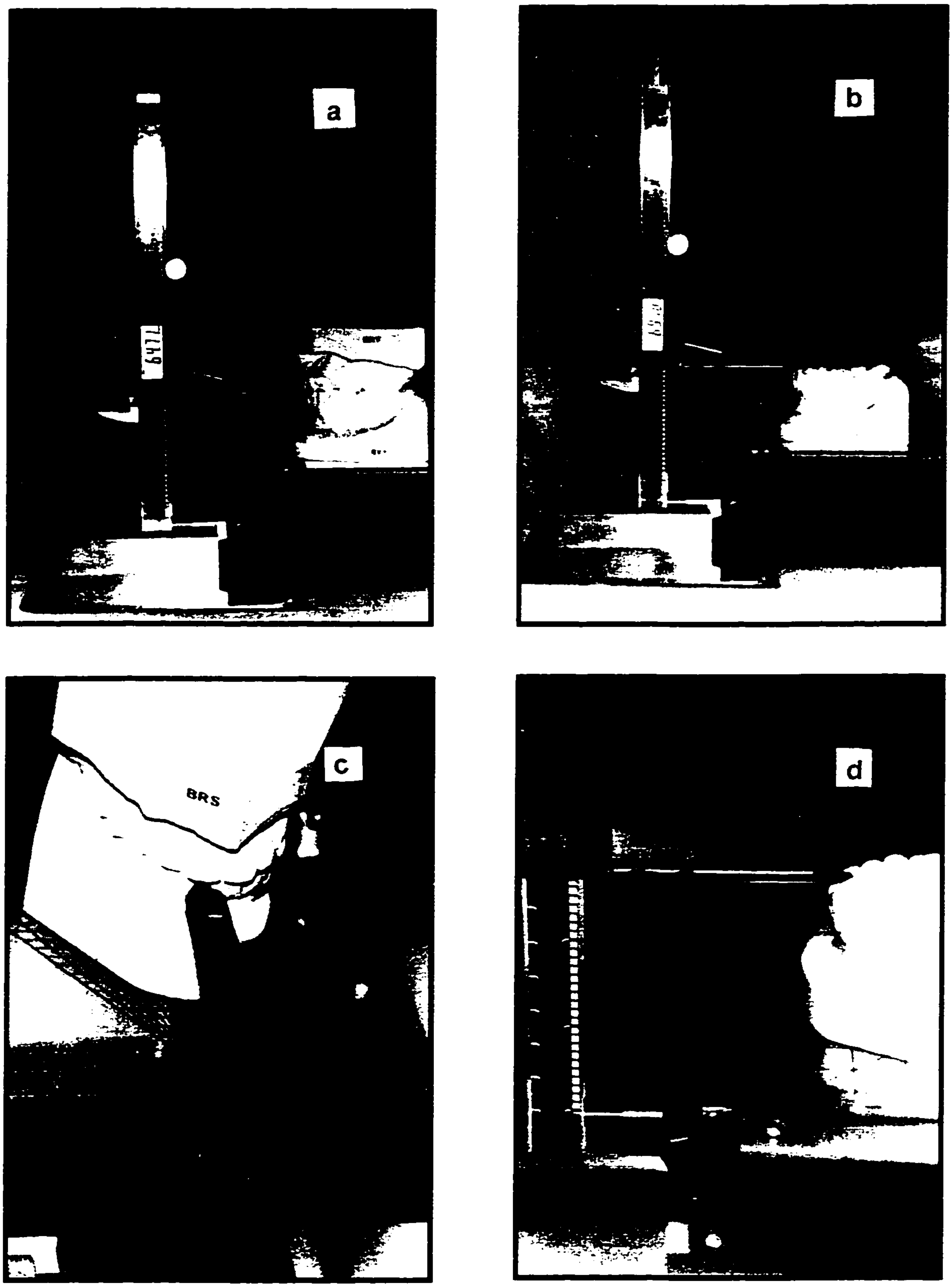
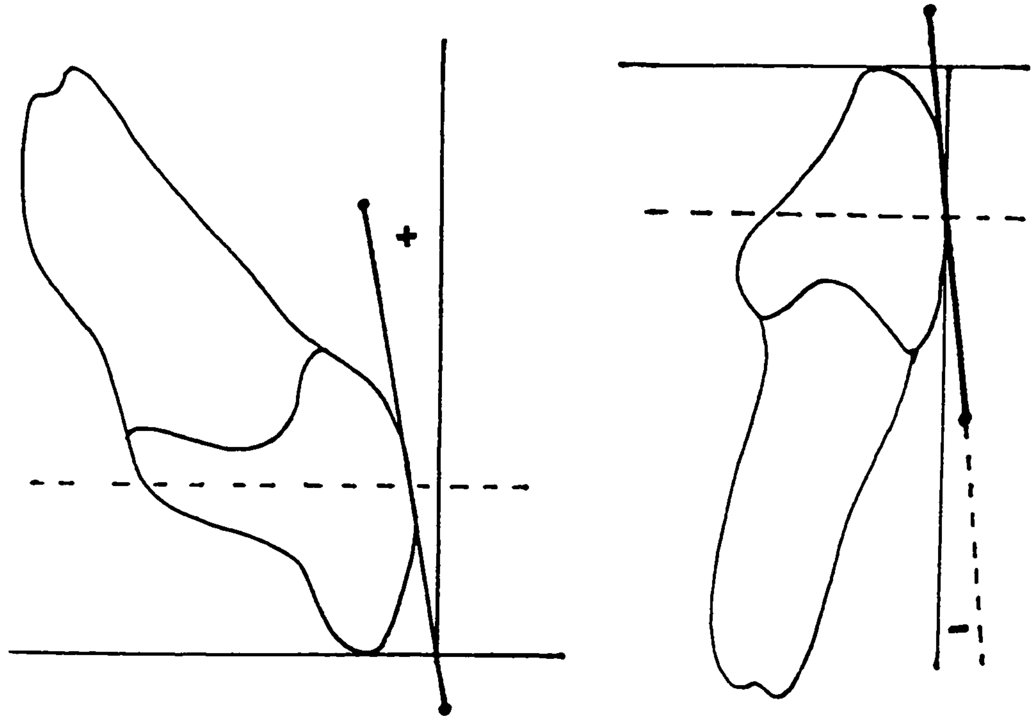


Figure 2.4 Crown Torque*

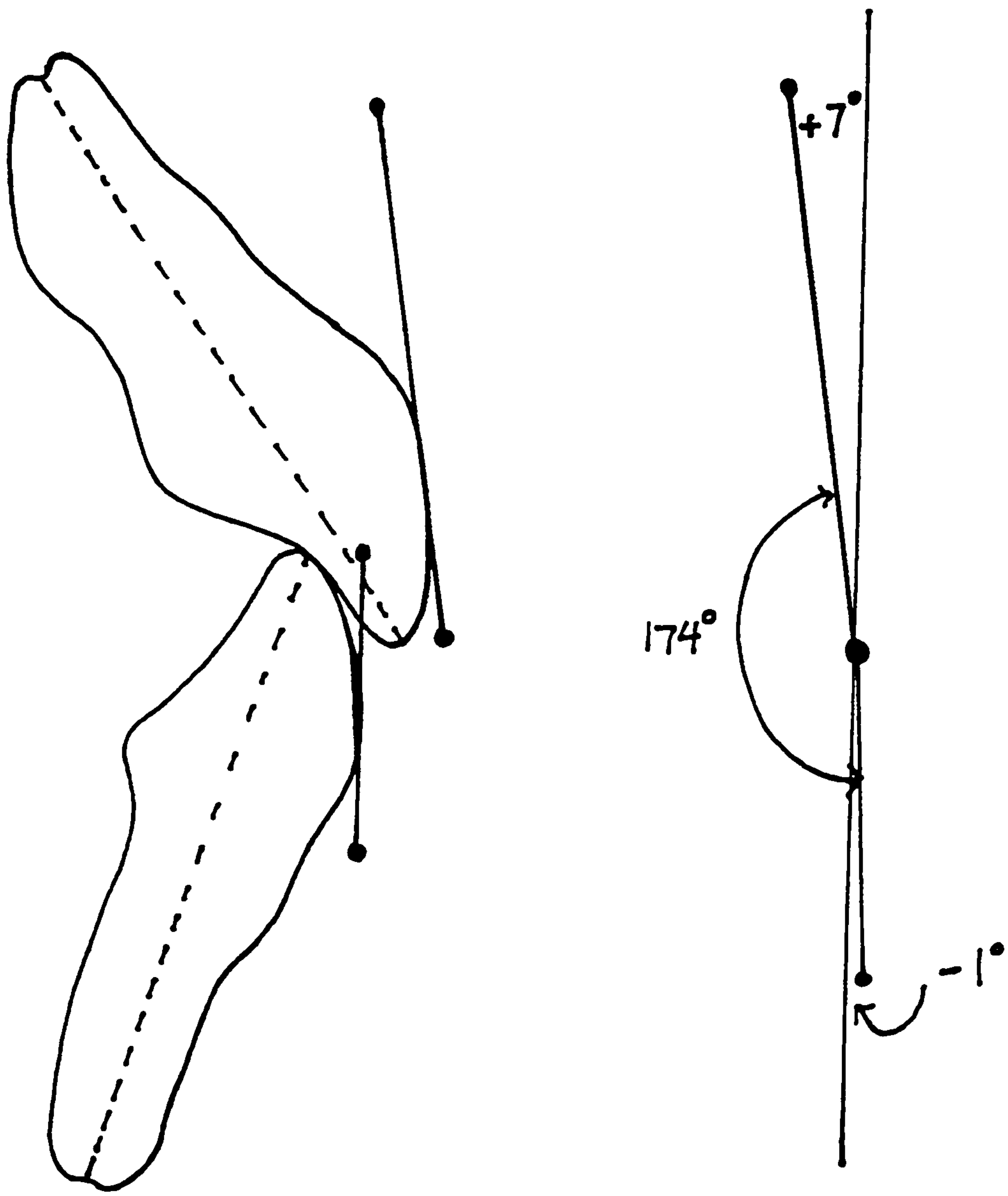


Maxillary Incisor Crown Torque

Mandibular Incisor Crown Torque

(* after Andrews' diagram[18])

Figure 2.5 Interincisal Crown Angle*



180°- (+7°) - (-1°) = 174°

(* after Andrews' diagram[18])

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Chapter Three

Research Paper Two

Pre and Post Treatment

Comparison of the Bolton Analysis

Chapter Three Research Paper Two

Pre and Post Treatment Comparison of the Bolton Analysis

3.1 Introduction

The Bolton Analysis is the tooth size analysis used most often in orthodontics.[1-3] When the analysis is applied, it is performed most often on pretreatment study models to diagnose potential tooth size discrepancies and evaluate different treatment options prior to commencing therapy.[4-6] If significant tooth size discrepancies are identified, potential choices for the patient may include extraction decisions or prosthetic solutions involving important financial considerations. If undetected or misdiagnosed initially, uncompensated tooth size discrepancies may limit coordination of posterior intercuspation or anterior relationships as the case nears completion of treatment.[2,5]

The Bolton Analysis was established in a study of "excellent" occlusions; 44 were treated orthodontic cases and 11 were excellent naturally occurring cases.[7] Several subsequent studies have found similar results when comparing the tooth size analysis of ideal or completed orthodontic cases to Bolton's Index values.[8-10] A number of studies have analysed samples with malocclusions and compared the mean ratio values to Bolton's Indices. These studies reported similar mean values but wider ranges of ratios.[1,11-15]

Tooth width measurements can be made with relative ease on well aligned or excellent dentitions. However, estimation of the ideal interproximal contact points may be required in maloccluded cases, and determining an accurate Bolton ratio may be difficult due to an altered interpretation of the maximum mesiodistal dimensions of the teeth.[2]

Appropriate conclusions on tooth size can be made only if pretreatment measures are similar to the measures attained after alignment. It would be beneficial to ascertain in a randomly selected orthodontic patient sample whether the pretreatment diagnostic information is valid and therefore of assistance in predicting post treatment tooth size relationships.

The purpose of this retrospective comparative study was to perform tooth size analyses on before and after treatment models of orthodontic cases to determine if there were significant differences in the mean Bolton ratio values obtained.

3.2 Materials and Methods

Sample

A sample of 90 cases was obtained from the private practice of an Edmonton-area orthodontist. The orthodontic models were prepared and finished to orthodontic standards. The sample was randomly selected from a ten year archive pool; the first 90 cases encountered that met the criteria were accepted into the study without regard for the specific type of malocclusion.

The following selection criteria were used for the casts included in the sample:

1. Orthodontic treated dentitions with both pre and post treatment casts available for study.

2. Both sets of casts having:
   - All permanent teeth present to the first molars.
   - No obvious distortion or apparent alterations.

3. Post treatment casts evidencing:
   - No treatment that would alter the dimensions of the clinical crowns.
   - Class I molar and canine relationships with an acceptable orthodontic result.

Cast Analysis

Mitoyoto* electronic digital calipers, coupled with a Mitoyoto UP-1 data relay, were used to transmit tooth size width measurements into a 486 IBM clone PC. The outer edges of the tips of both caliper arms were specially milled to fine needle points, and the digital calipers provided readouts in hundredths of a millimeter. See Appendix C for details on hardware and software.

A data-gathering system was developed utilizing the calipers and computer to aid in record keeping and to replace tables or charts traditionally used in Bolton's Analysis. Software was customized to record measurement data and a spreadsheet was designed to subsequently calculate the anterior and overall tooth size discrepancies from the tooth width measurements, Appendix D.

Procedure

The maxillary and mandibular pretreatment and post treatment models were measured. Mesiodistal widths were determined from the right first molar through the left first molar for the twelve maxillary and mandibular teeth for each set of casts: The widest portion of each crown was measured with the tips of the calipers held parallel to the incisal edge or occlusal surface.[16-19]

The 90 cases randomly selected for the final sample were analysed for inter arch tooth size discrepancy using the both the Anterior and Overall Bolton Analyses. The analysis calculations were made separately on both the pretreatment and post treatment models.

(* Mitoyoto MTI Canada Ltd., Mississauga, Ont., ABS Digimatic Caliper)

Reliability and Error Determination

To determine reliability and the size of the measurement error, a pilot project was conducted on casts that met the sample criteria of the main project.

Inter Rater Reliability

Six sets of casts were measured on two occasions, at least one day apart, by four senior orthodontic graduate residents to establish inter examiner reliability in a pilot project. Anterior Bolton ratio measurement reliability was determined for averaged ratings using the Analysis of Variance.[20] The inter rater reliability index was equivalent to the average correlation between all pairs of raters[20] and the reliability of K = 4 raters was 0.953 for the pilot project. There was a high degree of reliability between the examiners for the Anterior Bolton ratio result.

Intra Examiner Reliability

Measurements on seven sets of casts were taken by the principal investigator on two occasions, separated by at least one day, and analysed for intra examiner reliability. The repeatability or Reliability Coefficients comparing the first measurement to the second was 0.941 for the Anterior Bolton Analysis ratio and 0.980 for the Overall Bolton Analysis ratio (Appendix F). The standard deviations of the Anterior Bolton ratios taken between time one and two ranged from 0.22 to 1.31% for the seven cases. The standard deviation of the Anterior Bolton ratio averaged over seven cases was 0.67%.

Tooth Size Measurement Error

The average standard deviation for individual tooth size measurements ranged from 0.09 to 0.13 mm for the twelve individual anterior teeth when all examiners' figures were evaluated for tooth size measurement error. The average standard deviation between time one and two for all anterior tooth measures for all four examiners was 0.11 mm.

Statistical Analysis

The means, standard deviations, and ranges were computed for the ratios for both the pretreatment and post treatment models using SPSS for MS WINDOWS Release 6.1. Correlation coefficients (*r*) were performed between the two sets of casts for both the Anterior and Overall analysis. To determine whether there was a difference in the values of the tooth size ratios of the pretreatment and post treatment models, Paired t-Tests were performed. For all statistical analyses the level of significance was set at 5%. In addition the post treatment cast ratios were compared to Bolton's Index values using the Independent t-Test.

3.3 Results

The means and standard deviations for the pre and post treatment Anterior and Overall Bolton ratios are presented in Table 3.1. The results of the Correlation coefficients (*r*) indicate that there was a significant correlation between the pre and post treatment ratios for both the Anterior ($r = 0.851$) and Overall ($r = 0.779$) Bolton Analysis, as indicated in Table 3.2. There was no statistically significant difference in the pre and post treatment Anterior and Overall Bolton ratios when evaluated by Paired t-Tests. Table 3.3 shows p-value > 0.05 for both ratios.

The post treatment Anterior and Overall Bolton mean ratios of 77.22 and 91.93 compared closely with Bolton's Indices of 77.2 and 91.3 as shown in Table 3.4. No statistical difference was found using Independent t-Tests to compare the Anterior and Overall Bolton mean ratios with Bolton's Indices, with p-value > 0.05 for both ratios, (Table 3.5). The mean Anterior Analysis and Overall Analysis tooth size discrepancy values were less than 0.10 mm and 0.65 mm respectively when calculated for both pre and post treatment casts.

3.4 Discussion

The results from this study show no statistically significant difference in tooth size analysis when performed on casts before and after alignment. In addition the tooth size ratios obtained for the post treatment casts in this study were not statistically different from the Bolton study ratio values. The mean anterior ratio value was nearly identical to Bolton's Anterior Index and the mean overall ratio value was slightly higher than Bolton's Overall Index.[7] The ranges and standard deviations were higher for this study, likely reflecting the fact that the sample consisted of general orthodontic cases and were not "excellent" occlusion cases.

There was a high degree of reliability between the analyses made by different investigators, and intra examiner error was low in the pilot project for the present study. These results are in agreement with the findings of others.[1,2,15]

Based on analysis of 15 pretreatment cases, Shellhart et al.[2] concluded that significant measurement error can occur when Bolton Analyses are performed on crowded models. The results of the present study do not agree or disagree with his findings. Since the sample for the present study consisted of a variety of malocclusions, comment cannot be made regarding error in the analysis of crowded cases alone. The results allow inferences nonetheless about the average likelihood of obtaining different analysis values on pre and post treatment casts encountered in randomly selected nonextraction orthodontic cases.

Adherence to a consistent definition of the mesiodistal definition is important for precise or repeatable measures.[19] The mesiodistal diameter is the crown dimension most frequently reported in dental odontometrics,[21] however numerous interpretations of this dimension appear in the literature. Crown size has been defined as the greatest distance between the points of interproximal contact.[16,22] When a tooth was malaligned, the points where normal contact should occur were used as landmarks by Moorrees and Reed.[16] Hunter and Priest[17] measured the mesiodistal width on the normal contact areas, most often with a labial insertion with the calipers held at a right angle to the long axis. When teeth were rotated the normal contact areas were chosen.

An alternative methodology describes the mesiodistal crown diameter as the maximum mesiodistal dimension, with the two points of the measuring instrument making contact with the tooth parallel to the occlusal plane.[19] Kieser stated that the measures taken tangential to the most mesial and distal points of the crown need not correspond to the points of interstitial contact.[20] This method seems most likely to allow consistent measurements to be performed on malaligned and aligned teeth.

In order to apply the Anterior and Overall Bolton Analysis on both pre and post treatment models, a full complement of teeth from first molar to first molar was required on both sets of casts in the present investigation. Due to the selection criteria, cases that were treated with extractions or with restorative treatment were eliminated. Therefore, extremely high Bolton ratio cases that would have required mandibular incisor extractions or maxillary build-ups were excluded from the sample. Similarly extremely crowded cases requiring other combinations of extractions were not included in this study.

Further extension of this investigation might include a study comparing Bolton Analysis of pre and post treatment of patients classified and compared with regard to the type of malocclusion. In addition a study using a quantifiable index to measure the amount of individual arch or total case spacing or crowding could potentially shed more information on the reliability of the pretreatment Bolton Analysis in specific circumstances.

3.5 Conclusions

The results of this study on a random sample of 90 non extraction orthodontic cases indicate that on average analyses of tooth size are valid when based on pretreatment study models. Pretreatment and post treatment comparison of Bolton's Anterior and Overall Analyses showed no significant differences in results. The mean ratios derived from the post treatment casts in this study were similar to Bolton's Indices but the ranges and standard deviations were larger than the Bolton study values. The clinical implications of this study are that both the Anterior and the Overall Bolton Tooth Size Analyses are valid diagnostic aids in assessing tooth size discrepancy when non extraction orthodontic therapy is being considered.

Table 3.1 Anterior and Overall Bolton Analysis Ratio Results Pretreatment and Post Treatment

n = 90	Mean	SD	Range	SEM	Median
Anterior Ratio PreTx	77.41%	2.41	71.36-82.28%	0.254	77.32%
Anterior Ratio Post Tx	77.22%	2.24	71.82-81.88%	0.236	76.79%
Overall Ratio PreTx	91.78%	1.90	88.31-96.58%	0.200	91.77%
Overall Ratio Post Tx	91.93%	2.01	87.66-97.28%	0.212	91.80%

Table 3.2 Correlation Coefficients of Pretreatment and Post Treatment Bolton Ratios

n = 90	Correlation Coefficient r	p value 2- tailed Significance
Anterior Ratio PreTx to Post Tx	0.851	≈ 0.000
Overall Ratio PreTx to Post Tx	0.779	≈ 0.000

Table 3.3 t-Tests for Paired Samples Comparing Pretreatment and Post Treatment Bolton Ratios

n= 90 (paired differences)	t value	p value
Pre and Post Tx Anterior Ratios	-1.44	0.152
Pre and Post Tx Overall Ratios	1.05	0.292

Table 3.4 Comparison of Bolton Analysis Indices and Post Treatment Ratio Results

	n	Mean	SD	Range	SEM
Bolton's Anterior Index	55	77.2%	1.65	74.5-80.4%	0.22
Post Tx Anterior Ratio	90	77.22%	2.24	71.82-81.88%	0.236
Bolton's Overall Index	55	91.3%	1.91	87.5-94.8%	0.26
Post Tx Overall Ratio	90	91.93%	2.01	87.66-97.28%	0.212

Table 3.5 t-Tests for Independent Samples Comparing Bolton's Indices to Post Treatment Bolton Ratios

df = 143	t value	p value
Bolton's Anterior Index and Post Tx Anterior Ratios	-0.06	p > 0.05
Bolton's Overall Index and Post Tx Overall Ratios	-1.88	p > 0.05

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Chapter Four

Research Paper Three

Bolton Analysis Related to Arch Form

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Bolton Analysis Related to Arch Form

4.1 Introduction

The Bolton Analysis has been used extensively since its development in the 1950's to provide information on inter arch tooth size discrepancy in orthodontics.[1-6] Although the effects of incisor thickness and the degree of incisor inclination have been discussed in the literature,[7-10] the effects of arch form have not been completely addressed in relation to the Anterior Bolton Analysis.[6,11,12] An individual's dental arches and teeth can vary in shape and size.[13-17] A potentially harmonious occlusion may exist among individuals when upper and lower jaws have complementary dimensions of both arch form and tooth structure.[14,15,17]

Dental arch form is determined by the relative positioning of the teeth, alveolar bone and denture base within the jaw.[15] Arch form is influenced by genetic, developmental, functional and environmental factors, and by orthodontic treatment.[13,14,18,19]

A variety of qualitative descriptions have been applied to the form of the dental arch. Bonwill[20] in 1884 outlined a set of geometrical principles which he believed provided the form of an ideal arch. Hawley's early 20th century adaptation of Bonwill's principles used a portion of a circle to position the incisors in an ideal arch; the radius of the circle was equal to the combined mesiodistal widths of the patient's central, lateral, and canine teeth.[21] Various other types of conic sections such as the ellipse, parabola, trifocal ellipse, and the catenary curve have been used to characterize arch shape.[15,22-24] G.V. Black[13] described the upper teeth arrangement in the form of a semi-ellipse. Angle[14] described the "true line of occlusion" as more or less a parabolic curve. Izard's 1927 study identified the frequency of arch forms as 75% elliptical, 20% parabolic and

5% as square or "U" shaped.[25] The catenary proposed by MacConaill and Scher as the ideal curve of "common occlusion", was the curve assumed by a fine chain when suspended by its ends and allowed to hang freely.[24] Brader[15] proposed the concept of a trifocal ellipse based on the balance between antagonist muscles, taking into account oral functions as essential morphologic factors of the mandibular arch.

Many studies have sought to quantify and determine a geometric arch form on the basis of landmarks recorded in a system of coordinates.[26-30] Other studies have used mathematical functions in fitting a curve to give an accurate and reproducible representation of the size and shape of the dental arch.[31] Polynomial functions of the fourth and sixth degree have been used frequently.[31-33]

Measures and ratios of arch dimensions have been used to analyse dental arch form. Two easily obtained linear measurements, arch width and arch length, have been used to estimate the arc length of the dental arch, yielding a result close to the estimate obtained by the fitting of a fourth degree polynomial.[31] Arch widths and arch lengths have been used in the computation of dental arch area, dental arch index, and arc length.[34] Dimensional ratios using sagittal and transverse measurements have also been used to determine a sectorial analysis of the dental arch. The ratio of the anterior arch depth to intercanine width characterized the anterior curve according to Raberin et al.[30]

The degree of curvature is most evident in the anterior of the dental arch,[15,36,37] however a literature review revealed few articles that specifically dealt with arch form in relation to the Anterior Bolton Analysis.[6,11] Reported investigations have primarily used mathematical equations or theoretical models to develop tables and offer hypothetical findings that relate the Anterior Bolton Analysis to the curvature of both maxillary and mandibular arches.[6,11,12,37]

The relative harmony in mesiodistal width of the maxillary and mandibular dentitions becomes a major factor in coordinating posterior interdigitation, overbite, and overjet.[4,8,38] The importance of these particular geometric relationships becomes especially apparent in the finishing stages of treatment in a case with a tooth size discrepancy.[4,38,39] The variables overjet, overbite and torque were included in this investigation, to see whether they improved the predictability in relating anterior arch form to the Anterior Bolton ratio.

The purpose of this retrospective correlational study was to explore the potential interrelationships of anterior arch form and the Anterior Bolton Analysis. Correlations were sought between other inter arch parameters and the Anterior Bolton ratio. Gender specific differences in arch form were also examined in this study.

4.2 Materials and Methods

Sample

The sample for this study consisted of study casts from 88 individuals, 39 males and 41 females, with 8 unlabelled as to gender. The casts were chosen from a larger sample of over 120 cases from the L.F. Andrews Foundation collection of Non-Orthodontic-Normals (N.O.N.), located in San Diego, California.

The following selection criteria were used for the casts included in the sample:

- Naturally occurring, non-orthodontically treated optimal dentitions.
- All permanent teeth present to the first molars.
- Angle Class I molar and canine relationships.

- Optimal intercuspation: "straight and pleasing in appearance, a bite which generally looked correct and would not benefit from orthodontic treatment."[40]
- No spacing or crowding greater than 1 mm in total for either arch.
- No rotation of teeth.
- No apparent loss of tooth contour due to attrition or restorations.
- Casts free of obvious distortion or apparent alterations.

The casts used in this study were defined as "optimal" occlusions.

Cast Analysis

Mitoyoto electronic digital calipers, coupled with a Mitoyoto UP-1 data relay, were used to transmit cast measurements into a 486 IBM clone PC. The outer edges of the tips of both caliper arms were specially milled to fine needle points, and the digital calipers provided readouts in hundredths of a millimeter. See Appendix C for details on hardware and software.

A data gathering system was developed utilizing the calipers and computer to aid in record keeping and to replace tables or charts traditionally used in Bolton's Analysis. Software was customized to record measurement data and a spreadsheet was designed to subsequently calculate the anterior and overall tooth size discrepancies directly from the tooth width measurements. See Appendix D, Bolton Tooth Size Analysis Custom Spreadsheet.

Procedure

The upper and lower models were measured on site and the following measurements were obtained for each set of casts:

- Mesiodistal widths were determined for the six maxillary and mandibular anterior teeth from the right canine through the left canine. The widest portion of each crown was measured with the tips of the calipers held parallel to the incisal edge or occlusal surface.[41-45] (See Figure 4.1)

- Overjet was obtained by measuring the distance projected parallel to the occlusal plane, between the labial surface of the maxillary central incisors, at midpoint of the incisal edge, to the labial surface of the directly opposing mandibular incisor. The overjet between right and left sides was averaged. (See Figure 4.2)

- Overbite was assessed by first measuring the height of the incisal edge at the midpoint of the labial surface of each maxillary central incisor. Second the incisal edge of the opposing mandibular incisor was measured at the point which corresponded, mesiodistally, to the midpoint of the maxillary central incisor. The average distance between maxillary and mandibular central incisor edges was then calculated and used as the overbite. (See Figure 4.3 a, b, c, and d)

- Anterior Arch Width (Intercanine Width) was measured for both maxilla and mandible from distal of canine to distal of canine, at the labial embrasure of the contact points between the canine and first bicuspids. (Figure 4.1 and 4.4)

- Anterior Arch Length from interincisal midline to distal of canine for all quadrants, was measured at the labial embrasure of the contact points. (Figure 4.1 and 4.5)

The following derived measurements or calculations were obtained:

- Anterior Arch Depth was calculated using the Pythagorean Theorem[46] to estimate sagittal depth of the anterior segment for the maxillary and mandibular arches. (Figure 4.1)

- Anterior Area was calculated using Anterior Arch Depth and Intercanine Width to estimate a simple triangular anterior segment area for both arches.[46]

- Anterior Area Ratio was calculated by comparing the anterior segment areas in a ratio of mandibular over maxillary areas resulting in an Anterior Area ratio for each case.

- Maxillary and Mandibular Incisor Torque values were obtained from Andrews' published data of optimal cast measurements.[16] Andrews measured the angle between a line perpendicular to the occlusal plane and a line tangent to the midpoint of the facial axis of the maxillary or mandibular incisor clinical crowns as viewed "from the mesial or distal perspective, the tangent being equidistant from the gingival and incisal portions of the crown."[16] Seventy-one of the 88 cases in this study were included in Andrews' published data. The average of the right and left central incisor measurements was calculated and used as maxillary or mandibular torque for these cases. (Figure 4.6)

- Interincisal Crown Angle was defined as the "combined angle between the occlusal plane and a line tangent to the midpoint of the facial axis of the maxillary and mandibular incisor clinical crowns".[16] To calculate the interincisal crown angle in each case, the maxillary and mandibular central incisor torque values obtained from Andrew's published data[16] were subtracted from 180 degrees. (Figure 4.7)

Anterior arch form was characterized by the proportionality of arch depth and width:

- Mandibular Form Index and Maxillary Form Index were determined by dividing the anterior arch depth by one half the intercanine arch width dimension for each case. These indices quantified *individual arch form*. (Figure 4.8)

- Form Ratio was defined as the ratio of the Mandibular Form Index divided by the Maxillary Form Index, providing a relative comparison of the lower and upper arch forms. Thus, the Form Ratio quantified *inter arch form* comparison. (Figure 4.8)

- Case Form was derived by multiplying the Mandibular Form Index by the Maxillary Form Index. Case Form was used to determine which cases had narrow or broad maxillary and mandibular arch forms. (Figure 4.8)

The landmarks and parameters measured or calculated are listed in Appendix E. The 88 cases selected for the final sample were analysed for inter arch tooth size discrepancy. The Anterior Bolton Analysis ratio was established for each case in the sample, in the same manner as described by Bolton:

The anterior ratio was derived by dividing the sum of the mesiodistal widths of the six mandibular anterior teeth, by the sum of the widths of the opposing six maxillary anterior teeth, and multiplying by 100 to obtain a percentage.[8]

Reliability and Error Determination

Inter Examiner Reliability

Six sets of casts were measured on two occasions, at least one day apart, by four senior orthodontic graduate residents to establish inter examiner reliability in a pilot project. Anterior Bolton Measurement Reliability was determined for averaged ratings using the Analysis of Variance.[47] The inter rater reliability index was equivalent to the average correlation between all pairs of raters[47] and the reliability of K = 4 raters was 0.953 for the pilot project. There was a high degree of reliability between the examiners for the Anterior Bolton ratio results.

Intra Examiner Reliability

Measurements on seven sets of casts were taken by one investigator on two occasions, separated by at least one day, and analysed for intra examiner reliability. The repeatability or Reliability Coefficients comparing the first measurement to the second for each individual parameter ranged from 0.938 to 0.998. When analysed as a group, the Reliability Coefficient for all 12 parameters was 0.864 (Appendix F). The standard deviations of the Anterior Bolton ratios taken between time one and two ranged from 0.22 to 1.31% for the seven cases. The standard deviation of the Anterior Bolton ratio averaged over seven cases was 0.67%.

Tooth Size Measurement Error

The average standard deviation for individual tooth size measurements ranged from 0.09 to 0.13 mm for the twelve individual anterior teeth when all examiners' figures were evaluated for tooth size measurement error. The average standard deviation between time one and two for all anterior tooth measures for all four examiners was 0.11 mm. These findings are similar to the error values reported in other studies.[43,48,49]

Statistical Analysis

The mean, standard deviation, and range were computed for the various measurements and for the derived calculations. The Anterior Bolton Analysis ratios for the entire 88 case sample were compared to the Bolton study's ratio values, using an Independent t-Test to identify significant differences.

Correlation coefficients and Multiple Regression Analyses were used to evaluate the strength of associations between the dependent variable Anterior Bolton Analysis ratio and the independent variable Case Form as well as the additional variables overjet, overbite, incisor torque, interincisal angle and gender. A cluster analysis was also performed, based on the variable Case Form, and low and high clusters were evaluated for differences in Anterior Bolton Ratios. The level of significance was set at 5% for all statistical analyses performed.

In addition the cases in the study were rank ordered according to their calculated Anterior Bolton Analysis ratios. Those with low anterior Bolton ratio (relative mandibular deficiency/ maxillary excess) were compared to those ranked as high anterior Bolton ratio cases, in order to search for clinically significant differences for a number of arch dimensions and ratios. Cases approximately ±1 SD from the sample mean anterior

Bolton ratio were selected for comparison. Cases ranked 1 to 16 had low anterior Bolton ratios and cases ranked 73 to 88 had high Bolton ratios. Using Independent t-Tests, statistically significant differences were sought between the sixteen lowest and highest Anterior Bolton ratio cases for the following variables: overjet, overbite, arch width, arch length, arch depth, arch area, arch area ratios, incisor torque and interincisal crown angle, Form Index, Form Ratio, Case Form, and gender.

4.3 Results

The mean Bolton Tooth Size Analysis ratio obtained for the "Optimal" occlusion sample of 88 cases was not significantly different from Bolton's Index for the Anterior Bolton Analysis (p-value > 0.05). See Table 4.1 for comparison of ratio results to Bolton's study values. Evaluation of the entire "Optimal" occlusion sample for arch form parameters gave the following results:

1. Individual Arch Form: Form Index values: maxillary mean form index was 0.73, SD 0.08, range 0.50 to 0.94 and the mandibular mean form index was 0.60, SD 0.07, range 0.42 to 0.76. (Table 4.2)
2. Inter Arch Form Comparison: Form Ratio: the mean ratio comparing mandibular form index to maxillary form index was 0.82, SD 0.07, with a range 0.67 to 0.99. (Table 4.2)
3. Total Case Form: mean value was 0.44, SD 0.09 with a range 0.21 to 0.70. (Table 4.2)
4. All independent variable Correlation Coefficients with the Anterior Bolton were lower than 0.4 with the exception of Overjet, which correlated ratio at a value of r = 0.423. (Table 4.3)

5. Multiple Regression coefficient was $R^2 = 0.318$ with the inclusion of Overjet, Form Ratio and Mandibular Incisor Torque in examination of the dependent variable Anterior Bolton Ratio. (Table 4.4)
6. Males and females had significantly different anterior arch form parameters and arch dimensions. (Table 4.5)

Comparison of the Low ranked Anterior Bolton Ratio group to the High ranked Anterior Bolton Ratio group gave the following results:

1. The Anterior Bolton Analysis ratio mean was 73.44% for the Low group and 80.23% for the High group with a statistically significant difference, p-value < 0.01. (Table 4.6)
2. The mandibular intercanine width was significantly lower in the Low Bolton group (0.05 > p-value > 0.025). (Table 4.7)
3. The mandibular/maxillary depth ratio and the mandibular width/maxillary width ratio were significantly different between the Low and High Bolton groups. (Table 4.7)
4. The difference in both the depths and the widths of the mandibular arch values subtracted from the maxillary were significantly different between the Low and High Bolton groups. (Table 4.7)
5. The Mandibular Form Index and Maxillary Form Index were not significantly different between the two groups. (Table 4.8)
6. The Form Ratio and the Case Form were not significantly different between the two groups. (Table 4.8)
7. Area ratios showed a significantly larger mandibular area relative to maxillary area for the High Bolton group (p-value < 0.01). (Table 4.8)

4.4 Discussion

Quantification of Form in the 88 case sample

Examination of the form index values (arch depth divided by one half the intercanine width) revealed that on average the mandibular arches had decreased depths relative to their widths when compared to maxillary arches. That is, the mandibular arch form was generally broader than the maxillary arch. Review of the data showed only a few cases had nearly matched Form Indices of the upper and lower arches (Match = 1). Thirteen cases had above 0.90 and 13 cases had below 0.75, using Form Ratio values as an indication of match in form. This indicated the upper and lower arches did not have closely matched anterior arch proportions within each case in the optimal sample. (Table 4.2)

Case Form ranged from a low value of 0.21 (Md FI 0.42 X Mx FI 0.50), where neither arch had a high ratio of depth to width, to a low value of 0.70 (Md FI 0.74 X Mx FI 0.94), where both arches had relatively deep and narrow arch forms. (Table 4.2)

The Anterior Bolton Analysis ratios were not significantly different between groups of narrow and broad cases, as assessed by the variable Case Form. High and low total form cases, when grouped by cluster analysis, did not have Bolton ratios that differed significantly from each other or from the sample average.

No statistically significant correlation was found between the Anterior Bolton ratio and Case Form. Similarly there was no significant association between the anterior ratio and the individual arch form indices or ratios of the indices. Arch form did not correlate significantly with the Anterior Bolton Analysis ratio.

Arch form has not been studied in connection to the Bolton Anterior Index in a definitive case study. The investigations reported to date on these combined topics offered only hypothetical findings using model systems. Halazonetis[6] developed a speadsheet program to evaluate how the Anterior Bolton Index was affected by changes in labiolingual incisor thickness and arch radius. The spreadsheet model showed that small changes in incisor thickness changed the Bolton ratio. Also, by altering the radius, for example changing from flatter broad shaped arches to more curved narrow forms, the Bolton ratio decreased in the model. Halazonetis suggested that changing the anterior curvature in both arches simultaneously could change the Anterior Bolton ratio, and could therefore be useful in treating anterior tooth size discrepancy. Theoretically a maxillary excess could be treated by increasing the convexity and, conversely, a maxillary deficiency could be treated by flattening the anterior curvature. Epker and Fish[12] likewise suggested that changing the anterior arch form from a gentle to a tighter curve required an increase in upper arch length to maintain the same overjet or canine relationships. Cordato's mathematical model of anterior inter arch relationships partially supported this premise when hypothetical measurements were used.[11] The anteroposterior differences in arch depth gradually increased as the angles of curvature of both arches increased. Thus, based on theoretical examples, it appeared possible that changing the amount of curvature, that is changing the anterior form of the maxillary and mandibular arches simultaneously, might require an alteration in the mesiodistal tooth mass. The data from this sample, however, indicate that Anterior Bolton ratios are not different between groups based on total arch form and that overjet is only weakly correlated to the Anterior Bolton ratio. The findings of this study do not agree with the results of the theoretical model systems, which have demonstrated potential changes in the Bolton ratio as a result of simultaneous alterations of upper and lower arches from broader to narrower arch forms.[6,11,12]

Correlations between the Anterior Bolton Analysis ratio and the inter arch parameters of overbite and interincisal angle were not significant in this portion of the study where the entire 88 case sample was examined. Overjet showed a weak correlation to the anterior ratio (R^2 = 0.179). The Multiple Regression Analysis showed some improvement (R^2 = 0.319) but was not strongly significant in its ability to predict the Anterior Bolton Ratio with the inclusion of overbite and mandibular incisor torque in addition to the variable overjet in the analysis. Various authors have reported on the interactions of tooth size discrepancy with the anterior inter arch relationships.[7,11,39,50-52] According to Bolton, an anterior mean ratio of 77.2% provides a satisfactory anterior relationship if the labiolingual inclination of the incisors is correct and if the thickness of the incisal edges is not excessive.[9,38] A decrease in overjet has been shown in clinical examples of high anterior Bolton ratio cases.[9] The findings of this study support a weak association between increased Bolton ratio and decreased overjet. Similar to the findings of Bolton and Lundstrom,[8,41,53] statistically significant correlations were not evident between overbite and the anterior ratio in the 88 case optimal occlusion sample.

The optimal cases where gender was identified were also analysed for sex differences. Males (n=39) and females (n=41) had similar Anterior Bolton Analysis ratios but significantly different curve parameters. Males had relatively flatter, broader maxillary and mandibular anterior segments compared to females. These findings are consistent with previous investigations that found slightly more narrow anterior arch segments in females.[30,34]

In most studies on arch form that considered gender, the arch dimensions were smaller in females.[30,34,54] In this study maxillary and mandibular intercanine widths and arch lengths were statistically different between males and females. Transverse dimensions were also smaller for females in Raberin et al.'s[30] study. Arch depth was not significantly related to gender in this study, a result similar to Raberin et al.'s findings.[30]

Differences in Low and High Anterior Bolton ratio groups

The low ranked Anterior Bolton ratio group was compared to the high ranked Anterior Bolton ratio group for a number of parameters. The Anterior Bolton ratio was 73.44% on average for the Low group and 80.23% on average for the High group. The mean Anterior ratio, mandibular perimeters, interincisal crown angles, overjet and overbite measurements were significantly different between High and Low Bolton groups, Table 4.6.

Differences in Low and High Anterior Bolton ratio groups related to arch form

Arch widths and lengths have been used in the computation of arch areas and arch indices to provide objective and simple methods of quantifying arch form.[34] In this investigation an estimation of anterior segment arch area was obtained using two parameters, arch length from central incisors to distal of the canines and intercanine width. The proportions of the arch forms in the Low and High ranked anterior Bolton ratio groups were distinct from each other when mean arch areas were examined. Areas of both arches were not statistically significantly different between groups. However, calculating the difference between the anterior areas of the maxillary and mandibular arches, and the difference between the ratios of the arch areas, revealed a notable contrast between groups. The maxillary arch areas were significantly larger than their opposing anterior mandibular sections in the Low Bolton group when compared to the High Bolton group. The ratio of mandibular to maxillary areas was on average greater in the High Bolton group, Table 4.7. This reflects the relative increase in mandibular perimeter in the High Bolton group mentioned above.

The dental arch index utilized in the present study modified Raberin et al.'s ratio of arch depth to intercanine width which they used to describe anterior curvature.[30] The shapes and proportions of the arch forms in the low and high ranked anterior Bolton ratio groups were distinct from each other when mean arch dimensions were examined. The mandibular intercanine width was statistically different between the two groups with a decreased mean value in the Low Bolton group. The maxillary arches were significantly deeper and wider relative to their opposite anterior mandibular sections in the Low Bolton group when compared to the High Bolton group. This is shown in Table 4.7, in the rows listing the inter arch ratios of mandibular/maxillary depth and ratios of intercanine width, and also supported by the data for inter arch differences in depth and width for the two groups.

The moderately narrow to broad arch forms of the cases present in this sample had nearly equal ranges of Anterior Bolton ratios values. The naturally occurring optimal cases did not exhibit the extremely differences in anterior arch form that might be required to cause a decreased Bolton ratio as hypothesized.

Further extension of this investigation of optimal occlusion cases might include analysis of their anterior curvatures using polynomial functions, generated by a coordinate system, to identify potential correlations with the Anterior Bolton Analysis ratio.

4.5 Conclusions

No statistically significant correlation was found in the complete 88 optimal occlusion sample between the Anterior Bolton ratio and the overall arch form (expressed as Case Form). Individual arch forms also had no correlation with the Anterior Bolton Analysis ratio. There were significant differences between genders in proportion and arch dimensions in both arches. Males had relatively flatter, broader maxillary and mandibular anterior segments compared to females. Correlations between the Anterior Bolton Analysis ratio and the inter arch parameters of overbite and interincisal angle were not significant in this portion of the study. Overjet was weakly correlated to the anterior ratio.

Comparison of low and high ranked Anterior Bolton Analysis ratio cases showed a decrease in overjet, overbite and interincisal angle in the high ranked group. There was a relative increase in mandibular perimeter and mandibular intercanine width in the higher ranked Anterior Bolton ratio cases. There was however no significant difference in the anterior arch form case totals between the low and high ranked Anterior Bolton Analysis cases in this study.

Table 4.1 Comparison of Present Study Ratios to Bolton's Values

	n	Mean	SD	Range	SEM
Bolton's Anterior Index	55	77.2%	1.65	74.5 - 80.4%	0.22
Present Study Anterior Ratio	88	76.71%	2.43	70.16 - 85.12%	0.26
Low Anterior Bolton Group	16	73.44%	1.02	70.16 - 74.37%	0.26
High Anterior Bolton Group	16	80.23%	1.62	78.93 - 85.22%	0.41

Table 4.2 Arch Form Parameter Results

Entire 88 case Sample	**Mean**	**SD**	**Range**
Form Index Mx (depth / 0.5 intercanine width)	0.73	0.08	0.50 - 0.94
Form Index Md (depth / 0.5 intercanine width)	0.60	0.07	0.42 - 0.76
Form Ratio (FI Md / FI Mx)	0.82	0.07	0.67 - 0.99
Case Form (FI Md X FI Mx)	0.44	0.09	0.21 - 0.70

Table 4.3 Results of Linear Regression and Correlations of Compared Variables

Between Anterior Bolton Ratio and Form Parameters	r Correlation Coefficients	p-value	R^2 Coefficient of Determination	ß Regression Coefficient
Form Index Maxilla	0.113	0.294	0.013	-3.463
Form Index Mandible	0.068	0.532	0.005	2.307
Form Ratio	0.252	0.018	0.063	9.28
Case Form	-0.015	0.888	0.000	-0.401
Overjet	-0.423	0.000	0.179	-1.506
Overbite	0.266	0.012	0.071	-0.593
Interincisal Angle	-0.167	0.168	0.028	-0.058
Torq 1 Maxilla	0.015	0.899	0.000	0.011
Torq 1 Mandible	0.227	0.058	0.052	0.106

Table 4.4 Results of Multiple Regression of Anterior Bolton Analysis Ratio and Additional Variables

Dependent Variable Anterior Bolton Ratio	Independent Variables	p-value	R^2 Coefficient of Determination
Anterior Bolton Ratio	Overjet	0.000	0.179
Anterior Bolton Ratio	Form Ratio	0.018	0.063
Anterior Bolton Ratio	Overjet	0.000	0.223
	Form Ratio	0.030	
Anterior Bolton Ratio	Overjet	0.000	0.318
	Form Ratio	0.021	
	Torq 1 Mandible	0.019	
Anterior Bolton Ratio	Overjet	0.001	0.319
	Form Ratio	0.024	
	Torq 1 Mandible	0.020	
	Overbite	0.847	

Table 4.5 Comparison of Male and Female Parameter Values

Differences Between Males and Females Entire Optimal Sample	males n=39	females n=41	t - Test Statistic	p-value
Anterior Bolton Ratio (%)	76.8	76.4	0.72	0.475
Form Parameters				
Form Index Maxilla	0.71	0.75	-2.04	0.044†
Form Index Mandible	0.58	0.61	-2.09	0.039†
Form Ratio	0.82	0.82	-0.45	0.652
Case Form	0.42	0.46	-2.00	0.049†
Other Variables				
Overjet (mm)	2.2	2.3	0.03	0.979
Overbite (mm)	4	4.5	-1.89	0.062
Interincisal Angle (degrees)	176.1	175.3	0.42	0.678
Torq 1 Maxilla (degrees)	6.9	6.8	0.09	0.930
Torq 1 Mandible (degrees)	-2.6	-1.8	-0.56	0.579
Arch Dimensions				
Maxillary Intercanine Width (mm)	38.0	36.0	5.03	0.000†
Mandibular Intercanine Width (mm)	30.5	28.9	5.31	0.000†
Maxillary Arch Depth (mm)	13.5	13.4	0.46	0.647
Mandibular Arch Depth (mm)	8.8	8.8	-0.05	0.961
Maxillary Arch Length (mm)	23.4	22.4	3.89	0.000†
Mandibular Arch Length (mm)	17.6	16.9	3.95	0.000†

(† Significant difference $p < 0.05$)

Table 4.6 Low and High Bolton Anterior Ratio Groups Compared by t-Test Statistics Anterior Parameters

Parameter	Average of entire sample of 88 optimal cases	Low 16 Anterior Bolton Group Mean	High 16 Anterior Bolton Group Mean	t - Test statistic	t statistic greater or less than	p value Significant difference Low & High Groups
Anterior Bolton (%)	**76.71**	73.44	80.23	-14.16	2.75	p <0.01
Mx6 (mm)	**46.7**	47.27	46.22	1.05		N.S.
Md6 (mm)	**35.81**	34.7	37.08	-3.15	2.75	p < 0.01
Ave OJ (mm)	**2.23**	2.81	1.99	3.19	2.75	p < 0.01
Ave OB (mm)	**2.43**	2.99	1.85	3.21	2.75	p < 0.01
Interincisal Angle** (degrees)	**175.26**	176.82	171.89	2.3	2.042-2.457	0.05 >p > 0.025
Torq 1 Mx* (degrees)	**6.7**	7.75	7.04	0.55		N.S.
Torq 1 Md* (degrees)	**-1.96**	-4.57	1.07	-3.54	2.75	p < 0.01

(*directly from, and **derived from data tables in Andrews LF. Straight Wire: The Concept and Appliance.San Diego, California: L.A. Wells Publisher, 1989.)
(N.S. = Not Significant difference p > 0.05)

Table 4.7 Low and High Bolton Anterior Ratio Groups Compared by t -Test Statistics Dimensions and Ratios

Parameter	Average of entire sample of 88 optimal cases	Low 16 Anterior Bclton Group Mean	High 16 Anterior Bolton Group Mean	t - Test statistic	t statistic greater or less than	p value Significant difference Low & High Groups
Mx intercanine width (mm)	**37.12**	36.95	37.06	-0.13		N.S.
Md intercanine width (mm)	**29.80**	29.22	30.54	-2.08	2.042-2.457	0.05 >p > 0.025
Md IC width /Mx IC width	**0.80**	0.79	0.82	-5.30	2.75	p < 0.01
Mx depth (mm)	**13.45**	13.88	13.39	1.04		N.S.
Md depth (mm)	**8.86**	8.77	9.19	-1.28		N.S.
Md depth / Mx depth	**0.66**	0.63	0.69	-3.25	2.75	p < 0.01
Mx-Md depth (mm)	**4.58**	5.10	4.20	2.99	2.75	p < 0.01
Mx-Md intercanine width (mm)	**7.32**	7.73	6.52	3.68	2.75	p < 0.01
AveAreaMx6 (mm2)	**249.60**	256.85	248.59	0.69		N.S.
AveAreaMd6 (mm2)	**132.12**	128.30	140.76	-1.91		N.S.
Mx-MdArea (mm2)	**165.37**	179.93	149.96	2.76	2.75	p < 0.01
AreaRatio	**0.53**	0.50	0.57	-4.74	2.75	p < 0.01

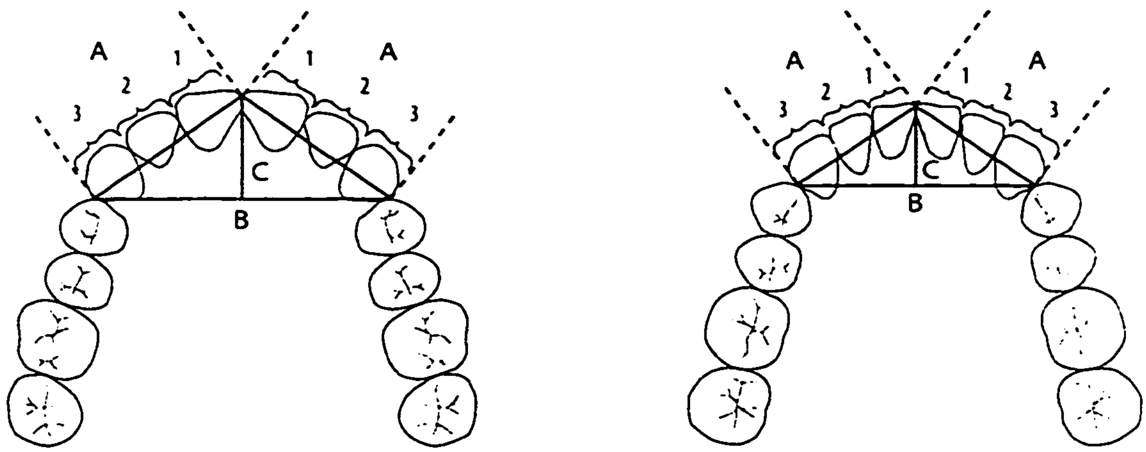
(N.S. = Not Significant difference p > 0.05)

Table 4.8 Low and High Bolton Anterior Ratio Groups Compared by t -Test Statistics Form Parameters

Parameter	Average of entire sample of 88 optimal cases	Low 16 Anterior Bolton Group Mean	High 16 Anterior Bolton Group Mean	t - Test statistic	p value Significant difference Low & High Groups
Form Index Mx (depth /0.5 IC width)	**0.73**	0.75	0.72	1.13	N.S.
Form Index Md (depth / 0.5 IC width)	**0.60**	0.60	0.60	-0.04	N.S.
Form Ratio (FI Md / FI Mx)	**0.82**	0.80	0.83	-1.56	N.S.
Case Form (FI Md X FI Mx)	**0.44**	0.46	0.44	0.61	N.S.

(N.S. = Not Significant difference $p > 0.05$)

Figure 4.1 Cast Measurements



Measurements:

1 - 3	**Mesiodistal Measures of Tooth Width**
A	**Anterior Arch Length**
B	**Intercanine Width**

Calculations:

C	**Anterior Arch Depth**

Figure 4.2 Overjet

Figure 4.3 Overbite

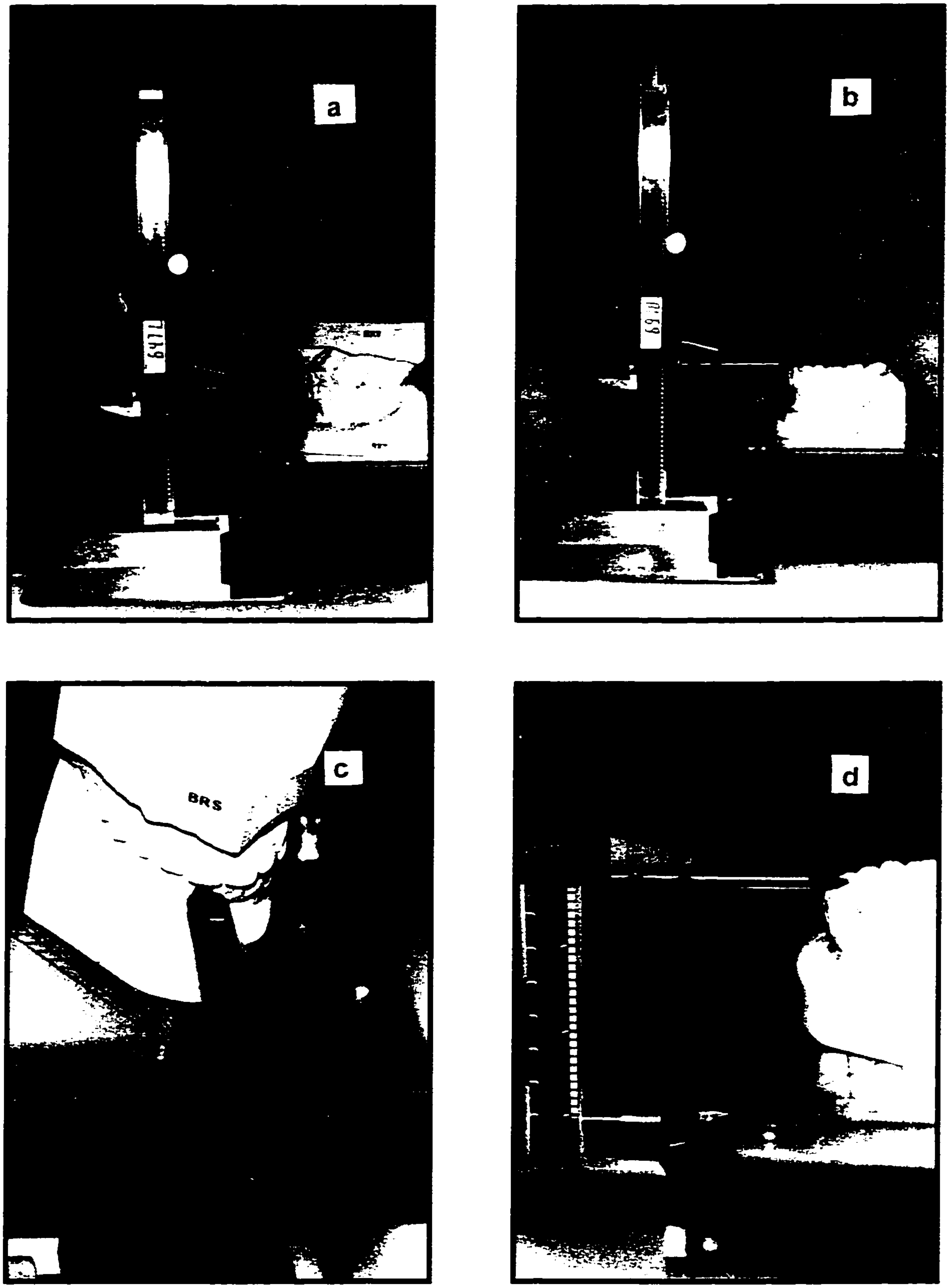


Figure 4.4 Intercanine Width

Figure 4.5 Anterior Arch Length

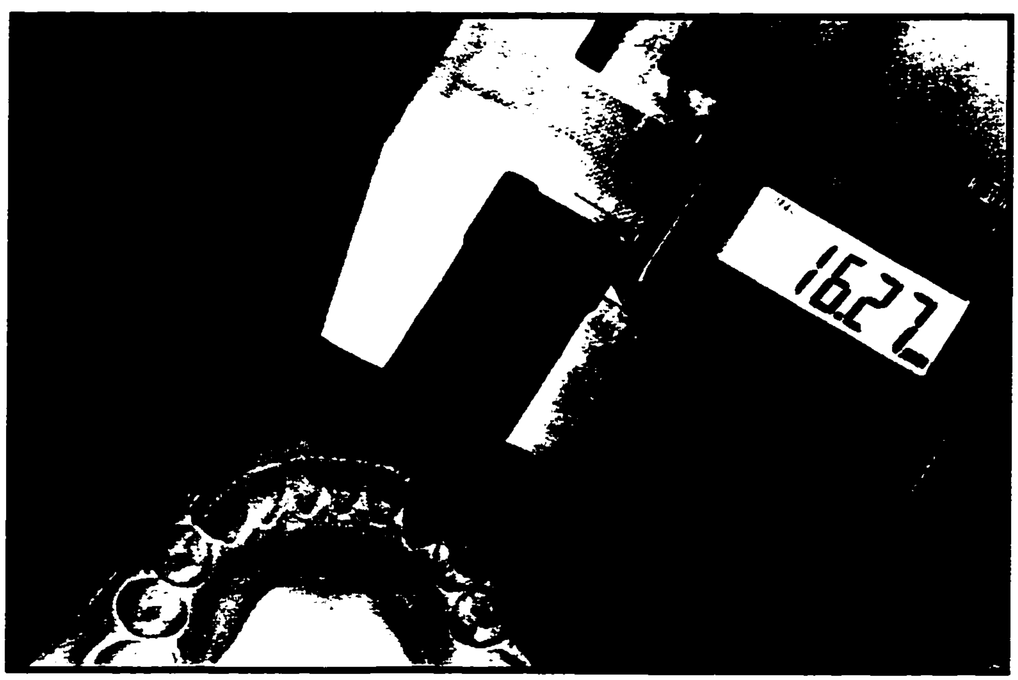
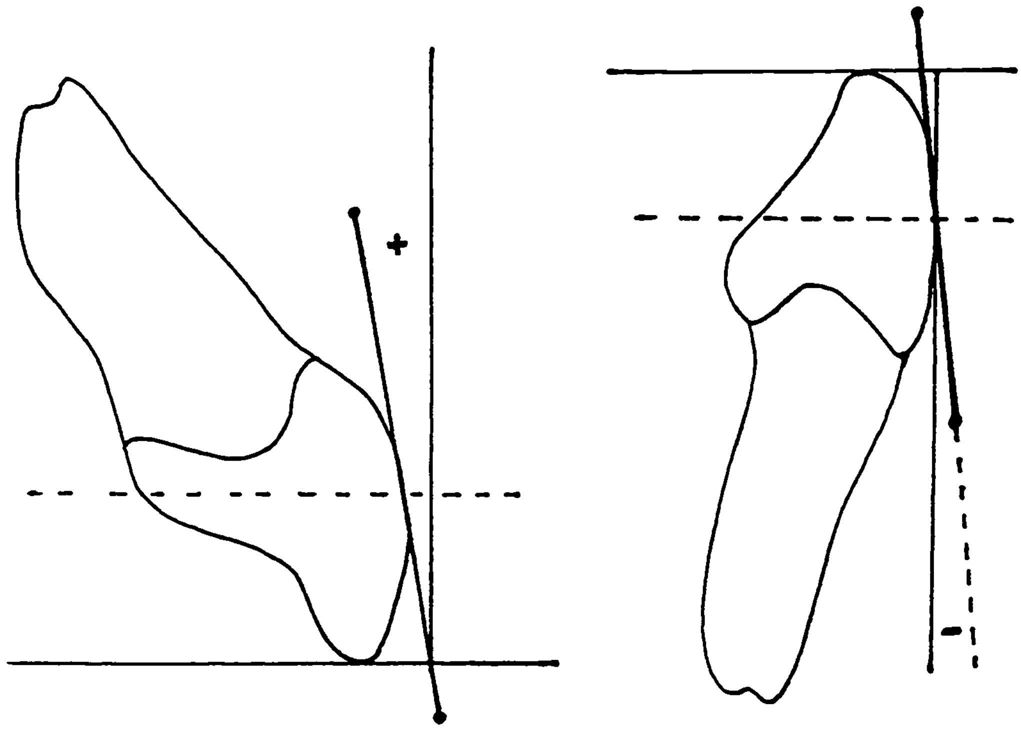


Figure 4.6 Crown Torque*

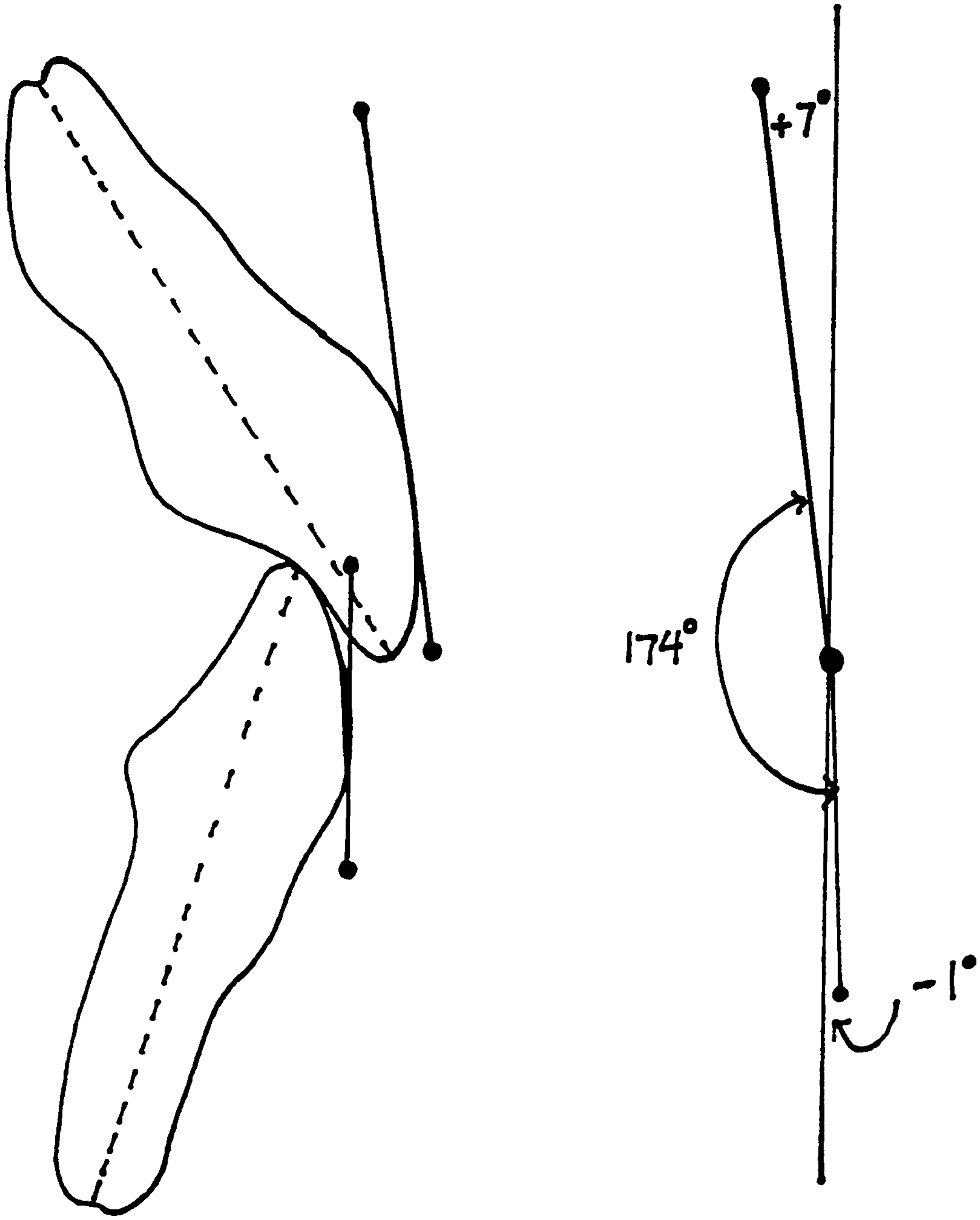


Maxillary Incisor Crown Torque

Mandibular Incisor Crown Torque

(* after Andrews' diagram[16])

Figure 4.7 Interincisal Crown Angle*



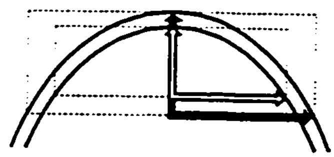
180°- (+7°) - (-1°) = 174°

(* after Andrews' diagram[16])

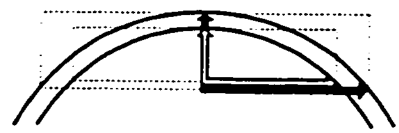
Figure 4.8 Form Parameters

Hypothetical Examples*

Narrow



Broad



Anterior six teeth in both forms in this example have a Maxillary perimeter of 46.7 mm and Mandibular perimeter of 35.8 mm

Form Index = depth/ 1/2 intercanine width

Narrow Md Form Index = 0.61
Narrow Mx Form Index = 0.75

Broad Md Form Index = 0.39
Broad Mx Form Index = 0.48

Narrow arch form has higher Form Indices than Broad arch form.

Form Ratio = Md Form Index / Mx Form Index

Narrow Form Ratio = 0.61 / 0.75= 0.81

Broad Form Ratio = 0.39 / 0.48 = 0.81

Closely matched form proportions within both cases result in high Form Ratio values. Identical maxillary and mandibular arch forms would have a Form Ratio of 1.0.

Case Form = Md Form Index X Mx Form Index

Narrow Case Form = 0.61 X 0.75= 0.46

Broad Case Form = 0.39 X 0.48 = 0.19

Different form proportions exist between Narrow and Broad cases.

Narrow case arch proportions are higher than Broad case. This results in higher combined proportions with a larger Case Form value.

* after American Orthodontics Brader Arch Form and "A" Company Orthodontics Tru-Arch®Form

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Chapter Five

Discussion and Recommendations

Chapter Five General Discussion

5.1 Discussion

Quantification of tooth size discrepancy is important for successful orthodontic treatment. Large discrepancies in intra arch tooth size proportions need to be considered in planning decisions at the start of treatment.[1-5] If overlooked, subtle discrepancies also can complicate or prevent successful completion of orthodontic therapy.[2,6,7] The procedure most commonly used in contemporary practice to assess tooth size is the Bolton Analysis.[8-10] Both the analysis and the values derived by Bolton have gained general acceptance as orthodontic diagnostic tools.[6,11,12] Only one study prior to the present investigation, however, had used a sample similar in composition to that of Bolton's. That study analysed 24 ideal cases and obtained results consistent with Bolton's.[13]

The primary purpose of this study was to test the validity of the Anterior Bolton Analysis in a larger sample, using naturally occurring optimal occlusions. Lundstrom and Neff independently studied large numbers of random occlusions and malocclusions and obtained higher ratios (78.5% and 79% respectively) for the anterior analysis.[14,15] Others studied orthodontic patients and found mean ratios similar to Bolton's[16] with larger ranges and standard deviations.[3,8] In part one of the present study naturally occurring non-orthodontically treated dentitions were used to test the validity of Bolton's Anterior Mean Index and Overall Mean Index. The validity of Bolton's Tooth Size Analysis Indices were reconfirmed in this study: neither the anterior ratio of 76.71% nor the overall ratio of 91.10% was statistically significantly different from Bolton's Index (p-values > 0.05).

The average individual tooth widths recorded in the present study were slightly smaller than Bolton's tooth sizes, but the ratios of the perimeter sums were close in value to Bolton's Indices.[17] The differences in mean tooth sizes may be in part due to

Bolton's use of three-inch needle point dividers to measure the greatest mesiodistal diameter of the teeth.[17] Use of dividers gave, on average, a significantly larger measurement of tooth size than did sliding calipers when evaluated in Hunter and Priest's comparative study on discrepancy in measurement of tooth size.[18]

The cases in this study were drawn from a larger sample of untreated optimal occlusions from the L.F.Andrews Foundation collection of Non-Orthodontic-Normals (N.O.N.). Andrews describes these cases as occlusions that do not require or would not benefit from orthodontic treatment.[19] Presumably these cases were clinically acceptable in esthetics and function. All were Caucasian except for one Hispanic case. Bolton's study did not provide ethnic background.[17] The cases included in this optimal sample demonstrated a normal distribution when the Anterior Bolton Analysis ratio values were plotted in a frequency histogram.

The wide range of Anterior Bolton ratio values found within this sample of optimal occlusions demonstrates that clinically acceptable occlusions exist with Bolton ratios greater than 1 SD from Bolton's Index value of 77.2%. Compensations for the calculated tooth size discrepancies in this sample likely resulted from combinations of minor spacing or crowding as well as from variations of overjet and or overbite that were within normal ranges. The findings of this study indicate that a clinically acceptable result may be possible in cases with minor to moderate tooth size discrepancies without tooth size modification and thus individual assessment should be applied in each orthodontic case.

The mean Anterior Bolton Analysis ratio was 76.82% for the 39 males in this study and 76.42% for the 41 females; the mean Overall Bolton Analysis ratio was 91.21% for males and 90.81% for females. No statistically significant differences were found between males and females in either analysis when the sample was evaluated for correlations between sex and Bolton ratio, ($p > 0.05$).

To further test the validity of the Bolton analysis as a diagnostic tool, part two of the study compared the pretreatment and post treatment Bolton Analysis ratios of orthodontic cases. This comparison was made to determine whether Bolton ratios were adversely influenced by the measurement of width on malposed teeth. Tooth width measurements can be made with relative ease on well aligned or excellent dentitions. However, estimation of the ideal interproximal contact points may be required in maloccluded cases, and determining an accurate Bolton ratio may be difficult due to an altered interpretation of the maximum mesiodistal dimensions of the teeth.[9] A previous study concluded that significant measurement errors occur with Bolton Analysis performed on pretreatment casts cases with over 3 mm of crowding.[9]

It was observed in part two of this study, using a randomly selected sample of 90 orthodontic patients that the Bolton Analysis values obtained from the pretreatment casts were not statistically different from the post treatment cast values when analysed by Paired t-Tests. It was concluded that the Bolton Analysis can be used to make appropriate decisions on tooth size based on pretreatment diagnostic information. The analysis was found to be a valid diagnostic aid for treatment planning and predicting post treatment tooth size relationships.

The results of the ninety case random orthodontic sample were also compared to Bolton's study values. The post treatment Anterior and Overall Bolton mean ratios of 77.22% and 91.93% were similar to Bolton's Indices of 77.2% and 91.3%. No statistical difference was found using Independent t-Tests to compare the Anterior and Overall Bolton mean ratios with Bolton's Indices, with p-value > 0.05 for both ratios. Mean values of the Anterior Analysis and Overall Analysis tooth size discrepancies were less than 0.10 mm and 0.65 mm respectively when calculated for the after treatment casts.

Arch form was assessed on natural "optimal occlusion" dentitions again in part three of the study. The purpose of this study was to determine potential correlations with the Anterior Bolton Analysis. Considerable research has been devoted to the examination of arch curvature but prior studies had not definitively assessed the relationship of tooth size proportions to arch curvature.[20-26] Measures and ratios of arch dimensions were used in this study to quantify arch form, using methods similar to those of previous studies. Lavelle used a "Curve Index" to quantify individual arch shape, dividing intercanine width by anterior arch length.[27] Raberin et al. also used the ratio of anterior arch depth and intercanine width as a measure of anterior arch form.[28]

A method for quantifying combined arch form or total case form was developed for this research, to assess the relationship of the Anterior Bolton ratio to changes in arch form in both the maxilla and mandible. Case Form was the product derived from multiplying the Mandibular Form Index by the Maxillary Form Index. This study found that anterior arch form as expressed by total Case Form was unrelated to the Anterior Bolton Analysis ratio. These findings are in contrast to the projections of theoretical model systems of Halazonetis, Cordato, and the implications of Epker and Fish's text.[10,29,30] The models suggested that simultaneous changes of curvature in both arches would alter the Bolton ratio value if there were no adjustments in the canine relationships or overjet. A decrease in overjet has been shown in clinical examples of high anterior Bolton ratio cases.[2] The findings of this study support a weak association between increased Bolton ratio and decreased overjet while maintaining a Class I canine relationship.

Correlations between the Anterior Bolton Analysis ratio and the inter arch parameters of overbite and interincisal angle were not significant in this portion of the study. The Multiple Regression Analysis showed some improvement but was not strongly significant in its ability to predict the Anterior Bolton Ratio with the inclusion of overbite and mandibular incisor torque in addition to the variable overjet in the analysis. Various authors have reported on the interactions of tooth size discrepancy with the anterior inter arch relationships.[6,11,30-33] According to Bolton, an anterior mean ratio of 77.2% provides a satisfactory anterior relationship if the angulation of the incisors is correct and if the labiolingual thickness of the incisal edges is not excessive.[2,12] Similar to the findings of Bolton and Lundstrom, statistically significant correlations were not evident between overbite and the anterior ratio in the 88 case optimal occlusion sample.[14,17] Incisor thickness was not evaluated in this investigation.

Individual maxillary and mandibular arch form proportions were also found to be unrelated to the anterior ratio in the sample of optimal occlusions. Form Ratio (the ratio of the Mandibular Form Index divided by the Maxillary Form Index), which provided a relative comparison of the lower to the upper arch form, also did not show a significant correlation with the Anterior Bolton ratio.

The optimal cases where gender was identified were analysed for sex differences; the results showed that males and females had significantly different arch dimensions and arch form proportions. Males had relatively flatter, broader maxillary and mandibular anterior segments, and lower total Case Form compared to females. These findings are consistent with previous investigations that found relatively narrower anterior arch segments in females.[28] In most studies on arch form that considered gender, the arch dimensions were smaller in females.[28,34] In this study maxillary and mandibular intercanine widths and arch lengths were statistically different between males and females. Arch depth was not significantly related to gender in this study, a result similar to Raberin et al.'s findings.[28]

In addition the optimal cases in the project were rank ordered according to their calculated anterior Bolton ratios. Those with a low anterior Bolton ratio (relative mandibular deficiency/ maxillary excess) were compared to those ranked as high anterior Bolton ratio cases to search for clinically significant differences between groups for a number of measured and calculated parameters. Cases ranked 1 to 16 had low anterior Bolton ratios and cases ranked 73 to 88 had high Bolton ratios.

Using Independent t-Tests, statistically significant differences were sought between the sixteen lowest and highest Anterior Bolton ratio groups for the variables maxillary perimeter, mandibular perimeter, overjet, overbite, incisor torque, interincisal angle, arch width, arch length, arch depth, arch areas, arch areas ratios, individual arch form (Form Index), relative inter arch form comparison (Form Ratio), and total case arch form (Case Form). The comparison showed the Anterior and the Overall Bolton ratios were significantly different for the High and Low groups. The High Bolton group on average had a significantly larger mandibular anterior perimeter relative to the maxillary arch. The maxillary perimeters were not statistically different for the two groups.

The average overjet measurement was 40% higher in the Low Bolton group, at 2.8 mm compared to 2 mm. An increase in overjet can be seen clinically with Low Bolton cases and could be considered an associated compromise in treatment if the relative maxillary excess were not apparent until the finishing stages of treatment.[2,4,7,32] The average overbite measurement was 40% higher in the Low Bolton group, at 2.99 mm compared to 1.85 mm. Bolton and Lundstrom were unable to find statistically significant correlations between overbite and the anterior ratio in their investigations and the results from the 88 case sample were in agreement with their findings.[14,17] If the ideal Bolton

Index applies to only moderate overjet and overbite cases, an increase in overjet and/or overbite should be associated with mandibular deficient cases, for example.[2,31] The findings of this part of the study comparing only Low and High Anterior Bolton groups support associations between: relative maxillary excess and increased overjet and overbite; and relative mandibular excess and decreased overjet and overbite.

The variation in interincisal angle between the Low and High Bolton groups was due mainly to a significant difference in the mandibular central incisor torque. The mandibular central incisor torque was minus 4.6 degrees in the Low Bolton group and plus 1 degree in the High Bolton group. The average for the entire 88 case sample was minus 1.86 degrees. The lower incisors were significantly more retroclined in the Low Bolton group. This may be related to the increase in overjet and overbite also found in this same group.

Arch widths and lengths have been used in the computation of arch areas to provide objective and simple methods of quantifying arch form.[27] An estimation of anterior segment area was obtained using two parameters, intercanine width and arch length from central incisors to distal of the canines. The shapes and proportions of the arch forms in the Low and High ranked anterior Bolton ratio groups were distinct from each other when mean arch areas were examined. Areas of both arches were not statistically significantly different between groups. However, calculating the difference between the areas of the maxillary and mandibular arches, and the difference between the ratios of the arch areas, revealed a notable contrast between groups. The maxillary arches were significantly larger in area relative to their opposite anterior mandibular sections in the Low Bolton group as compared to the High Bolton group. The ratio of mandibular to maxillary areas was on average greater in the High Bolton group. This reflects the relative increase in mandibular perimeter mentioned above.

The mandibular intercanine width was statistically different between the two groups with a decreased mean value in the Low Bolton group. The maxillary arches were significantly deeper and wider relative to their opposite anterior mandibular sections in the Low Bolton group when compared to the High Bolton group.

The narrow to broad arch forms of the cases present in this sample had nearly equal ranges of Anterior Bolton ratios values. The naturally occurring optimal cases did not contain the extreme differences in total case arch form that might be required to cause a change in Bolton ratio as hypothesized.

5.2 Relevance of the Data-Gathering Protocol

The computer-integrated Bolton Tooth Size Analysis developed in this study can aid diagnosis and treatment planning. Measurements obtained from orthodontic casts using electronic digital calipers are directly transmitted into a spreadsheet based analysis. Summed data from tooth width measurements, when applied to a formula using Bolton's Anterior Index of 77.2%, result in the automatic calculation of a patient's anterior tooth discrepancy. Direct transfer of cast measurements into a spreadsheet and automatic calculation of arch and tooth size discrepancies can be used to eliminate inputting, calculation and interpretation mistakes. The analysis can be achieved efficiently and the calculations made accurately. The value of this method as a clinical and research tool was demonstrated through its use in rapid data gathering and instant calculation of the numerous analyses called for in this project. The protocol developed here, using digital calipers and a computerized analysis, greatly facilitates the use of the Bolton Analysis. No previously published articles suggesting these methods or techniques were located in the orthodontic literature. The same methodology could be adapted for use in many other applications in odontometrics and cephalometrics.

5.3 Recommendations For Future Study

Future studies in the areas of tooth width and tooth size proportion analysis could address the limitations in methodology and expand the scope of the present investigation.

1. The odontometric literature contains a variety of definitions of mesiodistal widths of tooth size, and each definition is subject to the examiner's interpretation. Application of the definition also depends on the orientation of the tooth, especially if idealized rather than actual contact areas are selected. A tooth size measurement training module could be designed where an individual examiner would have access to an audiovisual or a written instructional process to develop a clear image of the tooth landmarks to be used; self-testing through repeated measures could then determine the reliability of the individual's tooth size analyses. Each orthodontist would be able to assess the magnitude and frequency of the errors that manifest in their own assessments of tooth size discrepancy.

2. A study on tooth size proportions could be designed with stricter criteria for inclusion in the sample. Though it would be challenging to find a substantial number of natural occurring ideal cases, zero spacing or crowding would likely limit the ranges of the results and perhaps change the tooth size analysis mean ratio results. The optimal occlusion sample criteria of this study also did not include an initial assessment or exclusion based on overbite, overjet or incisor angulation.

3. Maxillary and mandibular canine torque and incisor thickness measurements could be included in future studies along with overjet, overbite, and incisor torque, to provide information and search for additional correlations with the Anterior Bolton Analysis.

4. An optimal occlusion sample could be used to determine mesiodistal tooth size variability between antimeres and tooth size sexual dimorphism. Data on tooth width measurements from the optimal cases could be compared to previously determined mesiodistal tooth size data for both antimeric variability and sexual dimorphism.

5. A study comparing Bolton Analysis of pre and post treatment of patients classified and compared with regard to the type of malocclusion would have potential for clinical applicability. In addition a study using a quantifiable index to measure the amount of individual arch or total case spacing or crowding could possibly shed more information on the reliability of the pretreatment Bolton Analysis in specific circumstances.

6. A mathematical model could be developed to study the effects of varying factors considered in the Anterior Bolton Tooth Size Discrepancy Analysis. Factors to be studied might include: arch size, arch form or curvature, tooth thickness, overjet, overbite, and tooth angulation. The analytic model could be used to demonstrate the effects of altering each of several individual occlusal-dental factors. With a standard Anterior Bolton Index of 77.2% in place in a computerized spreadsheet model, changes in arch size and dimensions, tooth thickness, overjet, overbite, or incisor torque could be demonstrated to have specific results. Variables under the

orthodontist's control might be altered in the model, the results potentially influencing treatment planning decisions.

7. Further extension of this investigation of optimal occlusion cases might include analysis of their anterior curvatures using polynomial functions, generated by a coordinate system, to identify potential correlations with the Anterior Bolton Analysis ratio.

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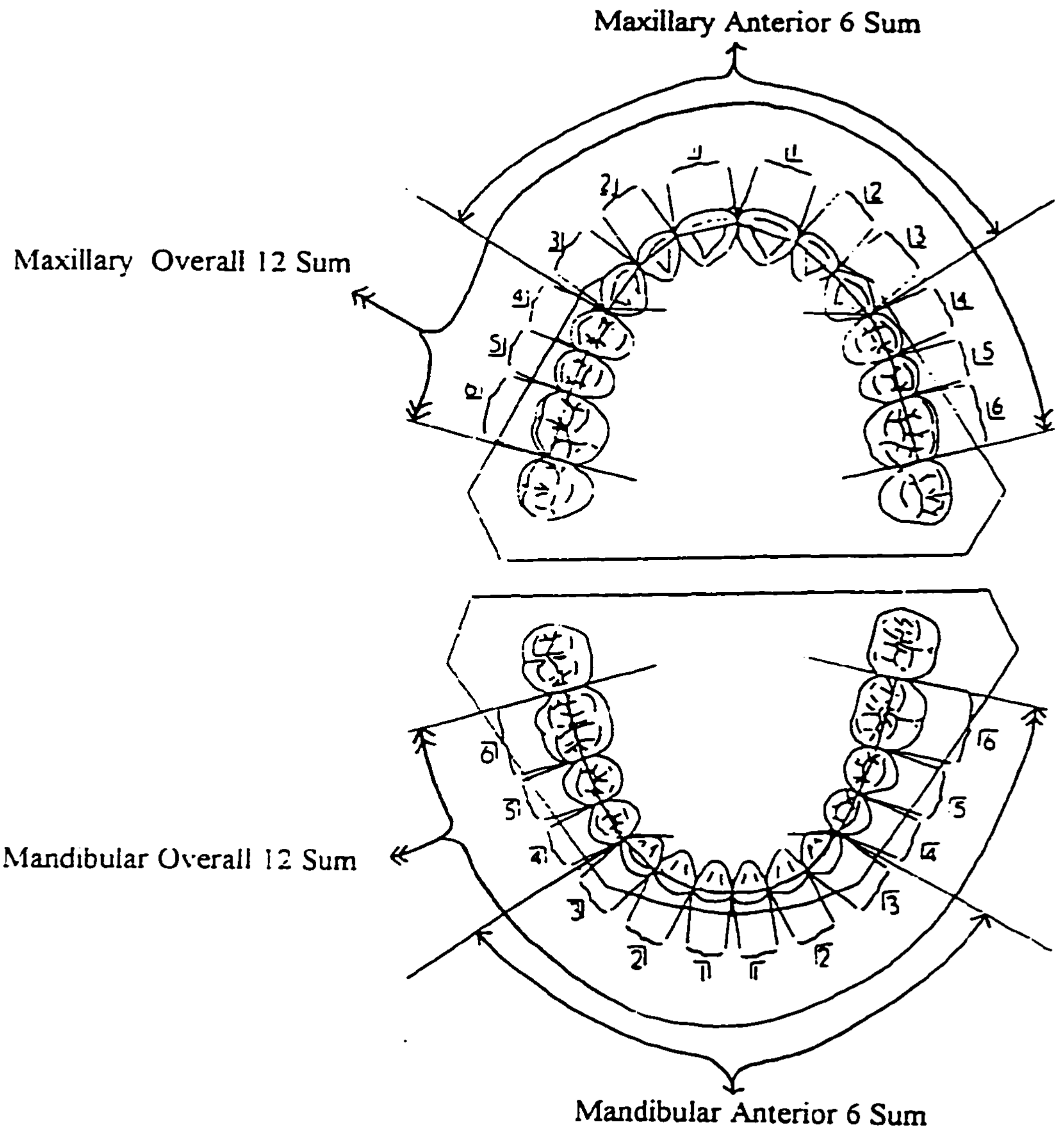
Appendices

APPENDIX A Mesiodistal Measures of Tooth Width for the Anterior and Overall Bolton Analysis



(*diagram from Bolton WA. Disharmony in tooth size and its relation to the analysis and treatment of malocclusion. Angle Orthod 1958;23(3):113-130.)

APPENDIX B Bolton's Anterior and Overall Analysis Ratios

$$\frac{\text{(sum mandibular 6)}}{\text{(sum maxillary 6)}} \times 100 = \text{Bolton's Anterior Six mean } 77.2.\%,\ 1.65 \text{ SD}$$

$$\frac{\text{(sum mandibular 12)}}{\text{(sum maxillary 12)}} \times 100 = \text{Bolton's Overall mean } 91.3\%,\ 1.91 \text{ SD}$$

APPENDIX C Hardware and Software Components

Electronic Digital Measuring Apparatus

- Mitoyoto* Calipers (Code # 500-171, Model # CD-6"C)
- Mitoyoto Connecting Cable (# 959150)
- Mitoyoto UP-1 Relay
- serial cable from UP-1 Relay interface to IBM clone PC
- custom machined base stand and measuring arm attachment for calipers
  measuring arm attachment: Centre Line Gauge (#050001)
  (for overjet and overbite measurements only)

Software

- DOS based custom program to record measurement data in Q-Basic
- Excel for Windows (3.1).
- custom designed Excel based spreadsheet Bolton Tooth Size Analysis
- SPSS for MS Windows (Release 6.1)

(* Mitoyoto MTI Canada Ltd., Mississauga, Ont., ABS Digimatic Caliper)

APPENDIX D BOLTON TOOTH SIZE ANALYSIS CUSTOM SPREADSHEET

Patient: #1 example

SIZE (mm)	TOOTH				
10.00	#16				
7.00	#15				
7.20	#14				
7.05	#13				
6.50	#12				
8.20	#11				
8.00	#21				
6.50	#22				
7.05	#23	sum max. "6"	43.30		
7.20	#24				
7.00	#25			sum max. "R"	45.95
10.00	#26	sum max. "12"	91.70	sum max. "L"	45.75
11.25	#36				
7.00	#35				
7.00	#34				
6.40	#33				
5.80	#32				
5.50	#31				
5.30	#41				
5.80	#42				
6.40	#43	sum mand. "6"	35.20		
7.00	#44				
7.00	#45			sum mand. "L"	42.95
11.25	#46	sum mand. "12"	85.70	sum mand. "R"	42.75

BOLTON ANALYSIS CALCULATIONS

Overall Ratio	=	sum mand. "12" / sum max. "12"	=	85.70 / 91.70	93.5%
(>91.3 %)	(actual mand. "12") - 85.70	(corrected mand.'12") 83.72	=	1.98	mand."12" discrepancy
(<91.3 %)	(actual max. "12") - 91.70	(corrected max.'12") 93.87	=	-2.17	max."12" discrepancy
Anterior Ratio	=	sum mand. "6" / sum max. "6"	=	35.20 / 43.30	81.3%
(>77.2 %)	(actual mand "6") - 35.20	(corrected mand."6") 33.43	=	1.77	mand."6" discrepancy
(<77.2 %)	(actual max. "6") - 43.30	(corrected max."6") 45.58	=	-2.28	max. "6" discrepancy

APPENDIX E Parameters Studied

Recorded Parameters

Recorded Parameters	
Cast ID Number	identification code
Gender	male or female (sex = 0 or 1)
W #16	tooth 16 width size in millimeters
W #15	tooth 15 width size in millimeters
W #14	tooth 14 width size in millimeters
W #13	tooth 13 width size in millimeters
W #12	tooth 12 width size in millimeters
W #11	tooth 11 wdth size in millimeters
W #21	tooth 21 width size in millimeters
W #22	tooth 22 width size in millimeters
W #23	tooth 23 width size in millimeters
W #24	tooth 24 width size in millimeters
W #25	tooth 25 width size in millimeters
W #26	tooth 26 width size in millimeters
W #36	tooth 36 width size in millimeters
W #35	tooth 35 width size in millimeters
W #34	tooth 34 width size in millimeters
W #33	tooth 33 width size in millimeters
W #32	tooth 32 width size in millimeters
W #31	tooth 31 width size in millimeters
W #41	tooth 41 width size in millimeters
W #42	tooth 42 width size in millimeters
W #43	tooth 43 width size in millimeters
W #44	tooth 44 width size in millimeters
W #45	tooth 45 width size in millimeters
W #46	tooth 46 width size in millimeters
AAW MX	anterior arch width maxilla
AMX1	anterior arch length 1st quadrant
AMX2	anterior arch length 2nd quadrant
AAW MD	anterior arch width mandible
AMD3	anterior arch length 3rd quadrant
AMD4	anterior arch length 4th quadrant
OJ #11	overjet measured at tooth11
OJ #21	overjet measured at tooth 21
IE #11	incisal edge height at tooth 11
IE #21	incisal edge height at tooth 21
IE #41	incisal edge height at tooth 41
IE #31	incisal edge height at tooth 31

APPENDIX E Parameters Studied (continued)

Calculated Parameters Chapter 2 and 4

Calculated Parameters	
Mx6 (mm)	sum of maxillary anterior 6 tooth size widths
Md6 (mm)	sum of mandibular anterior 6 tooth size widths
Mx12 (mm)	sum of maxillary 12 tooth size widths
Md12 (mm)	sum of mandibular 12 tooth size widths
Bolton 6 (%)	Bolton Anterior 6 ratio
Bolton12 (%)	Bolton Overall 12 ratio
Bolton 6 Ranking	case ranking within sample by Bolton Anterior ratio
Md 6 discrepancy (mm)	Md ant excess (or deficiency) compared to Bolton's correct arch perimeter
Mx 6 discrepancy (mm)	Mx ant excess (or deficiency) compared to Bolton's correct arch perimeter
Ave OJ (mm)	average overjet
Ave OB (mm)	average overbite
Torq 1 Mx* (degrees)	average maxillary incisor torque
Torq 1 Md* (degrees)	average mandibular incisor torque
Interincisal Angle**(degrees)	Interincisal Crown Angle

Calculated Parameters Chapter 4

(Amx1+2)/2 (mm)	average anterior maxillary arch length
Mx base/2 (mm)	1/2 anterior maxillary intercanine arch width
Mx HypSqd-BaseSqd	Pythagorean Theorem, equals Mx altitude squared
Mx square root=alt	solve for altitude anterior Mx arch segment
Mx depth (mm)	anterior maxillary arch depth = Mx altitude
x intercanine width (mm)	maxillary intercanine arch width = Mx base
(Amd3+4)/2 (mm)	average anterior mandibular arch length
Md base/2 (mm)	1/2 anterior mandibular intercanine arch width
Md HypSqd-BaseSqd	Pythagorean Theorem, equals Md altitude squared
Md square root=alt (mm)	solve for altitude anterior Md arch segment
Md depth (mm)	anterior mandibular arch depth = Md altitude
d intercanine width (mm)	mandibular arch intercanine width = Md base
Ave Area Mx6 (mm^2)	average maxillary anterior arch area
Ave Area Md6 (mm^2)	average mandibular anterior arch area
Mdarea/Mxarea	inter arch areas ratio
Md depth/Mx depth	inter arch depth ratio
Md IC width/Mx IC width	inter arch intercanine width ratio
Md Form Index	ratio maxillary depth divided by 1/2 mandibular intercanine width
Mx Form Index	ratio maxillary depth divided by 1/2 maxillary intercanine width
Form Ratio	mandibular Curve Index divided by maxillary Curve Index
Case Form	mandibular Curve Index multiplied by maxillary Curve Index

(*directly from and **derived from data tables in L.F. Andrews Straight wire: The concept and appliance. San Diego, California: L.A. Wells Publisher, 1989.)

APPENDIX F Intra Examiner Reliability

R E L I A B I L I T Y   A N A L Y S I S
S C A L E   (A L P H A)

N of Cases = 7 sets of casts

Each Parameter Measured Twice	Reliability Coefficients	
Anterior Bolton Ratio	Alpha =	0.941
Overall Bolton Ratio	Alpha =	0.980
Maxillary anterior 6 sum	Alpha =	0.998
Mandibular anterior 6 sum	Alpha =	0.983
Maxillary Discrepancy	Alpha =	0.938
Mandibular Discrepancy	Alpha =	0.938
Maxillary Intercanine Arch Width	Alpha =	0.957
Mandibular Intercanine Arch Width	Alpha =	0.977
Maxillary Arch Length	Alpha =	0.997
Mandibular Arch Length	Alpha =	0.995
Overjet	Alpha =	0.990
Overbite	Alpha =	0.996
First 2 Parameters measured twice	Alpha =	0.975
First 4 Parameters measured twice	Alpha =	0.872
All 12 Parameters measured twice	Alpha =	0.864

APPENDIX G Anterior Bolton Ratio Histogram

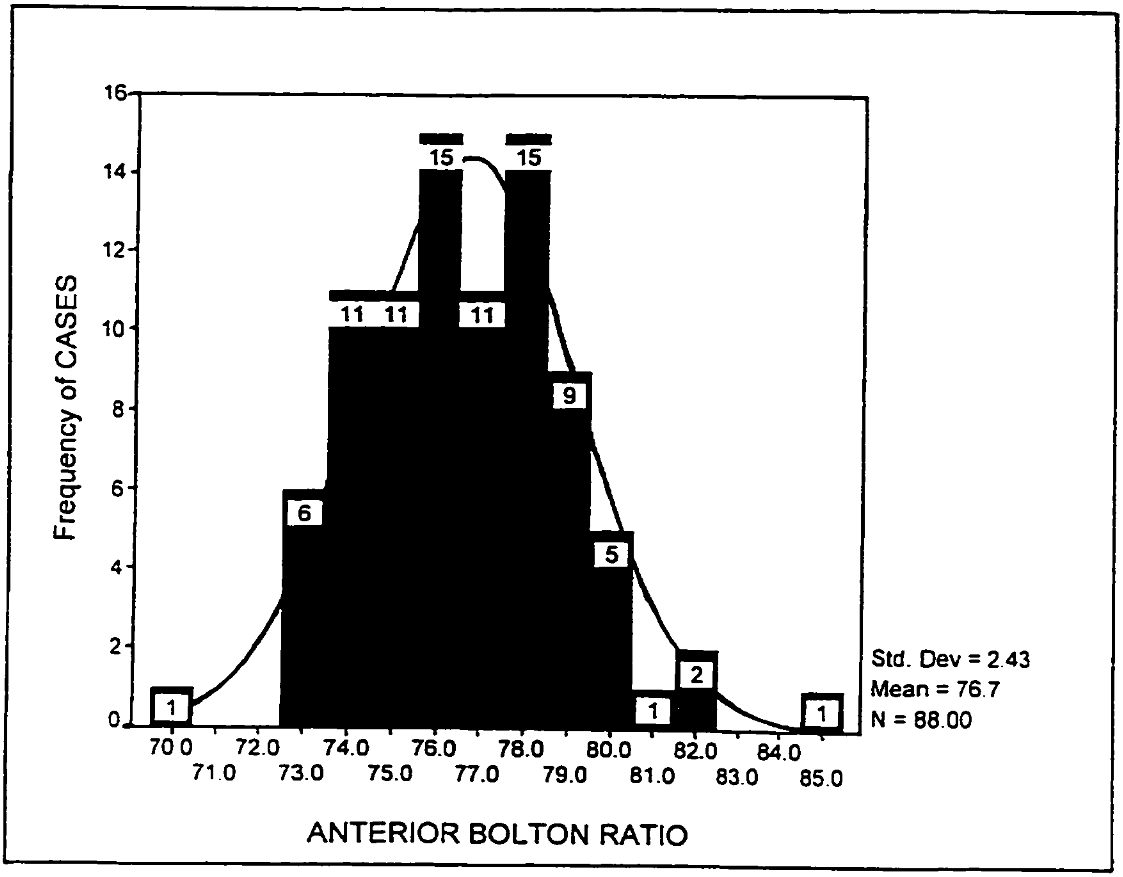


IMAGE EVALUATION TEST TARGET (QA-3)

150mm

6"

APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
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