Revisiting Bolton Analysis Using American Board of Orthodontics Cast Models

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THESIS

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This thesis is dedicated to my wife, (*Samar*), without whom it would never have been accomplished.

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LIST OF ABBREVIATIONS

3-3 Ratio	Anterior Tooth Size Ratio
6-6 Ratio	Overall Tooth Size Ratio
A	A Point (A Landmark on a cephalogram)
ABO	American Board of Orthodontics
B	B Point (A Landmark on a cephalogram)
IPR	Inter-Proximal Reduction
IRB	Institutional Review Board
MP	Mandibular Plane
N	Nasion Point (A Landmark on a cephalogram)
PAR	Peer Rating Index
PHI	Protected Health Information
PI	Principal Investigator
S	Sella Point (A Landmark on a cephalogram)
SD	Standard Deviation
SPSS	Statistical Product and Service Solutions (A computer program for statistics)
UIC	University of Illinois at Chicago
U1	Upper Central Incisor
U2-2	Upper Right Lateral to Upper Left Lateral
U3-3	Upper Right Canine to Upper Left Canine

SUMMARY

The study was carried out to determine the applicability and the accuracy of the Bolton's tooth size discrepancy analysis for both the overall and the anterior ratios. The study was also intended to determine if there is a correlation between either the overall or the anterior tooth size ratio and any of the following factors: overjet, overbite, anterior teeth proclination, interincisal angle, and upper anterior tooth thickness. Evaluating those factors could be helpful in enabling the clinician to better assess and predict tooth size descrypancies so that ideal orthodontic treatment results could be achieved.

The study was conducted by using a sample of 94 cases that passed the American Board of Orthodontics examination, a measure of outstanding orthodontic results. Both the dental stone models and the final cephalometric radiographs of these finished orthodontic cases were utilized. All of the 94 cases were included for the anterior tooth size ratio part of the study. Only 52 cases were included for the overall tooth size ratio part of the study, mostly due to extractions performed in the posterior region as part of treatment. The mesiodistal width of each tooth was measured to determine the Bolton ratios. Tooth width, overjet and overbite were measured using the dental stone models. Anterior tooth angulations were measured using the final cephlometric radiographs.

The results suggest that the Bolton analysis is a reliable diagnostic tool for assessing tooth size discrepancy. However, there were specific cases in the study sample with a significant tooth size discrepancies, yet those cases met the American Board of Orthodontics examination requirements.

There are other factors that may play a role in achieving ideal orthodontic treatment results despite having a tooth size discrepancy. Upper anterior tooth thickness, overjet, and overbite are factors that have an inverse correlation with tooth size ratios. In cases of higher tooth size ratios, the ideal occlusion could be achieved with a shallower overbite and a decreased overjet. On the other hand, in cases with lower tooth size ratios, an ideal occlusion could be achieved with a deeper overbite and an increased overjet. In a nutshell, Tooth thickness, overbite, and overjet were correlated to the Bolton ratios but the correlation was relatively low and the quantitative contribution of these factors to the Bolton ratio cannot be determined. It is recommended to prepare a preliminary diagnostic setup in cases that may show a significant tooth size discrepancy.

1. INTRODUCTION

1.1 Background

It is commonly accepted that the sizes of the maxillary and the mandibular teeth must be proportionate to accomplish excellent occlusal interdigitations with ideal overjet and overbite (Smith et al., 2000; Bolton, 1958). A disproportion between the sizes of maxillary and mandibular teeth is defined as a tooth size discrepancy (Proffit, 2000).

In any given orthodontic case with significant malocclusion it would be a challenge for the practitioner to predict whether the maxillary and the mandibular dental arches will fit properly in an excellent occlusion, after orthodontic treatment. Before the discovery of the mathematical formulas that evaluate tooth size discrepancy as described by Neff (1949), and subsequently by Bolton (1958), clinicians used diagnostic plaster setups as the main tool to evaluate tooth size discrepancy (Kesling, 1945). Nowadays most clinicians use mathematical formulas as their preliminary diagnostic tool to assess tooth size discrepancy. Diagnostic setups is performed on cases of malocclusion that have a severe tooth size discrepancies in order to better diagnose and treatment plan those cases (Bolton, 1958; Fields, 1981).

One of the best studies of intermaxillary tooth size discrepancy and its relation to malocclusion was done by Dr. Wayne Bolton in 1958. He described an analysis that would aid in identifying interarch tooth size discrepancies. Clinically significant tooth size discrepancies may prevent ideal interdigitation of upper and lower dentition.

He developed two formulas for interarch tooth size ratios, based on a sample of fifty-five patients with excellent occlusions. The first ratio is the overall ratio which includes teeth from first molar to first molar of upper and lower arches and the second ratio is the anterior ratio which includes teeth from canine to canine (Bolton, 1958).

Bolton's mathematical formulas pertaining to tooth size discrepancy have limitations. It has been speculated that Bolton's study subjects were mostly white females. The reason is that tooth size ratios found in that group most closely matches Bolton's ratios. Furthermore the majority of orthodontic patients during the 1950s were derived from white female population group (Othman and Harradine, 2006). This sampling would reflect a selection bias and possibly inaccurateness of the resultant mean ratios.

Later, many studies challenged the reliability of Bolton's analysis in predicting malocclusions related to tooth-size discrepancy (Paredes et al., 2006; Heusdens et al., 2000; Rudolph et al., 1998). Some speculated that, tooth dimensions exhibit significant difference for both mesio-distal width and labio-lingual thicknesses when comparing different ethnicities and different genders, which may affect the ideal tooth size mean ratios of the general population (Gillien et al., 1994; Merz et al., 1991; Lavelle, 1972; Moorrees et al., 1957).

Moreover, the concept of having an ideal tooth size ratio for the general population has been challenged (Freeman et al, 1996; Fields, 1981). Cases with significant Bolton discrepancies have been shown to have good occlusion while on the other hand cases with normal Bolton ratios has been shown to have a difficulty achieving a good occlusal relationship. The reason may be due to the involvement of other factors besides tooth size ratios leading to the resultant occlusal relationship. Many studies have suggested that the overbite (Bolton, 1958), overjet (Bolton,

1962), tip of incisors (Tuverson, 1980), torque of incisors, interincisal angles (Tuverson, 1980; Bolton, 1962), and lastly tooth thickness (Rudolph et al., 1998; Bolton, 1962) may affect ideal tooth size ratios in order to achieve an acceptable occlusal result in a given case. It has been shown using diagnostic setups that changes in the incisal angulation of the anterior teeth may result in an increase or a decrease of arch length suggesting a change in the ideal tooth size ratios (Tuverson, 1980). Furthermore when a dentition has excess labio-lingual thickness of upper incisors the ideal tooth size ratios may be decreased (Bolton, 1962). It is interesting to mention that the degree of overbite of the Bolton study sample varied from 11.8% to 53.9% of anterior central lower incisor coverage with a mean of 31.3% which is generally considered as a deep overbite according to commonly accepted standards. This observation denotes that the overbite of the Bolton study sample may have affected the resultant ideal tooth size ratios suggested by the study.

So the pressing question would be whether the tooth size discrepancy analysis using Bolton's ratios (91.3% for overall ratio, and 77.2% for anterior ratio) is an accurate diagnostic tool to be used in treatment planning patients with malocclusion seeking orthodontic treatment. If not, is there a better method that could be developed to improve the accuracy of the tooth size discrepancy analysis possibly by involving other factors that would affect achieving an ideal occlusion including the overjet, overbite, tip of anterior teeth, torque, interincisal angle, and anterior tooth thickness?

To answer that question, it is important to highlight the American Board of Orthodontics (ABO) clinical examination and its potential benefit to this research project. In brief, the American Board of Orthodontics offers an orthodontic specialty examination to orthodontists trying to qualify as ABO diplomates. ABO certification is a prestigious accomplishment and can

be used as a partial fulfillment for licensure to practice orthodontics in some states in the United States. The exam is divided into two parts: the first part is theoretical and the second part is a clinical one. The clinical part includes presenting orthodontically treated cases using a set of standards established by the ABO examination committee. The American Board of Orthodontics has been working relentlessly to improve their examination criteria, accuracy, and standardization. As a result candidates who passed the clinical exam have finished cast models with best occlusal interdigitation judged by the most objective standards available.

Orthodontic practitioners always strive to finish their cases to an ideal occlusion, but what is the definition of an ideal occlusion? The majority of the orthodontic community agrees that an ABO finished case would be very close to an ideally finished case. Conducting the research using models of ABO finished cases is beneficial. By using cases that passed the American Board of Orthodontics clinical examination, subjectivity in sample collection and investigator bias regarding identification of an ideal or an excellent occlusion would be greatly reduced.

After determining the accuracy and applicability of Bolton's tooth size ratios, the next step is to determine possible correlations between tooth size ratios and any of the following factors: overjet, overbite, axial angulation of incisors, interincisal angle, and thickness of anterior teeth. The anterior tooth angulation in the Bolton study was measured using the facial surface plane of the anatomical crowns. The measurement obtained may not represent a true reflection of the axial inclination of the anterior teeth because of the anatomical variability of these teeth. Using lateral cephalograms to measure anterior teeth angulations may represent a better reflection of anterior tooth angulation and eventually have a more accurate correlation with the tooth size ratios of the study models included in this research.

This study is intended to provide a better understanding of ideal interarch tooth size ratios and their relation with many other factors contributing to a good occlusion. To have such an understanding would provide a better diagnostic tool for clinicians, and that would result in a more effective treatment of malocclusions.

1.2 Objectives

- The main objective of this research is to determine the applicability and the accuracy of Bolton tooth size discrepancy analysis by using cases that passed the American Board of Orthodontics examination.
- To determine the correlation between the Bolton ratios and any of the following factors: overjet, overbite, anterior teeth inclination, interincisal angle, and upper anterior tooth thickness.

1.3 Null Hypothesis

There is no significant difference between Bolton's tooth size ratios (91.3% for overall teeth and 77.2% for anterior teeth) as published in the Bolton study (1958) and the corresponding ratios obtained from cases that passed the American Board of Orthodontics examination.

2. LITERATURE REVIEW

2.1 Historic Background

It is widely accepted that a certain proportion between the maxillary and mandibular dental arch length should exist in order to fit teeth into good occlusion, proper interdigitation, ideal overbite, and overjet (Smith et al., 2000; Bolton, 1958). In the past, clinicians have used few methods to predict tooth size discrepancies in malocclusion cases seeking treatment. One of the most important methods was to perform diagnostic setups to evaluate whether or not a tooth size discrepancy exist in malocclusion cases about to be treated (Kesling, 1945). A diagnostic setup is still a valid diagnostic tool, yet most clinicians use mathematical formulas as a preliminary diagnostic method to assess tooth size discrepancies. Only cases with a severe tooth size discrepancy may need diagnostic setups in order to better assess the case (Othman and Harradine, 2006; Fields, 1981; Bolton, 1958). Other researchers proposed the use of occlusograms to do what is described as "occlusal simulation" to predict tooth size discrepancies (White, 1982). White suggested the occlusal simulation as a more accurate method than the diagnostic setups.

One of the first investigations to inspect the topic of tooth size, and to outline average teeth dimensions was done by G.V. Black in late nineteenth century. He measured a large number of human teeth, and constructed tables with their mean dimensions (Black, 1902); these tables are still considered as an important research reference today.

Neff measured the mesiodistal width of the maxillary and mandibular anterior teeth of two hundred casts before treatment using a bow divider. He then came up with an "anterior coefficient" by dividing the sum of the mesiodistal widths of the upper anterior teeth from canine to canine by the sum of the mesiodistal widths of the lower anterior teeth. The range of the coefficient was 1.17 to 1.41. Later in the study, he correlated the "anterior coefficient" to the degree of overbite using percentage measurements. By using cases with normal occlusion and 20% overbite. Neff showed that the "anterior coefficient" ranged from 1.20 to 1.22 (Neff, 1949).

One of the main investigators in dental anatomy was Wheeler. He published a text book containing tooth dimensions which have been formulated so that artificial teeth could be fabricated and set together in an ideal occlusion (Wheeler, 1940).

In 1958 a study conducted by Wayne A. Bolton investigated tooth size discrepancy which he described as tooth size disharmony. The study was carried out in a manner similar to the Neff study in 1949. The aim of the Bolton study was to analyze a group of individuals with what he described as "excellent occlusions" and to determine whether or not statistically proven mathematical ratios could be established between the summed length of the lower dental arch and the summed length of the upper dental arch, both for overall dental arch length (first molar to first molar) and anterior dental arch length (canine to canine). By establishing a way for assessing tooth size discrepancy, Bolton helped clinicians in diagnosing and treatment planning malocclusion as well as to aid in determining the outcome of treatment (Bolton, 1958).

Bolton's sample consisted of fifty five subjects with "excellent occlusions" according to the author. Forty four cases were treated orthodontically with non-extraction and eleven cases were untreated but were in excellent occlusions (Bolton, 1958). The sample was collected from

ten different private practices as well as the Department of Orthodontics, School of Dentistry, University of Washington. The mesiodistal widths of the twelve mandibular teeth (right first molar to left first molar) were summed and divided by the corresponding summation of the maxillary teeth and multiplied by a hundred to obtain the overall ratio of interarch tooth size relation.

$$\text{Overall ratio} = \frac{\text{Sum of MD widths of mandibular 12 teeth (first molar} - \text{first molar)}}{\text{Sum of MD widths of maxillary 12 teeth (first molar} - \text{first molar)}} \times 100$$

Figure 1. The overall tooth size ratio formula as described by Bolton, 1958

A similar mathematical formula was determined to produce what is called the anterior ratio of interarch tooth size relation.

$$\text{Anterior ratio} = \frac{\text{Sum of mandibular anterior 6 teeth}}{\text{Sum of maxillary anterior 6 teeth}} \times 100$$

Figure 2. The anterior tooth size ratio formula as described by Bolton, 1958

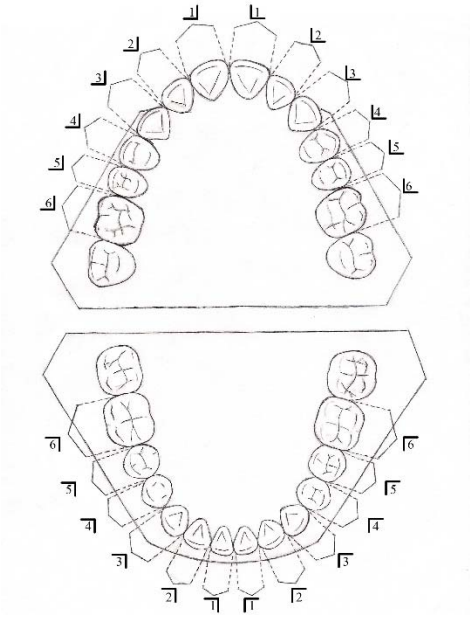

Figure 3. Drawing of the mesiodistal measurements being recorded. Adapted from Bolton (1958)

The degree of overbite was measured as the amount of coverage of the lower central incisor by the upper central incisor in maximum intercuspation and was reported as a percentage. Overjet was measured as a linear measurement from labial surface of lower central incisor to the incisal edge of the upper central incisor. Interincisal angle was recorded using the labial surface of the upper and lower central incisors. Cuspal height of the posterior teeth was measured from the cusp tip to the depth of the central fossa midway mesiodistally. The main reason for measuring the aforementioned entities was to establish a correlation coefficient between any of these factors and tooth size ratios. The study reported mean, standard deviations and a coefficient of variation for both overall ratio and anterior ratio (Table I).

TABLE I

OVERALL AND ANTERIOR RATIOS AS REPORTED BY THE BOLTON STUDY, 1958

	Overall ratio	**Anterior ratio**
Range	**87.5%-94.8%**	**74.5%-80.4%**
Mean	**91.3 %**	**77.2%**
Standard Deviation	**1.91**	**1.65**
Standard error of the mean	**0.26**	**0.22**
Coefficient of variation	**2.09%**	**2.14%**

Adapted from (Bolton, 1958)

The degree of overbite in his sample ranged from 11.8% to 53.9% with a mean of 31.2% which would be considered a deep bite. A significant correlation coefficient could not be found between the degree of overbite and anterior tooth size ratio, contrary to what was reported by Neff (1949). However the study concluded that the analysis could be used as a preliminary diagnostic tool in detecting tooth size discrepancy, but the final diagnosis should be based on a diagnostic setup (Bolton, 1958).

2.2 The Accuracy and Applicability of Bolton Analysis for Tooth Size Discrepancy Detection

Although the Bolton analysis for tooth size discrepancy determination has been considered to be handy and easy to use, its accuracy and validity have been discussed and disputed (Freeman et al., 1996; Fields, 1981). Many studies have reported that 20 to 30% of the general population inherently possess significant anterior tooth size discrepancies and yet demonstrate an excellent occlusion (Othman and Harradine, 2006). One study suggested that in cases with proclined incisors, smaller than normal interincisal angles, and thicker upper anterior teeth, the Bolton ratios may not be applicable (Bolton, 1962). Another study evaluated the effects of an artificially introduced tooth size discrepancy to typodonts with excellent occlusion. The teeth width were altered. The typodonts then were set together in the best occlusal fit possible. The study concluded that a tooth size discrepancy by up to twelve millimeters could still permit a satisfactory occlusion (Heusdens et al, 2000). Other studies have suggested overbite (Bolton, 1958), overjet (Bolton, 1962), tip of incisors (Tuverson, 1980), torque of incisors, interincisal angles (Tuverson, 1980; Bolton, 1962), and lastly tooth thickness (Rudolph et al., 1998; Bolton, 1962) as an influential factors in achieving excellent occlusion. It has been shown using diagnostic setups that an increase or a decrease in arch length results from changes in incisal angles (Tuverson, 1980). It's also important to mention that one study (Rudolph et al., 1998) reported a strong correlation between anterior tooth size ratio and upper incisal tooth thickness. Rudolph suggested two formulas for anterior tooth size relations under the circumstances of ideal anterior proclination.

Formula one: Predicted ideal ratio= -7.053(tooth thickness) +95.024 if tooth thickness <2.75mm.

Formula two: Predicted ideal ratio= -7.053(tooth thickness) +81.874 if tooth thickness ≥2.75mm.

The aforementioned study concluded that the new formulas were better than Bolton's ratio in predicting tooth size discrepancy.

2.3 The Importance of Using the American Board of Orthodontics Clinical Examination Standards to Assess Occlusal Outcome in Orthodontic Cases

The American Board of Orthodontics (ABO) continually strives to make the clinical examination an accurate and a reliable tool for assessment of finished orthodontic results by providing both the examiners and the examinees with the same set of criteria to determine the sufficiency of their finished orthodontic cases. The Board has created a "Model Grading System" to evaluate the final dental casts and panoramic radiographs as described by The ABO Grading System for Dental Casts and Panoramic Radiographs Guide, revised in June, 2012 (ABO Grading System for Casts-Radiographs, 2012). This evaluation method was developed methodically in the course of a cycle of four assessments which started in 1995 and stretched for five years (ABO Grading System for Casts-Radiographs, 2012).

In 1987 the Peer Assessment Rating Index (PAR) was considered by the ABO to assess dental occlusion at several stages of development. The PAR Index was considered to have good dependability and validity. On the other hand this method was not accurate enough to identify minor tooth position discrepancies (Richmond, 1992). In 1995 after a series of field tests, eight criteria were implemented over a period of five years in the evaluation of final dental casts and panoramic radiographs. These criteria are: alignment, marginal ridges, buccolingual inclination, occlusal relationships, occlusal contacts, overjet, interproximal contacts, and root angulation

(ABO Grading System for Casts-Radiographs, 2012). The evaluation system that was developed by the series of these four field tests was finally implemented in February 1999. It was also used for assessing outcomes of occlusions by numerous studies published in the most prestigious journals around the world (Kravitz et al., 2009; Hsieh et al., 2005; Abie et al., 2004; Pinskaya et al., 2004).

Due to the objective nature of the ABO examination, it would be beneficial to utilize orthodontically treated cases that passed the American Board of Orthodontics clinical examination, to further evaluate the accuracy of Bolton tooth size discrepancy. Bias in the sample collection and investigator preference regarding identification of ideal or excellent occlusion would be objectively addressed.

2.4 The Bolton Analysis: facts, deficiencies, and goals

Looking back at the literature we can summarize that in order for teeth to fit in good occlusion, a tooth size ratio should exist. Tooth size ratios can be manipulated up to twelve millimeters of discrepancy and still achieve an acceptable occlusion. Tooth size ratios may be influenced by other factors such as upper incisors thickness, anterior incisors inclination, overjet, and overbite.

The definition of an ideally finished orthodontic case is lacking objectivity because it relied on the investigators criteria and judgment to filter the sample, as found in all of the previous studies.

The goal is to further elucidate what constitutes an ideal orthodontic finish, and relevancy of tooth size ratio with ideal occlusal relationship.

3. MATERIALS AND METHODS

3.1 Performance Site

This investigation took place at the University of Illinois at Chicago, College of Dentistry.

3.2 Subject Description

Dental stone models obtained from candidates who passed the ABO examination and fit the inclusion and exclusion criteria mentioned later in the chapter were included in the research. Subjects were not equally spread between males and females, neither equally distributed among races. It is important to mention that the final cephalometric radiograph of every subject included in the study was used as described later in the methods section.

3.3 Methods

3.3.1 Phase One

The first step was to locate study models and final cephalometric radiographs of finished orthodontic cases that successfully passed ABO clinical examination from UIC data base. Most of those cases were gathered from former graduates of UIC, College of Dentistry orthodontic specialty program who took the ABO examination and passed. The rest of the cases were gathered from UIC faculty who took the ABO examination and passed. Each ABO certified person had about six cases that were included in this project. In a few cases there were persons able to offer about ten cases. Based on the Bolton study sample (1958) it was reasonable to try to

gather the same sample number which was 55 cases or even more to be able to compare the results to that of the Bolton's study. The final number gathered for the study was 52 cases with no missing or extracted teeth excluding the third molars, and 42 cases representing extraction cases. The total number of cases was 94.

After gathering the sample the principal investigator de-identified the data by blocking the patients' names on the ABO examination binders that belonged to each case. There were no identifiable data during the research process. The ABO case number was the only identifier that was used during this research in order to be able to link the stone models to the cephlometric radiographs of the same cases. No retained PHI information was included in the research material and there was no way to trace back the study models or the attached cephlometric radiographs. All the de-identified raw data were not available to anyone other than the principal investigator and the research staff.

3.3.2 Phase Two

All dental casts that did not fit the following inclusion criteria were excluded from the study.

1. Angle Class I molar relation.
2. Angle Class II molar relation was used for anterior canine to canine ratio only.
3. Angle Class III molar relation was used for anterior canine to canine ratio only.
4. Upper canine occludes into the embrasure between lower canine and first bicuspid.
5. As far as teeth alignment all cases were included unless there was a buccal to lingual contact discrepancy of more than 0.5mm translating to minor teeth crowding.
6. No anterior tooth extraction and no missing anterior teeth.

7. Posterior extraction or posterior missing teeth were still used for anterior canine to canine ratios only.
8. No spacing between teeth was allowed in the study.

3.3.3 Phase Three

The determination of tooth size discrepancy ratios for both anterior and overall relationships is described in detail later in this section. For casts that were used only to determine the anterior tooth size discrepancy ratio, the mesio-distal width of each tooth of both upper and lower anterior teeth from canine to canine was recorded individually. The casts that were used to determine both, the overall and the anterior tooth size discrepancy ratios, the mesiodistal width of each tooth of both upper and lower dentition from first molar to first molar were recorded individually. Only casts that did not have any spacing, missing or extracted teeth excluding second and third molars were included in the determination of overall tooth size discrepancy ratio. The measurements were conducted by a pointed head digital gauge caliber with an accuracy of 0.05mm. It is important to mention that in the event of having a mesiodistally angulated tooth, the clinical width at the interproximal contacts was measured instead of the anatomical width of that tooth.

The thickness of the incisal edge of each maxillary anterior tooth was measured from upper right canine to upper left canine 2mm gingival to the incisal edge at three points: 1mm away from the mesial proximal surface, 1mm away from the distal proximal surface, and in the middle of the mesio-distal distance. A crown thickness gauge was used to complete this task with an accuracy of 0.01mm.

The overjet was measured as the distance from the labial surface of the upper central incisor to the labial surface of the corresponding lower central incisor in maximum intercuspation. The overbite was measured as the distance from the incisal edge of the lower central incisor to the projection of the corresponding upper incisal edge on the labial surface of the same lower incisor in maximum intercuspation.

The overjet and the overbite were measured in maximum intercuspation with both upper and lower casts trimmed to the ABO standards held on their heels on a flat surface using a digital gauge caliber with an accuracy of 0.05mm. Both upper right central incisor to lower right central incisor and upper left central incisor to lower left central incisor were measured for overjet and over bite and then the right and the left measurements were averaged for each cast.

Finally, all final cephalometric radiographs were retraced by one operator and the following angle values were recorded respectively with its corresponding dental cast (interincisal angle, U1-SN, U1-NA, L1-MP, and L1-NB). The following paragraph is a description of the above mentioned cephalometric tracing angles.

The interincisal angle is the angle measured between long axis of upper and lower central incisors in maximum intercuspation.

U1-SN is the angle created between long axis of upper central incisor and Sella to Nasion plane.

U1-NA is the angle created between long axis of upper central incisor and Sella to point A plane.

L1-MP is the angle created between long axis of lower central incisor and mandibular plane. The mandibular plane is constructed by connecting Menton to constructed Gonion points.

L1-NB is the angle created between long axis of lower central incisor and Sella to point B plane.

3.3.4 Phase Four

The anterior tooth size discrepancy ratio was obtained by summing the mesio-distal width of the lower anterior teeth from lower right canine to lower left canine and dividing the result by the sum of the mesio-distal width of the upper anterior teeth from upper right canine to upper left canine and multiplying the resulting number by 100 as illustrated by the following equation:

$$\frac{\text{Sum mandibular “6”}}{\text{Sum maxillary “6”}} \times 100 = \text{anterior ratio (\%)}$$

The overall tooth size discrepancy ratio was obtained by summing the mesio-distal width of the lower teeth from lower right first molar to lower left first molar and dividing the result by the sum of the mesio-distal width of the upper teeth from upper right first molar to upper left first molar and multiplying the resulting number by 100 as illustrated by the following equation:

$$\frac{\text{Sum mandibular “12”}}{\text{Sum maxillary “12”}} \times 100 = \text{overall ratio (\%)}$$

3.3.5 Phase Five

The intra- and inter- reliability test of a repeated measure was accomplished using ten dental cases measured by the principal investigator twice with a two week time interval and a second assistant volunteer researcher measuring the same cases one time only. The variables were approximately normally distributed ($p>0.05$). A paired samples t-test was computed, the results indicated that the correlation coefficient of the variables in the study is a high positive

correlation (r>0.80), and provided a good support to the method used. Once that was accomplished the rest of the casts and cephalometric radiographs were measured to gather the raw data as previously described in this chapter.

3.3.6 Phase Six

At this stage means of anterior and overall tooth size discrepancy ratios were obtained and compared to the anterior and overall tooth size discrepancy ratios as suggested by the Bolton study. The null hypothesis was tested using this comparison.

Statistics were run using SPSS version 19.0. The sample size was (n = 52) for overall tooth size ratio and (n=94) for anterior tooth size ratio. A Pearson correlation test was run to determine the possible correlations of both tooth size discrepancy ratios derived from the study and the following variables, (upper anterior teeth thickness, overjet, overbite, U1-SN, U1-NA, L1-MP, L1-NB, or the interincisal angle).

3.4 Monitoring Plan

This research presented minimal risks. All data from the study could be accessed only by the principal investigator (PI), and the other research personnel. The PI will store all data until May, 2013 after which the data will be stored securely in the Department of Orthodontics at the College of Dentistry. The UIC Office for the Protection of Research Subjects has determined that this study does not meet the definition of human subject research as defined by 45 CFR 46.102(f). The IRB approval number is 20120640-69258-1 and was received on July 26, 2012.

4. RESULTS

4.1 Descriptive statistics

The raw data were analyzed using SPSS version 19.0. The outputs illustrated in the following tables and plots provide descriptive statistics for all the variables mentioned in the hypotheses.

TABLE II

DISCRIPTIVE STATISTICS OF THE OVERALL AND THE ANTERIOR RATIOS, OVERJET, OVERBITE, UPPER INCISORS THICKNESS, INCISORS ANGULATION, AND INTERINCISAL ANGULATION

	N	Mean	Std. Deviation	Range
3-3 Ratio	94	77.17	2.41	70.7%-82.3%
6-6 Ratio	52	91.3	1.78	86.3%-95.0%
Overjet Aver.	94	2.47	0.55	0.94-3.96mm
Overbite Aver.	94	1.82	0.64	0.15-3.4mm
U3-3 Aver. thickness	94	2.21	0.2	1.76-2.85mm
U2-2 Aver. thickness	94	2.14	0.37	1.75-2.88mm
U1 SN	94	106.46	7.6	88-123 degrees
U1 NA	94	23.91	7.83	4-40 degrees
L1 MP	94	97.15	8.29	75-116 degrees
L1 NB	94	31.69	5.76	15-47 degrees
Inter incisal Angle	94	120.82	7.47	103-137 degrees

Table II describes the mean average of the anterior ratios, overjet, overbite, upper incisors thickness, incisors angulation and interincisal angulation. It also describes the standard deviations, the highest and lowest readings of the study sample.

4.1.1 Test of Normality

TABLE III

KOLMOGOROV-SMIRNOV AND SHAPIRO-WILK TESTS

Tests of Normality

	Kolmogorov-Smirnov[a]		Shapiro-Wilk	
	N	P value	N	P value
6-6 Ratio	52	.200	52	.540
3-3 Ratio	94	.200	94	.231
Overjet Aver.	94	.200	94	.372
Overbite Aver.	94	.054	94	.181
U3-3 Aver. thick.	94	.200	94	.906
U2-2 Aver. thick.	94	.105	94	.060
U1 SN	94	.200	94	.445
U1 NA	94	.200	94	.631
L1 MP	94	.200	94	.443
L1 NB	94	.006	94	.082
Inter-incisal Angle	94	.167	94	.077

a. Lilliefors Significance Correction

All the variables in the study (anterior ratios, overjet, overbite, upper incisors thickness, incisors angulation and interincisal angulation) showed to be approximately normally distributed ($p>0.05$). Both Kolmogorov-Smirnov and Shapiro-Wilk tests were computed as illustrated in table III.

4.1.2 Student t-Test

TABLE IV

A COMPARISON OF THE OVERALL AND THE ANTERIOR RATIOS AS REPORTED BY THE BOLTON STUDY, 1958, WITH THE SAME RATIOS DERIVED FROM THIS STUDY

	Range	Mean	Standard Deviation	Standard error of the mean	Coefficient of variation
Overall ratio (Bolton, 1958)	**87.5%-94.8%**	**91.3**	**1.91**	**0.26**	**2.09%**
Overall ratio (This study)	**86.3%-95.0%**	**91.3 %**	**1.78**	**0.25**	**1.94%**
Anterior ratio (Bolton, 1958)	**74.5%-80.4%**	**77.2**	**1.65**	**0.22**	**2.14%**
Anterior ratio (This study)	**70.7%-82.3%**	**77.2**	**2.41**	**0.25**	**3.12%**

The coefficient of variation in the anterior tooth size ratio is 1.61 times higher than the coefficient of variation in the overall tooth size ratio. The Bolton study (1958) sample variation in the overall tooth size ratio is 1.08 times higher than the coefficient of variation in the study sample. The study sample coefficient of variation in the anterior tooth size ratio is 1.46 times higher than the coefficient of variation in the Bolton sample.

TABLE V

ONE SAMPLE T-TEST COMPARING THE MEAN OF THE OVERALL TOOTH SIZE RATIO DERIVED FROM THE STUDY SAMPLE AND ITS EQUIVELANT MEAN VALUE OF 91.3 SUGGESTED BY THE BOLTON STUDY, 1958

One-Sample Test

	Test Value = 91.3			
			95% Confidence Interval of the Difference	
	P value	Mean Difference	Lower	Upper
6-6 Ratio	0.998	-0.00073	-0.4963	0.4948

Coefficient of variation: (100 x std. deviation)/ mean = 1.94%

A one-sample t-test comparing the overall tooth size ratio of the study with the Bolton's study (table V) was computed. The test suggests that the overall ratio variable in the study does not show statistically significant differences from the norms derived from the Bolton Study.

TABLE VI

ONE SAMPLE T-TEST COMPARING THE MEAN OF THE ANTERIOR TOOTH SIZE RATIO DERIVED FROM THE STUDY SAMPLE AND ITS EQUIVELANT MEAN VALUE OF 77.2 SUGGESTED BY BOLTON

One-Sample Test

	Test Value = 77.2			
			95% Confidence Interval of the Difference	
	P value	Mean Difference	Lower	Upper
3-3 Ratio	0.906	-0.02945	-0.5228	0.4639

Coefficient of variation: (100 x std. deviation)/ mean = 3.12%

The same test comparing the anterior tooth size ratio of the study with the Bolton's study (table VI) was computed. The test suggests that the anterior ratio in the study does not show statistically significant differences from the Bolton Study (1958).

4.1.3 Test of Correlation

To investigate if there are statistically significant associations between the overall tooth size ratio, and each of the other variables in the study, a Pearson correlation test was computed. The same was done with anterior tooth size ratio. The test of correlation suggested that, three pairs of variables (overall tooth size ratio & overjet, overall tooth size ratio and overbite, and overall tooth size ratio and upper anterior teeth thickness) showed statistically significant correlations. The coefficient of correlation was negative with a range from -0.376 to -0.310, ($p<0.05$). The test of correlation suggested that three pairs of variables (anterior tooth size ratio and overjet, anterior tooth size ratio and overbite, and anterior tooth size ratio and upper anterior teeth thickness) showed statistically significant correlations, the coefficient of correlation was negative with a range from -0.342 to -0.300, $p<0.05$. The other variables did not show statistical significance of correlation ($p>0.05$).

TABLE VII

PEARSON CORRELATION TEST COMPARING THE OVERALL AND ANTERIOR TOOTH SIZE RATIOS WITH EACH OF THE FOLLOWING VARIABLES (ANTERIOR OVERJET, OVERBITE, UPPER ANTERIOR TOOTH THICKNESS, UPPER AND INCISOR ANGLES, AND INTERINCISAL ANGLE)

		3-3 Ratio	6-6 Ratio
Overjet Aver.	Pearson Correlation	-.338*	-.310*
	P value	.001	.025
	N	94	52
Overbite Aver.	Pearson Correlation	-.342*	-.342*
	P value	.001	.013
	N	94	52
U2-2 Aver. thickness	Pearson Correlation	-.300*	-.376*
	P value	.003	.006
	N	94	52
U3-3 Aver. thickness	Pearson Correlation	.004	-.155
	P value	.973	.273
	N	94	52
U1 SN	Pearson Correlation	.105	.000
	P value	.313	1.000
	N	94	52
U1 NA	Pearson Correlation	.176	.020
	P value	.090	.886
	N	94	52
L1 MP	Pearson Correlation	-.067	-.056
	P value	.519	.692
	N	94	52
L1 NB	Pearson Correlation	-.135	-.183
	P value	.194	.193
	N	94	52
Inter incisal Angle	Pearson Correlation	-.035	.169
	P value	.740	.232
	N	94	52

*. Correlation is significant.
Correlation of 0.1 to 0.3 or -0.1 to -0.3 is small
Correlation of 0.3 to 0.5 or -0.3 to -0.5 is medium
Correlation of 0.5 to 1.0 or -0.5 to -1.0 is strong

4.1.4 Statistical Plots

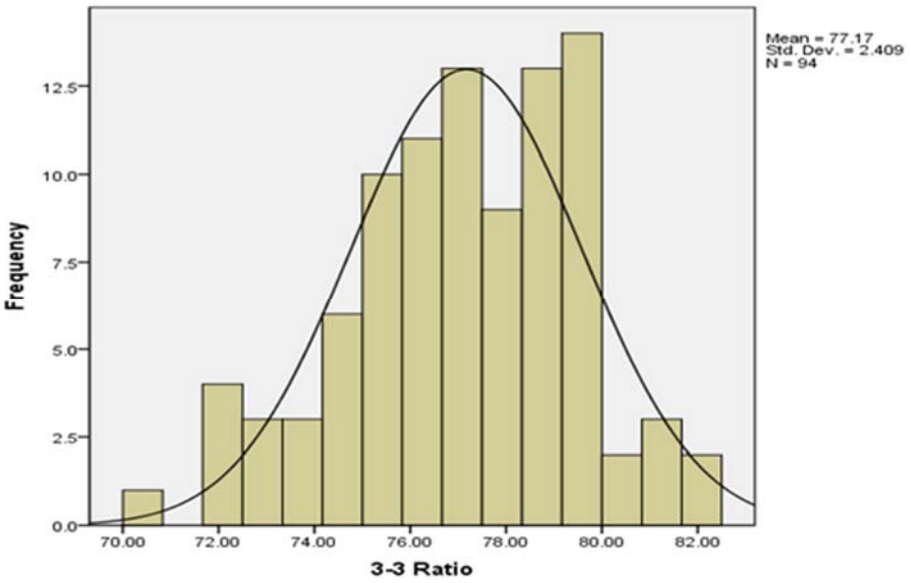

Figure 4. Anterior tooth size ratio distribution within the study sample.

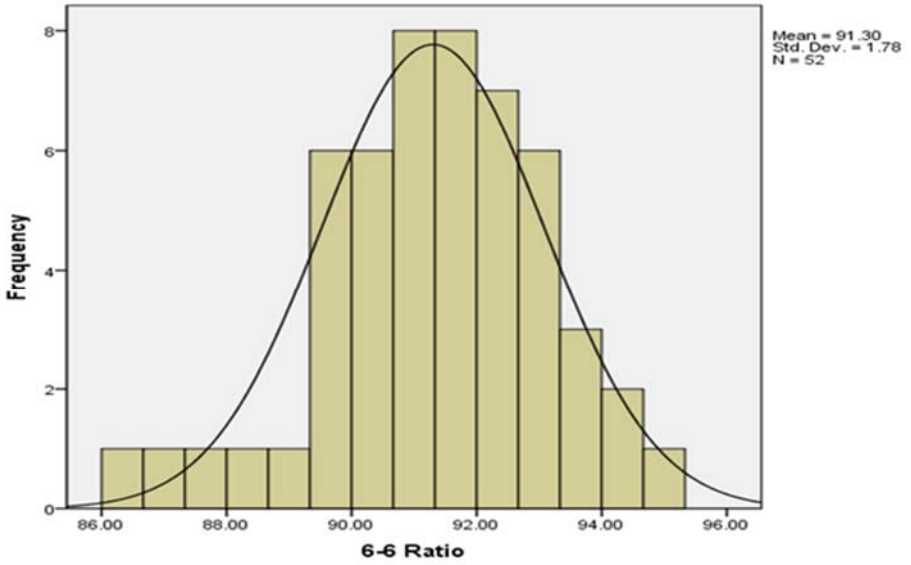

Figure 5. Overall tooth size ratio distribution within the study sample.

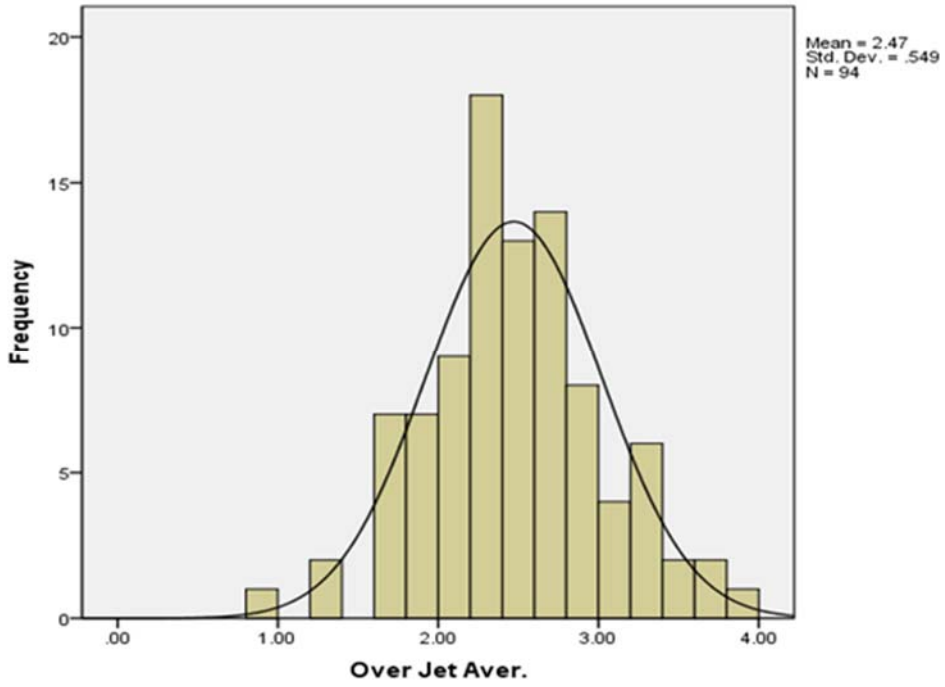

Figure 6. Anterior overjet distribution within the study sample**.**

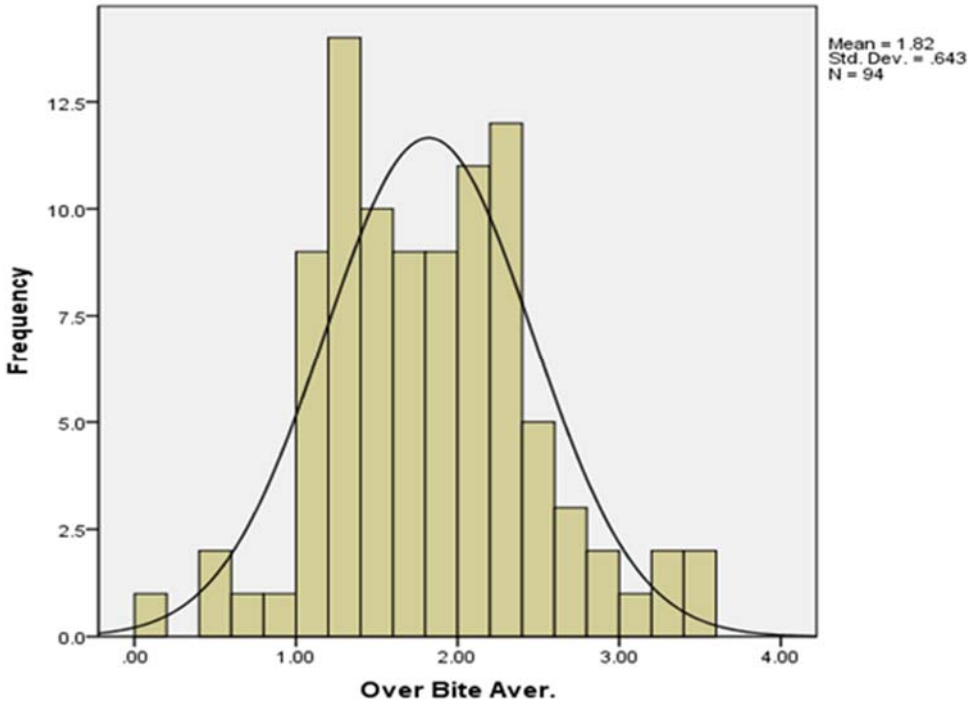

Figure 7. Anterior overbite distribution within the study sample.

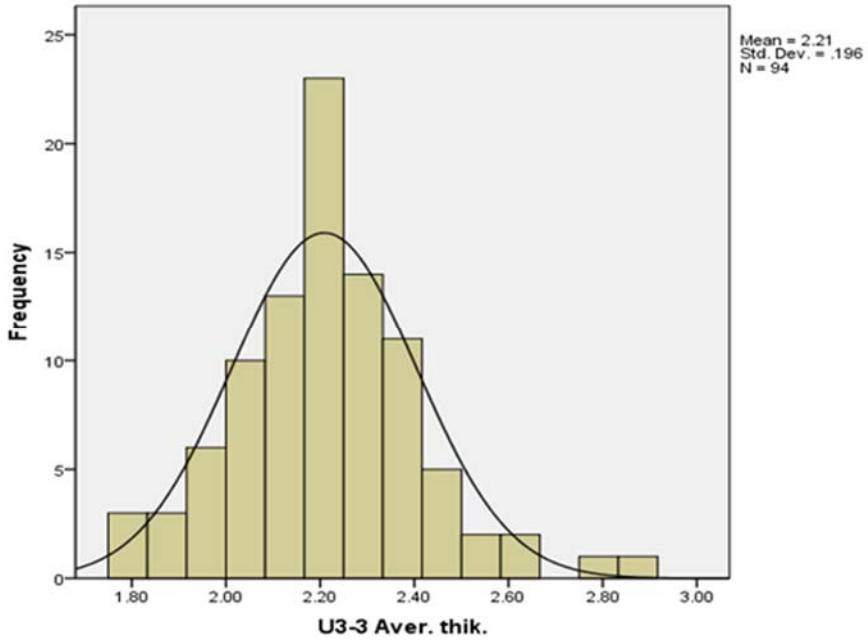

Figure 8. Distribution plot of the upper tooth thickness average of the anterior six teeth within the study sample.

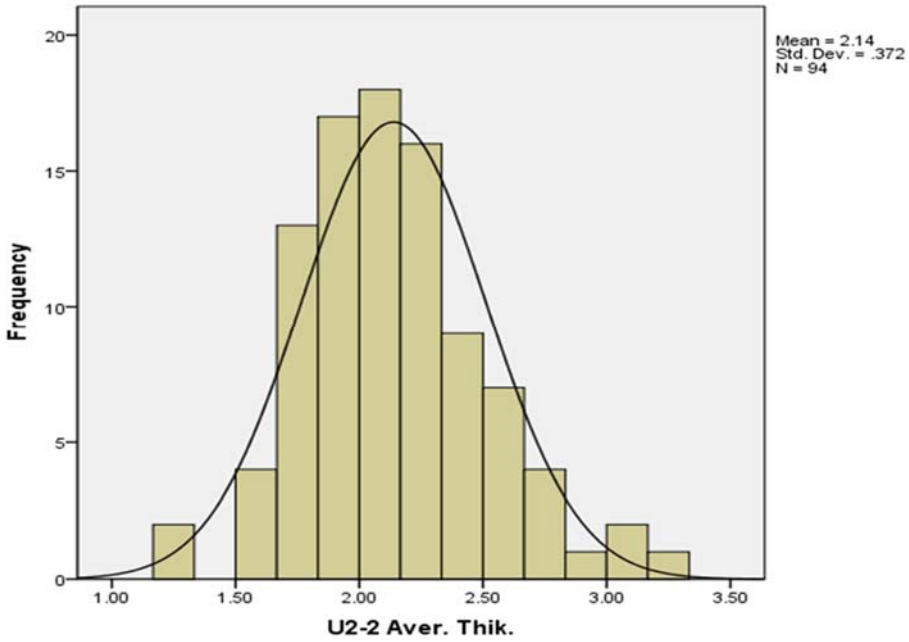

Figure 9. Distribution plot of the upper tooth thickness average of the anterior four teeth within the study sample

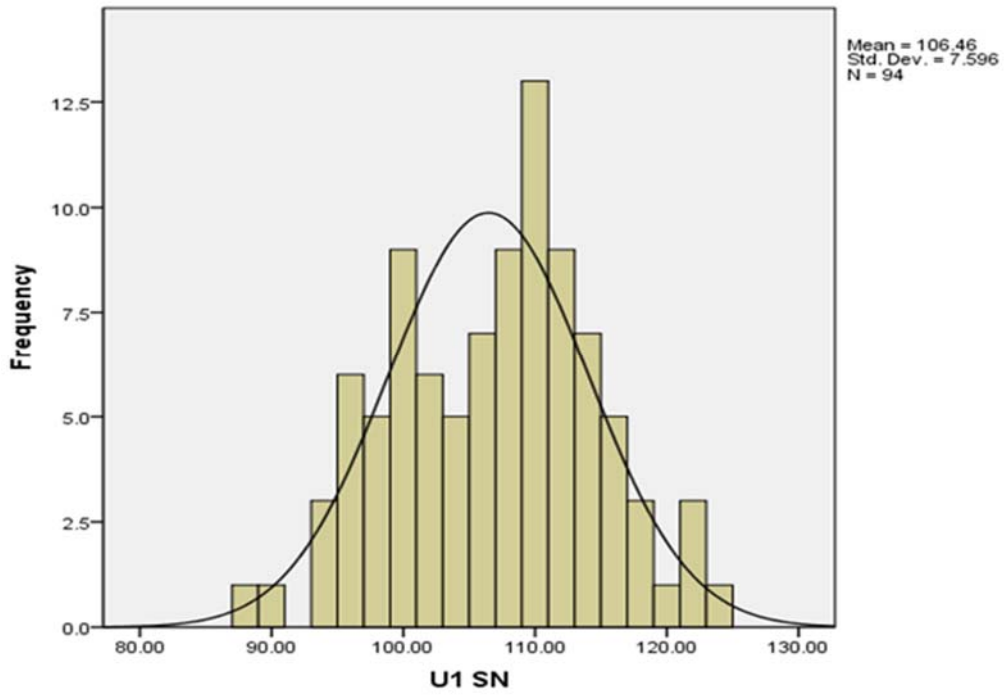

Figure 10. Distribution plot of the upper incisor angle in reference to Sella-Nasion Plane within the study sample.

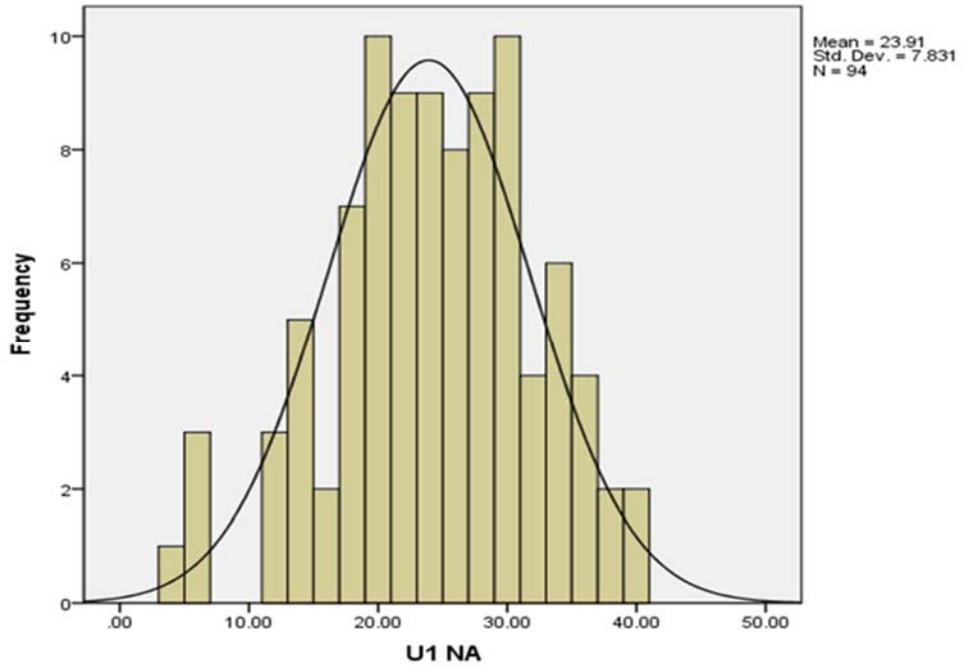

Figure 11. Distribution plot of the upper incisor angle in reference to Nasion-Point A Plane within the study sample.

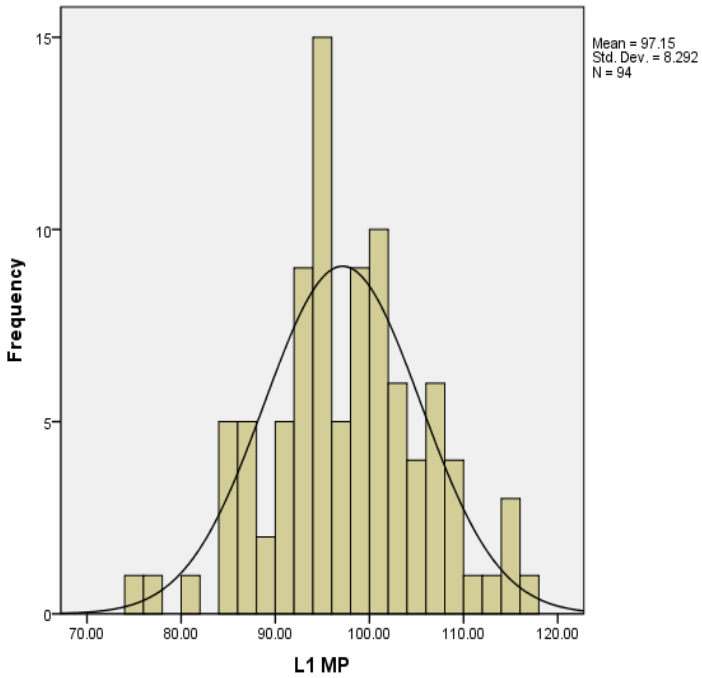

Figure 12. Distribution plot of the lower incisor angle in reference to the mandibular plane within the study sample.

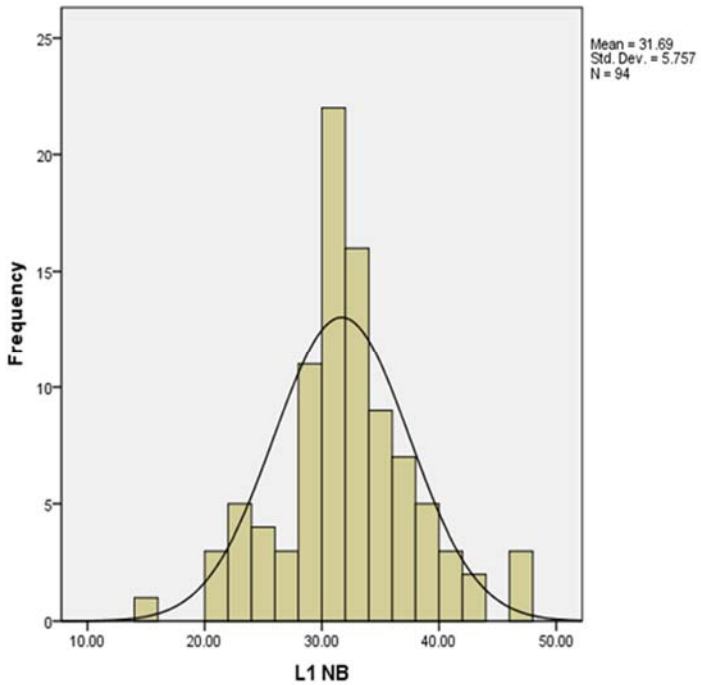

Figure 13. Distribution plot of the lower incisor angle in reference to the Nasion-Point B Plane within the study sample.

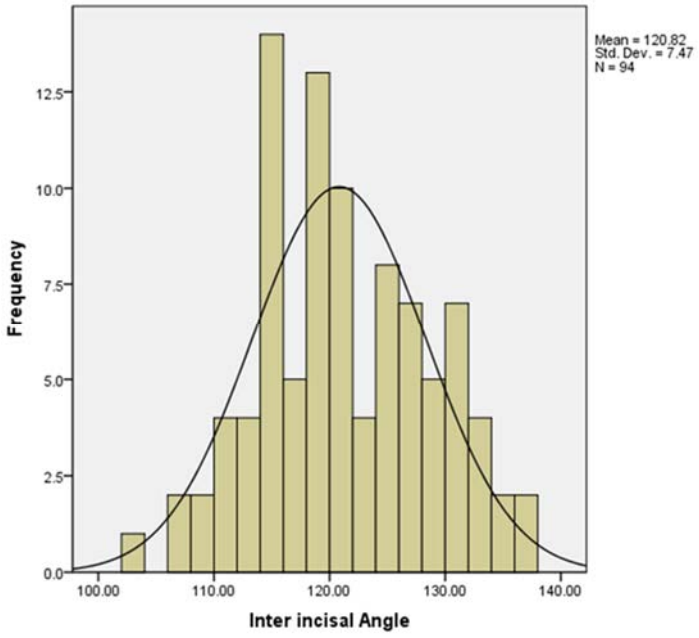

Figure 14. Distribution plot of the lower interincisal angle within the study sample.

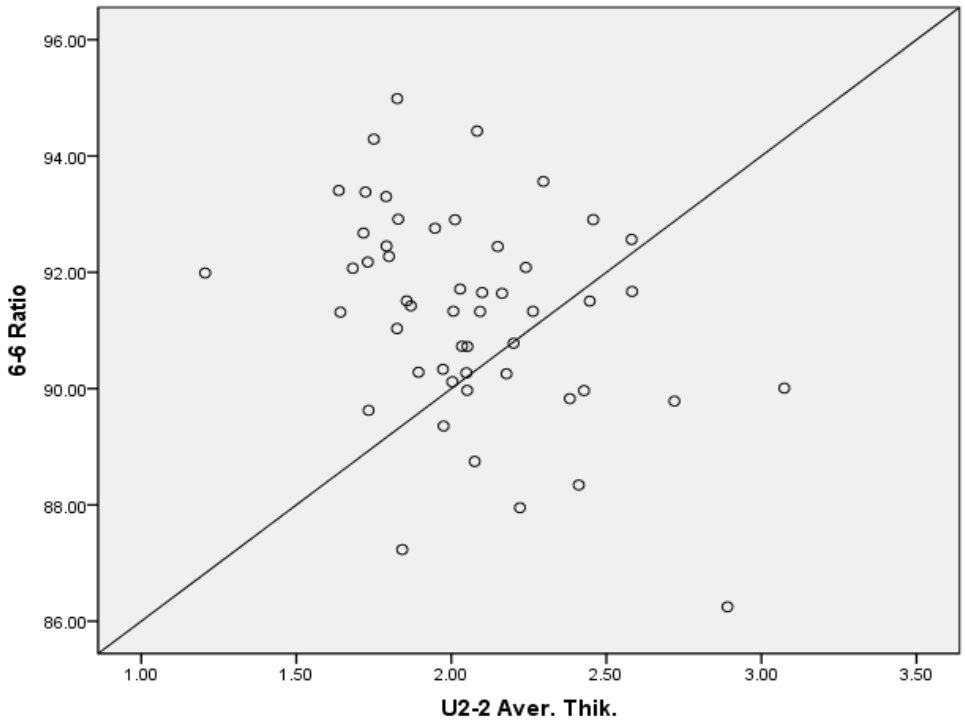

Figure 15. Scatter plot showing the inverse correlation between the overall tooth size ratio and the upper tooth thickness average of the anterior four teeth.

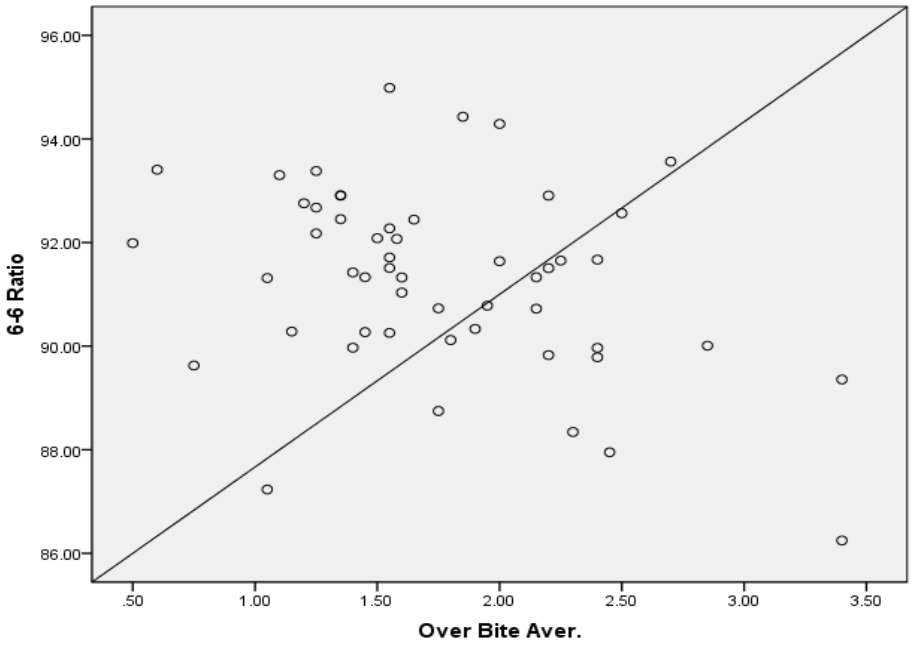

Figure 16. Scatter plot showing the inverse correlation between the overall tooth size ratio and the overbite.

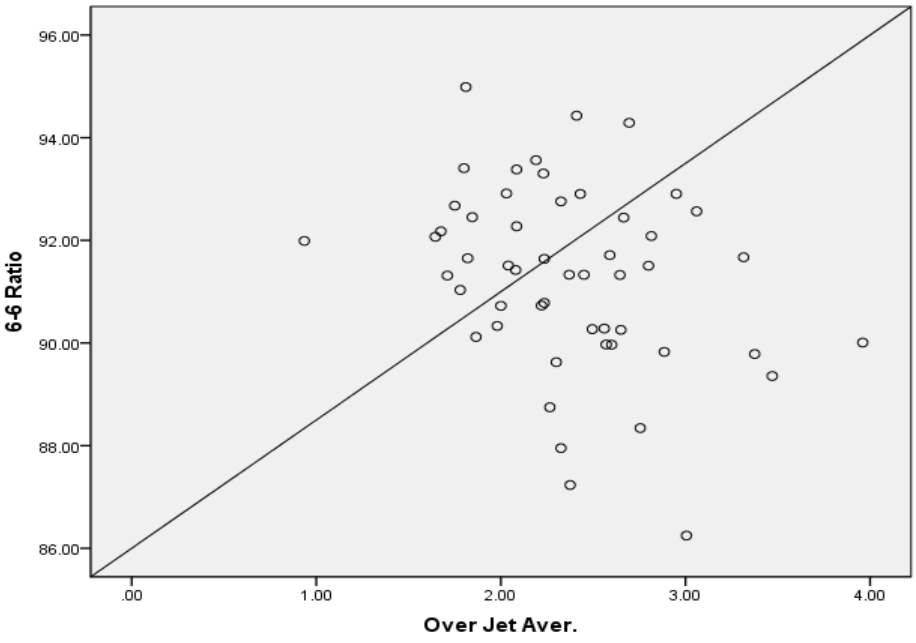

Figure 17. Scatter plot showing the inverse correlation between the overall tooth size ratio and the overjet.

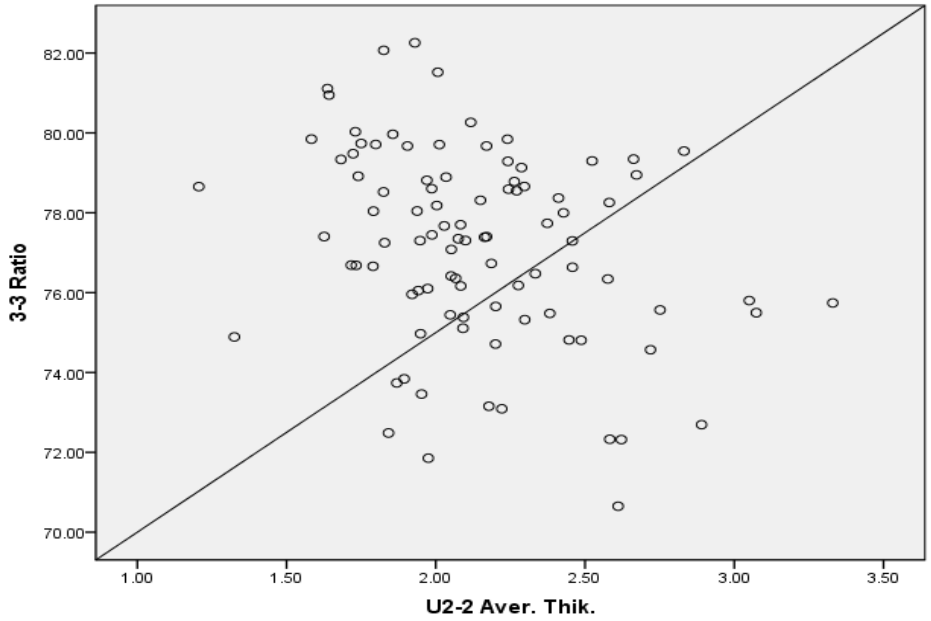

Figure 18. Scatter plot showing the inverse correlation between the anterior tooth size ratio and the upper tooth thickness average of the anterior four teeth.

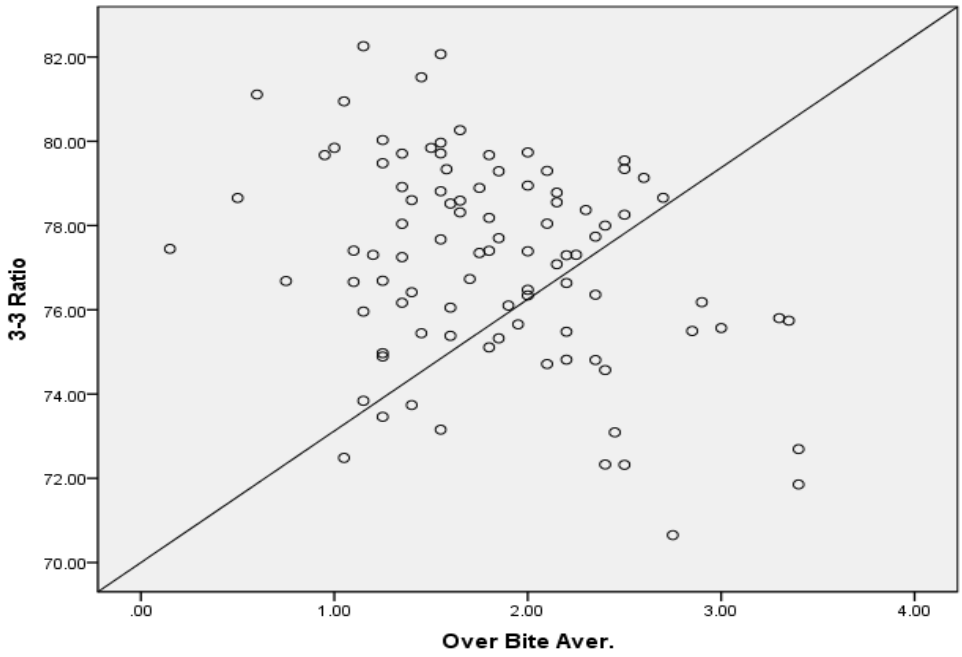

Figure 19. Scatter plot showing the inverse correlation between the anterior tooth size ratio and the overbite.

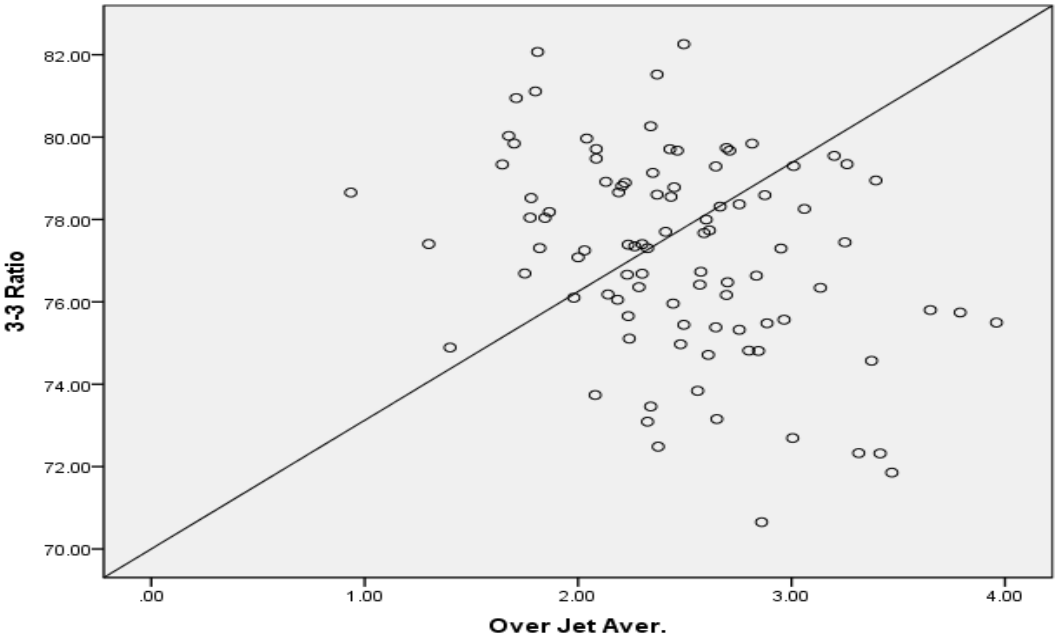

Figure 20. Scatter plot showing the inverse correlation between the anterior tooth size ratio and the overjet.

5. DISCUSSION

5.1 Findings of the Study

The main questions addressed by this study is as follows, "Using tooth size discrepancy analysis, are the Bolton ratios comparable to the ratios obtained from cases treated to an excellent result and passed the ABO clinical examinations? Is it necessary to account for other factors that would affect achieving an ideal occlusion such as overjet, overbite, axial inclination of anterior teeth, interincisal angle, and anterior tooth thickness to improve the accuracy of the tooth size discrepancy analysis? "

The one-sample t-test results showed that no statistical significant difference exists between Bolton's interarch tooth size mean ratios as published in Bolton's study (1958) and the corresponding mean ratios drawn from ABO finished orthodontic cases. Therefore, in this case we failed to reject the null hypothesis ($p>0.05$). This would mean that all of the measured ABO cases averaged within the same ratio as Dr. Bolton suggested in 1958. The overall ratio in this study ranged from 86.3% to 95.0% while the overall ratios reported by the Bolton study (1958) were 87.5% to 94.8%. That is a relatively insignificant difference on the clinical level. However, looking at the anterior ratio we would find a larger variation. The anterior ratio in this study ranged from 74.5% to 80.4% while the anterior ratios reported by the Bolton study, 1958 were 70.7%-82.3% and that is an obviously significant difference on the clinical level. To illustrate what that means, a good example would be a case in this study with an extremely low anterior ratio of 70.7% which is greater than two standard deviations and still managed to end with good occlusion and passed the ABO exam requirements.

TABLE IV

A COMPARISON OF THE OVERALL AND THE ANTERIOR RATIOS AS REPORTED BY THE BOLTON STUDY, 1958, WITH THE SAME RATIOS DERIVED FROM THIS STUDY

	Overall ratio (Bolton, 1958)	**Overall ratio (This study)**	**Anterior ratio (Bolton, 1958)**	**Anterior ratio (This study)**
Range	**87.5%-94.8%**	**86.3%-95.0%**	**74.5%-80.4%**	**70.7%-82.3%**
Mean	**91.3 %**	**91.3 %**	**77.2%**	**77.2%**
Standard Deviation	**1.91**	**1.78**	**1.65**	**2.41**
Standard error of the mean	**0.26**	**0.25**	**0.22**	**0.25**
Coefficient of variation	**2.09%**	**1.94%**	**2.14%**	**3.12%**

Table IV illustrates the findings by comparing the overall and the anterior mean ratios, the standard deviation, and the coefficient of variation between the Bolton study (1958) and this study. Notice that the coefficient of variation in the anterior tooth size ratio was 1.61 times higher than the coefficient of variation in the overall tooth size ratio as verses 1.02 times higher, when comparing the same ratios in the Bolton study (1958). This allows a relatively larger standard deviation for the anterior tooth size ratio, which provides more leeway for anterior tooth size discrepancy to exist and to still pass the ABO examination with acceptable overjet and overbite relationships. The coefficient of variation of the overall tooth size ratio in Bolton's study sample was 1.08 times higher than the coefficient of variation in the study sample. That is not a clinically significant change in the standard deviation of the overall tooth size ratios. Lastly, the study sample coefficient of variation in the anterior tooth size ratio was 1.46 times

higher than the coefficient of variation in the Bolton sample. This also allows a relatively larger standard deviation for the anterior tooth size ratio comparing to the Bolton study. The coefficient of variation of the anterior tooth size ratio is consistently larger than the overall ratio. It is puzzling to explain the findings, knowing that the overall ratio should have a bigger range because there are more teeth involved in the overall ratio.

Another aspect of the study is to investigate possible association between either the overall tooth size ratio, or the anterior tooth size ratio and each of the following variables: overjet, overbite, anterior teeth proclination, interincisal angle, and anterior teeth thickness. The test of correlation suggested that both the overall tooth size ratio and the anterior tooth size ratio showed a statistically significant association with each of the following variables (overjet, overbite, and upper anterior teeth thickness (the average of the upper anterior four teeth only, without including the upper canines). The correlations were negative and ranged from -0.376 to -0.300, ($p<0.05$), indicating medium strength relationships. Anterior teeth proclination, and interincisal angle did not show statistical significance of correlation with the overall tooth size ratio, or the anterior tooth size ratio ($p>0.05$). In other words, having thicker upper anterior teeth would correspond with having a lower tooth size ratio to accommodate for it. On the other hand having a lower tooth size ratio may increase the possibility of finishing a given orthodontic case with an increase of overjet, overbite or even a combination of both. Having a low tooth size ratio and yet with good treatment results may be explained with an occlusion that has a deeper overbite and subsequently an increased overjet to allow the lower incisal edges to touch the lingual surface of the upper incisors. The tendency to have a deeper bite in those cases is because, the lower dental arch line of occlusion should occlude against a smaller circumference on the lingual surface of the upper anterior incisors to compensate for the low tooth size ratio.

By having the lower incisal edges touch the upper teeth at a level where the tooth have a thicker section, the teeth could still come together into occlusion in the maximum intercuspation position. That would apply to cases wherever the lower arch circumference is smaller than ideal or the upper arch circumference is larger than ideal.

In order to be able to achieve treatment results that would pass the ABO examination requirements, cases had a range of variability between 0.2- 3.4mm for overbite and 0.94-3.96mm for overjet and finally a range of 1.8-2.9mm for upper incisal thickness, which reflects the acceptable overbite, overjet, and tooth thickness by the ABO standards.

TABLE VIII

BASIC MESURMENTS DERIVED FROM THIS STUDY SHOWING OVERJET, OVERBITE, AND UPPER ANTERIOR TEETH THICKNESS MEASURUNG FOUR UPPER ANTERIOR TEETH

	Sample size	**Mean**	**Std. Deviation**	**Range**
Overjet	**94**	**2.5mm**	**0.55**	**0.94-3.96mm**
Overbite	**94**	**1.8mm**	**0.64**	**0.15-3.4mm**
Upper four anterior teeth thickness	**94**	**2.2mm**	**0.37**	**1.75-2.88mm**

It would be prudent to take into account upper teeth thickness, overjet, and overbite when assessing tooth size ratios in orthodontic cases due to the inverse correlation that has been suggested by this study. It is recommended to use the Bolton tooth size ratios with the standard deviation suggested by this study. These numbers shows a wider range comparing to the Bolton's standard deviation numbers. That would provide more leeway in detecting tooth size

discrepancy. It is recommended to perform a diagnostic setup when the tooth size ratios are significantly deviated from the means, especially when there is a need to include inter-proximal reduction in the treatment. Another way to assess the necessity for interproximal reduction would be to align the upper and lower dental arches orthodontically and pursuit good interarch relation in all three dimensions. Then if the clinician encountered a difficulty to achieve a proper incisal relationship; it is recommended to perform selective interproximal reduction or dental buildups depending on the clinician's discretion to correct the tooth size discrepancy. As a summary, the Bolton analysis has been shown to be a reliable tool in detecting tooth size discrepancy in malocclusions. However, it is inaccurate to make final assumptions of the existence of tooth size discrepancies by only assessing tooth size ratios.

5.2 Limitations

One of the limitations of this study is the sample size which was 52 cases for the overall tooth size ratio sample and 94 for the anterior tooth size ratio sample, comparing to 55 for both overall and anterior tooth size ratio in the Bolton study sample (1958). It was suggested by Bolton and by many other authors that a larger size would insure more reliable results to build upon more solid conclusions (Bolton 1958; 1962; Neff 1949). Another limitation would be that most of the cases obtained for the study derived from orthodontic residents who used the UIC College of Dentistry's patient pool to obtain their ABO cases, consequently reflecting the ethnic, and gender distribution of the dental school's patient population, not the actual ethnic, and gender distribution of the general population. Although an inter- and an intra-reliability test of a repeated measure (n=10) was carried out with outcomes showing high positive correlation ($r>0.80$), human error of choosing landmarks when measuring casts and tracing cephlometric radiographs remains a limitation of any study of that type.

5.3 Future Research

Future research utilizing similar methodology could be assessed by preforming a meta-analysis study, and may predictably come of great value to develop more reliable conclusions that would represents a wider range of the general population. Such an approach would benefit the clinicians to better diagnose and predict tooth size discrepancy and treatment plan accordingly.

6. CONCLUSION

The Bolton analysis has been shown to be a reliable diagnostic tool for assessing tooth size discrepancy and subsequently aiding in the treatment planning of dental malocclusions. However, the study has shown that the Bolton analysis is not a decisive tool in predicting clinically significant tooth size discrepancies that would prevent from achieving good occlusions with ideal overjet and overbite, and ensure passing the American Board of Orthodontics examination requirements. It would be recommended to consider a diagnostic setup in malocclusions showing a significant tooth size discrepancy, especially if the treatment plan included having to do selective dental interproximal reduction (IPR). To avoid any misinterpretations of the analytic readings, another way to determine the need for IPR would be to align both upper and lower dental arches orthodontically and achieve good interarch relation in all three dimensions. Then if the clinician encountered a difficulty to achieve a proper bite; it would be prudent to perform selective IPR or dental buildups to correct the tooth size discrepancy at the clinician's discretion. It is important to consider upper teeth thickness, overjet, and overbite as influencing factors that would affect the final occlusion in orthodontic cases due to the inverse correlation that has been demonstrated in this study.

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