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An Evaluation of the accuracy of the Bolton and Ricketts growth prediction algorithms embedded in the Dolphin Imaging © software

By

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DEDICATION

I would like to dedicate this thesis to my dear father, Richard Banasik.

A loving father and husband and wonderful physician.

I miss you, dad.

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Abstract

Introduction: Our objective was to evaluate the accuracy of the Bolton and Ricketts' growth predictions embedded in the Dolphin Imaging software based on the subjects' chronological age.

Methods: Twenty-eight 12-year-old (time 1) and 28 14-year-old (time 2) cephalometric radiographs were selected from the Bolton Brush growth study located at the School of Dental Medicine in Cleveland, OH. All images. The T1 and T2 cephalometric x-rays were traced using the imaging software and superimposed on cranial base structures. The cephalometric landmarks were recorded as Cartesian coordinates with Sella serving as point 0,0. The following 11 landmarks were used for comparison: Nasion (Na), A-Point (A), B-Point (B), Pogonion (Po), Menton (Me), ANS, PNS and the root (RL1) and cusp tip (CL1) of the mandibular and maxillary incisors (RU1,CU1) The resulting differences in the location of the landmarks (T1 to T2)were considered the "Gold Standard" for comparison with the predictions. Each T1 radiograph was then used as the input data for the growth prediction, chronologic age was set at the age parameter, and a two-year prediction calculated. The difference between the T1 values and the predicted values was recorded for the same set of landmarks.

Results: Both predication algorithms were more accurate in the horizontal direction compared to vertical. For the Bolton the prediction of the location of B-

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Point and the upper and lower incisors were accurate when compared to the gold standard. For the Rickett's prediction the root tips of the upper and lower incisors were accurate as well as A-Point on the x-axis when compared to the gold standard. No skeletal landmarks were accurate for either prediction along the y-axis.

Conclusion: Neither the Bolton nor the Rickett's prediction algorithms as implemented in the Dolphin program provide reliable information for precise treatment planning in orthodontics.

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Review of the literature

The Bolton Brush Growth Study

The Bolton Brush Study is located in Cleveland, Ohio and is the largest study of its kind. It houses 22,000 longitudinally obtained radiographs of 5,000 children who were deemed to be representative of optimal Caucasian male and female facial growth in order to be able to obtain a norm for direct morphologic assessment as well as for linear and angular comparative measurements. (Braun; Broadbent, Broadbent and Golden) Thorough handwritten notes regarding nutritional, dental, and medical health status and disease history of each subject complemented the radiographic data.(Hans, Palomo and Valiathan)

The study was described as "unparalleled and heroic" by Drs. Broadbent Jr and Sr and William Golden in their introduction of the 1975 publication of the Bolton Standards. (Broadbent, Broadbent and Golden) The Bolton Study started in 1929 and examined normal craniofacial and dentofacial growth and development of 4309 children, twice a year from infancy to 20 years of age.(Hans, Palomo and Valiathan)Through the generosity of Francis Payne Bolton, about 40 cephalometers were provided to other institutions and researchers over the course of the next 30 years.

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This enabled the beginning of other comparable longitudinal growth studies of which some are also more well-known(Broadbent, Broadbent and Golden):

- The Iowa Growth Study starting in 1946
- The University of Toronto Burlington Growth Study started by Dr. Moyers in 1952
- The Forsyth Twin Sample
- The Mathew Implant Growth Study collected at the University of California at San Francisco School of Dentistry
- The Michigan Growth Study
- The Oregon Growth Study

As growth studies supplied the orthodontic profession with data, dentofacial growth could be examined and interpreted which lead to growth principles being established. (Sagun et al.)

The cephalometer and the study of growth

"Assessment and prediction of dentofacial growth are perhaps the most essential, yet to a great extent the most subjective aspects of clinical orthodontics" and being able to forecast and predict dentofacial growth in a dependable manner

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is essential for our patients and our profession and "lies at the very heart of contemporary clinical orthodontics." (Bishara) Because growth can work in favor of or against the orthodontist, a multitude of authors agree that it is important to be able to accurately predict the direction, timing and magnitude of the facial changes that occur with growth in an individual, therefore reducing the difficulty in treatment planning. (Sagun et al.; Bishara; Turchetta, Fishman and Subtelny; R. M. Ricketts)

It was after World War II that the cephalometer gained a more widespread popularity and hence pushed the research into growth and development. This momentum allowed for cephalometric analyses to be developed.(Sagun et al.)

Chronological records of the growth and development of the studied skulls provided the clinician with a valuable means of communicating and comparing overall morphology and dentition - so to speak a "common yardstick" for diagnosing, treatment planning, the understanding of treatment results, and the standardization of central values for use in research and aiding in communication both within the health professions and with the lay public. (Broadbent, Broadbent and Golden)

In 1946 Brodie was the first one to introduce the idea of facial patterns. He noted that the pattern of the individual is determined before birth and subsequently remains remarkably stable. He pointed out that the bones of the face show wide

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ranges of variability concerning the time and rate of growth, but that the growth of the pattern is proportional. (Brodie)

Two further central orthodontic principles were formed as results of the Bolton Brush study:

The idea of downward and forward face development was demonstrated by Broadbent and it was proposed that that the pattern of growth of the head and face is established at around the age of three.(Wahl; Broadbent)

At age 10 the cranium has practically reached its final size and the cranial base is usually considered to have reached its final shape. After the age of 10 or 12 years the increase in brain size is slight, whereas the facial skeleton continues to grow up to the age of 20 and beyond. Sutural growth ceases around the age of 10. Continued longitudinal growth of the upper facial structure is compensated mainly by formation of bone tissues on the outer surface of the frontal bone. Median contour of the anterior cranial fossa will therefore largely remain unaltered between the ages of 12 and 20.(Björk)

Orthodontic treatment planning is largely dependent on subjective criteria which makes it essentially a game of strategy against nature. But the overall approach should be founded on the available scientific information. (Bishara; Greenberg and Johnston)

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Edward Angle elevated Orthodontia to the status of a science when he laid down the definition of a normal occlusion. (Brodie) By developing teleroentgenography in the early twentieth century, Hofrath, Maves and Broadbent developed a way to plan and monitor treatment changes by establishing norms for growth and development. (Sheldon Baumrind and Robert C Frantz; R. M. Ricketts) And according the Broadbent and Behrents the cephalometer is the single greatest advance in the science and practice of orthodontics. (Sagun et al.) Broadbent is known to have invented the Western Reserve University craniostat with T. Wingate Todd in 1930. It was Todd who initiated the study of the appendicular skeleton in the Brush inquiry. In 1931 Broadbent published his x-ray method and initial findings in the first issue of the Angle Orthodontist.(Hans, Palomo and Valiathan)

While in the beginning cephalometric radiographs were used mainly as a tool for prosthetic planning and studying the development of craniofacial components, eventually those who had mastered growth, believed that they could utilize this knowledge for the prediction of growth.(Sagun et al.; R. M. Ricketts) One of the most important parts of using cephalograms for the analysis of treatment planning, treatment evaluation and growth prediction was the invention of the craniostat by Pierre Broca in the second half of the 19th century.(Hans, Palomo and Valiathan)

Although the percentage of adult patients has grown over the past years, most of orthodontic care is still directed towards pre-adolescent and adolescent

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patients. These patients are experiencing considerable changes in their occlusions, facial skeletons, and profiles. (Bishara)

Johnston and Greenberg postulated that the goal of cephalometric prediction is to decrease the clinician's "ignorance of the future"(Greenberg and Johnston) by aiding us in establishing the mode of treatment every patient needs on an individual basis. Each person has a distinctive growth pattern that is affected by their genetic makeup as well as external environmental factors such as function, disease, habits, and orthodontic treatment. Due to this array of factors, these changes tend to be quite complex and are the root for the great need for standards of dentofacial developmental and growth in the orthodontic profession so that combined with the timing of the anticipated pubertal growth spurt and the direction of growth we can initiate treatment at an optimal time for the patient.(Broadbent, Broadbent and Golden; Bishara)

Brodie et al. found in 1938 that there was a definite correlation between the success in treatment and good facial growth and therefore it is only logical for orthodontists to have the goal of mastering facial growth and facial growth potential and also possess an interest in in predictions developed from available data.(Sagun et al.; Turchetta, Fishman and Subtelny)

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Cephalometric analyses

Downs published the first radiographic cephalometric analysis in 1948 in order to help describe skeletal and dental patterns and their relationship to each other.(Hans, Palomo and Valiathan; Downs) Later in 1953 Cecil Steiner published his paper "Cephalometrics for you and me" and was the first one to include considerations about skeletal balance, incisor angulations, the extent of tooth size arch length discrepancies and profile characteristics.(Hans, Palomo and Valiathan; Steiner) Ricketts and Johnston each used the lateral cephalogram in order to help envision treatment outcomes via a Visual Treatment Objective (or VTO) and Pitchfork analysis.(Hans, Palomo and Valiathan) Finally in 1984 Behrents revolutionized the view on adult skeletal growth by showing that change in the skeletal never ceases to occur.(Behrents)

Growth and superimposition

As linear and angular measurements have been used to establish statistical means; grids of norms were calibrated, patterns established, and templates devised. Studies have been performed to determine the most stable element of the cranial base on which to superimpose on in order to achieve accurate representation of cranio-facial growth.(Sagun et al.) The cranial base, since the early works of Schuller, Keith and Campion, Huxley and Hellman and Todd, has been used as a

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reference plane. (Elmajian) De Coster stated the relative stability of the Sella-Turcica-ethmoid-frontal line and its value as an area for superimpositioning of lateral head films. He superimposed head films on the anterior lip of the Sella turcica, upper line of the sphenoid masses, Spheno-Ethmoidal suture, lateral masses of the Ethmoid, lamina cribrate, encephalic face of the frontal cells, foramen caecum, and the internal osseous line of the frontal bone above the crista frontalis. He concluded that the Sella Turcica-method is stable after seven years.(Elmajian)

Many investigators, including Brodie and Bjork, make use of the Sella-Nasion superimposition line registered at Sella. He did observe that it remained stable in 90% of the cases between the ages of 12 and 20, noting an increase in length of the S-Na line due to appositional growth of the outer surface of the frontal bone.

Different methods of growth prediction

Bolton Standards

The groundwork of the Bolton growth prediction algorithm in Dolphin Imaging © is based on templates that depicted average facial patterns of boys and girls.(Broadbent, Broadbent and Golden) The Bolton Standard Correlation, which is described as one of the uses of the Standards, involves the arbitrary assignment of the specific standard size to individual parts of the craniofacial complex. The

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term standard instead of norm, implies a rule for measuring or an optimum for use for making comparative clinical observations. The authors emphasized that the Bolton Standards do not in any way allow for an absentee diagnosis and emphasized forcefully the need for firsthand observation of the patient.(Broadbent, Broadbent and Golden)

From the group of 22.000 children the authors selected 16 male and 16 female controls – based on normal dental occlusion, esthetically favorable faces, absence of debilitating diseases, and the relation in of a composite of these patients' cephalometric measurements to a statistically derived mean.(Braun) Using this control group, sets of age-related AP and lateral statistically derived norms were obtained. The results are presented in table form, and as transparencies which can be placed directly over the lateral cephalogram.(Broadbent, Broadbent and Golden)

Bishara et al. emphasized this point of view as they observed that 77% of people were categorized as having the same facial type at 5 and 25, in 23% of subjects the face type shifted. The shifting from one face type to another mostly occurred in cases with borderline characteristics between 2 facial types for example from average to a long facial pattern. The standards have a significant communicative value with the patient and the parents. In addition, they make it possible to compare the overall morphology and dentition. The authors of the Bolton Standards were fully aware that these standards were just another step on the long path of

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understanding and predicting developmental growth processes.(Bishara; Broadbent, Broadbent and Golden)

Ricketts

In a study by Schulhof and Bagha, the computerized Ricketts long-term forecast was found to be the most accurate, being 21% more accurate than the Ricketts short-range method and 56% more accurate than the Johnston grid system.(Sagun et al.) The Ricketts prediction system is predominantly based on incremental values applied either in a linear direction or along an arc.(R. Ricketts "Evolution of Mandibular Growth Concepts in Orthodontic Science"; R. Ricketts "Philosophies and Methods of Facial Growth Prediction"; R. Ricketts "The Application of Arcs, Polar Centers, Gnomons and K Factors in Facial Growth Prediction") The system predicts mandibular growth first along the arcial growth line and the arbitrates the maxilla based on the predicted mandibular position and in the continuation of existing patterns. Ricketts' method dictates that growth stops at 14.5 for females and 19 for males. This method is limiting and not compatible with current thinking about maturational development.(R. Ricketts "The Discovery of a Law of Arcial Growth of the Mandible"; Turchetta, Fishman and Subtelny)

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Johnston

The Johnston prediction system uses Sella as a basic point of reference and bases growth on a grid. The grid grows in a certain linear direction. The grids are not equal in distance, thus adding some individuality based on chronologic age. Individualizing prediction by assessing maturational development can greatly increase the accuracy and reduce physiologic variability. Johnston's system is simplistic compared to wide ranging developmental variations. It is based on chronological age.(Turchetta, Fishman and Subtelny; Johnston) The Johnston forecasting technique is essentially a greatly simplified mean-change expansion and, as might be expected, it performs well when applied to published examples of other schemes for example, Ricketts's case T.M.(R. Ricketts "The Application of Arcs, Polar Centers, Gnomons and K Factors in Facial Growth Prediction") or the Bolton Standards of Case Western Reserve University. He himself wrote "Unfortunately, schemes of this type do not fit a random series of patients nearly so well".(Johnston) Johnston suggested the use of monitored height and weight, chronologic age, tooth status, onset of the menarche used rather than cephalometric prediction.

This approach seems more clinically applicable, especially because hand and wrist x-rays and lateral cephalograms are only taken at the beginning of treatment and are not retaken during an observation period.(Turchetta, Fishman and Subtelny) Based on similar thoughts this study also uses patient's chronologic age.

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Bjork

Bjork distinguished three methods of growth prediction:

- Longitudinal
- Metric
- Structural

The longitudinal method consists of observation of an individual over a period of time to determine the pattern of growth. Broadbent and Brodie have both implemented this concept.(R. M. Ricketts) In 2000 Bishara concluded that longitudinal growth prediction is limited in that it is accurate only when it is performed retrospectively, not prospectively.(Bishara) The metric method predicts facial development based on facial morphology, determined metrically from a single radiograph.(R. M. Ricketts) The structural method is based on Bjork's implant studies and recognizes specific structural morphological features in the mandible that would indicate future growth trends.(Björk)

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Fishman

The Fishman prediction gives the best prediction but is not available in Dolphin © and hence cannot be investigated in this study. (Turchetta, Fishman and Subtelny)

The difficulty of accurate landmark identification

One of the challenges of cephalometry is the accurate landmark identification. Three considerations determine the impact that an error in identification of a specific landmark will have on the linear and angular values involving that landmark(Sheldon Baumrind and Robert C Frantz):

- Actual magnitude of the error involved in identifying the specific landmark
- Linear distance on the tracing between the point representing the landmark and the points representing the other landmarks
- Direction from which the line segment between to landmarks intersects the envelope of error of each landmark

Regardless of the use to which a head film will be put, it is important to know how accurately measures on the films are being made and what are sources of measurement error. There are two types of error – the error of projection and the error of identification. A clinically acceptable reference mean of 1.5mm was established for clinical applicability purposed in a classic paper by Baumrind et

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al.(Sheldon Baumrind and Robert C Frantz; Sagun et al.; Sheldon Baumrind and Robert C. Frantz) Thankfully in samples that are large enough the error tends to randomize itself out in grouped data.

Unfortunately this does not apply to the individual case, where errors associated with the act of tracing superimpositions are sufficiently large to be of consequence in the interpretation of changes in dental and osseous changes.(Baumrind, Miller and Molthen)

The History of Digital Imaging and Dolphin Imaging ©

Orthodontics is considered among the most progressive specialties in Dentistry and Orthodontists have been using computer technology as early as the 1960ies. In that decade those technologies were limited to researchers and academicians.(Chester H Wang and Lisa Randazzo) Later in the 1980ies computer technology became more widely available and Orthodontists started using this type of technology for tasks like scheduling and financial tasks, tracking of recalls and staff salaries.(Chester H Wang and Lisa Randazzo)

Dolphin Imaging © was founded in 1988 and its programs for imaging are widely used by orthodontists around the world to predict growth and plan treatment and help visualize growth and treatment effects to the patient, helping to improve and refine existing algorithms benefits the patient and orthodontist. (Brodie)

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In the 1980ies and early 1990ies research into the application of digital technologies to lateral cephalometric radiography emerged.(Geelen et al.) Dolphin's © first application of digital tracing was called DigiGraph © imaging and Ceph Tracing software and started in 1990. The DigiGraph's © components consisted of a cabinet with a digitizer probe, computer, monitor, head holder, microphone array, video cameras, and software. The computer used the signals to combine the data sets which allowed the practitioner to perform cephalometric tracings and analyses, superimpositions, and virtual treatment objectives. It did not take long to realize that conventional x-rays would fit more into an Orthodontic office .(Chester H Wang and Lisa Randazzo)

In 1983 the American College of Radiology established a committee to come up with a standard for the transfer of digital data and finally in 1993 medical imaging was streamlined by a name change to Digital Imaging and Communication in Medicine (DICOM), in hopes of improving international acceptance.(Mustra, Delac and Grgic) A study in1985 found that the results from the digital image system are comparable with those obtained by the traditional method.(Jackson, Dickson and Birnie)

Yet already a few years later another study in 1989 found that digital images showed an improvement in image quality of digital cephalograms when using various digital enhancement and filtering techniques (Jäger, Döler and Schormann) and Geelen et al. concluded in 1998 that "digital radiography could revolutionize

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both clinical and research practice in craniofacial cephalometrics." (Geelen et al.) Finally during the 1990s, imaging grew to facilitate the incorporation of digital x-rays.(Chester H Wang and Lisa Randazzo)

The basis of computer aided cephalometry is a cartesian coordinate system that is based on biologically meaningful reference planes.(Baumrind and Miller) By the mid-2000s, 3-dimensional (3D) imaging was piquing the interest of the innovative players in the orthodontic community and soon there were a few companies developing CBCT machines. It was an appealing aspect for practitioners that a CBCT scan could serve as a patient's singular data set from which to obtain all the customary views of an orthodontic workup.(C. H. Wang and L. Randazzo)

Groundbreaking and subsequential work over the decades and years by Ricketts and Johnston has allowed the contemporary clinician to utilize Dolphin Imaging © to perform growth predictions. In 1975 he was concerned in paper that "arcane geometry and "space-age" technology require the expenditure of considerable time and money for even a modest clinical trial, leading most orthodontist to adopt a "wait and see" attitude.(Johnston) As currently 3D diagnosis and record taking have become the new standard, Dr. Johnston's worries about cost and attainability of predictions have become a worry of the past.(Turchetta, Fishman and Subtelny)

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Also worries about having to average bilateral structures, projection images leading to structures closer to the film be projected smaller than those farther away from the film and false head positioning occasionally leading to the entire image being distorted are now a thing of the past with the availability of CBCT's.(Hans, Palomo and Valiathan)

Also, with newer X-ray machines using less radiation than in the past, we can extract more information with less ionization. As described in a paper in 2013 it was shown that the ability to adjust the Field of View (FOV), milliamperage and optimization of filtration can reduce the radiation and maintain a reasonable contrast-to-noise ratio according which diagnostic tasks are being addressed by the scan.(Ludlow and Walker) As Larson said in 2012, "Cone-beam computed tomography is the imaging technique of choice for comprehensive orthodontic assessment."(Larson)

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Statement of the thesis

The aim of this retrospective study is to evaluate the accuracy of the Bolton and Ricketts growth prediction algorithms embedded in the Dolphin Imaging © software which are often used by orthodontists and orthodontic residents to estimate future growth.

Hypothesis I : The Bolton prediction method gives the clinician results that are clinically acceptable as defined by Baumrind[1] in 1971.

Null Hypothesis: The Bolton prediction method does not provide the clinician with results that are clinically acceptable as defined by Baumrind[1] in 1971.

Hypothesis II: The Ricketts prediction method gives the clinician results that are clinically acceptable as defined by Baumrind[1] in 1971

Null Hypothesis: The Ricketts prediction method does not provide the clinician with results that are clinically acceptable as defined by Baumrind[1] in 1971.

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An Evaluation of the accuracy of the Bolton and Ricketts growth prediction algorithms embedded in the Dolphin Imaging © software

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Abstract

Introduction: Our objective was to evaluate the accuracy of the Bolton and Ricketts' growth predictions embedded in the Dolphin Imaging © software based on the subjects' chronological age.

Methods: Twenty-eight 12-year-old (time 1) and 28 14-year-old (time 2) cephalometric radiographs were selected from the Bolton Brush growth study located at the School of Dental Medicine in Cleveland, OH. All images. The T1 and T2 cephalometric x-rays were traced using the imaging software and superimposed on cranial base structures. The differences between the cephalometric landmarks were recorded as Cartesian coordinates with Sella serving as point 0,0. The following 11 landmarks were used for comparison: Nasion (Na), A-Point (A), B-Point (B), Pogonion (Po), Menton (Me), ANS, PNS and the root (RL1) and cusp tip (CL1) of the mandibular and maxillary incisors (RU1,CU1) The resulting differences (T1 to T2)were considered the "Gold Standard" for comparison with the predictions. Each T1 radiograph was then used as the input data for the growth prediction, chronologic age was set at the age parameter, and a two-year prediction calculated. The difference between the T1 values and the predicted values was recorded for the same set of landmarks.

Results: Both predication algorithms were more accurate in the horizontal direction compared to vertical. For the Bolton the prediction of the location of B-

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Point and the upper and lower incisors were accurate when compared to the gold standard. For the Rickett's prediction the root tips of the upper and lower incisors were accurate as well as A-Point on the x-axis when compared to the gold standard. No skeletal landmarks were accurate for either prediction along the y-axis.

Conclusion: Neither the Bolton nor the Rickett's prediction algorithms as implemented in the Dolphin © program provide reliable information for precise treatment planning in orthodontics.

Keywords: Growth prediction, Bolton, Ricketts, Dolphin Imaging ©

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Introduction

Growth prediction is a key element of Orthodontic treatment planning and communication with the patient or their caretaker.[3] Orthodontics has long enjoyed a reputation for being among the most progressive of the dental specialties, and one milestone of this tradition of innovation began approximately 100 years ago in Cleveland.[4] The Bolton Brush growth study that was performed in Cleveland, OH is the largest of its kind in the world. It houses 22,000 longitudinally obtained radiographs of 5,000 children who were deemed to be representative of optimal Caucasian male and female facial growth in order to be able to obtain a norm for direct morphologic assessment as well as for linear and angular comparative measurements.[5]

This study opened the door to many more studies of this kind. Among others the University of Toronto Burlington Growth Study started by Dr. Moyers in 1952 and the Michigan Growth Study continued by Dr. Moyers after he succeeded the founder, Byron O'Hughes.[6] These studies were later used to establish norms for orthodontic treatment which means that the beginnings of growth prediction lie in multiple moments in radiologic and cephalometric history.

Dolphin Imaging © is the most popular software package for cephalometric tracing and is used in most orthodontic offices in the United States. One of the features

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that has been implementing in this software program is the ability to "grow" the cephalometric tracing of your patient to simulate what might happen with normal growth during treatment. The usual growth forecast or prediction is two years in keeping the common treatment time estimate of 24 months. Two methods of prediction have been implemented in the Dolphin © system. The first is called the "Bolton" prediction and the second the "Ricketts" prediction method. Although the exact algorithms used by Dolphin © to generate these predictions is not known, it is assumed that they are based on the Bolton Standards of Facial Growth published in 1970 by Broadbent et al and the Rocky Mountain Ricketts Growth database. The purpose of the present study is to determine if either of these algorithms is accurate enough to be a reliable tool for orthodontic treatment planning.

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Material and Methods

This retrospective study was determined by the CWRU IRB to be exempt from the exempt from the need for informed consent to use the data (Appendix 1). One hundred patient records from a PC housing over 1000 digitized versions of lateral cephalometric x-rays at the Bolton Brush study center at 10900 Euclid Ave. were chosen for a closer examination and downloaded on an external drive that could be transported. Each patient's X-rays are saved on a hard drive at the study center and there is a folder for each patient that is only distinguishable by the patient's study identifier (for example B2123). The timepoints chosen were 12 years old (T1) and 14 years old (T2).

X-rays were chosen based on the following inclusion criteria:

- T1 and T2 had to be within 7 months of the desired age (12 and 14) and have a full permanent dentition with the exception of the third molars.
- Only male subjects were chosen in order to achieve a more homogenous sample.
- The chosen subjects were not wearing any apparent removable or fixed appliances.

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- The chosen subjects' teeth were in full occlusion. Whether they are biting down in centric relation or centric occlusion could not be determined.
- The hard tissues and the cephalometric points of interests for this study had to be clearly visible and not cut off or covered in any way.
- Class 1 skeletal facial appearance without apparent craniofacial abnormalities.

The exclusion criteria were:

- Female gender.
- Fixed or removable appliances visible in x-ray.
- Critical landmarks obscured or missing on the image.
- Age of the patient was more than 7 months away from the desired T1-T2.
- Chronological age of the patient stated on the file folder did not coincide with the tooth status visible on the X-ray ie Deciduous teeth were present on the T1 radiograph.
- Patient's teeth were not in occlusion when the cephalometric X-ray was taken.
- Facial pattern deviating from Cl I skeletal pattern and the presence of craniofacial abnormalities.

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After close examination and the use of image enhancing technology in Dolphin Imaging ©, 28 males that fulfilled all selection criteria were chosen to be included in the study.

The growth prediction of the soft tissues was excluded from this study because the quality of the x-rays did not allow for adequate assessment of these and in most cases the chin and throat area were cut off completely, not allowing for even an attempt at a tracing and analysis. Additionally, the area around the soft tissue Nasion and chin area was distorted by the craniostat. Every sample was uploaded from the external drive into the Dolphin Imaging © program at the School of Dental Medicine, Department of Orthodontics and each sample was given the same identifier it previously had from the Bolton Brush study. Twenty-eight new patients were therefore created with the Bolton Brush identifier.

Every time point T1 and T2 for each radiograph was enhanced and uploaded and named according to the subjects' age in the given X-ray. For example, B2131 14Y11M which shows the Bolton Brush identifier from the original study and the exact age of the subject down to years and months. The scale of the X-rays verified using the four corner fiducial points as defined by Baumrind. The template for the fiducial lines is a rhombus.

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The measurements are:

- 17.5 cm across on the top border
- 17.7 cm across the bottom border
- 15.7 cm along the left-hand side
- 15 cm along the right-hand side

Fiducial points are clearly identifiable as such and were used to set the scale in millimeters when uploading each lateral cephalogram. The ML distance, the distance between the subject and the screen was copied from the records and it revealed that the magnification between the T1 and T2 radiographs was negligible (less than 0.1 per cent). The tracings were digitized using the Ricketts cephalometric landmark dataset, which requires the user to complete a full tracing of all required landmarks in the analysis. The embedded overlay function was used to trace the teeth and parts of the cranial base for enhanced accuracy and reproducibility.

The cephalometric landmarks located were:

- ANS
- A-Point
- B-point
- Basion
- Condylion

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- DC-Point
- Gonion
- Nasion
- Menton
- Orbitale
- PNS
- Pogonion
- Porion
- PT-Point
- R1-4
- Sella
- Maxillary and mandibular first permanent molar
- Maxillary and mandibular permanent central incisor
- Various soft tissue points required for the treatment prediction function of the Dolphin © program, including:
- Soft tissue Glabella
- Soft tissue Nasion
- Soft tissue Bridge of Nose
- Soft tissue tip of nose
- Soft tissue Subnasale
- Soft tissue A-point

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- Soft tissue upper lip
- Soft tissue lower lip
- Soft tissue B-Point
- Soft tissue Pogonion
- Soft tissue Menton
- Throat point

Gold Standard

The landmark locations of the 11 landmarks on the 12-year-old cephalogram were compared to the location of those same 11 landmarks on the 14 year old cephalometric film. The difference between these two time points was recorded for each landmark for each subject. The result was the difference in location in the x and y dimensions that occurred as the result of two years of actual growth. The actual T1 and T2 radiographs were superimposed using the method for cranial base superimposition recommended by the ABO. The areas used to superimpose are as follows:

- Anterior wall of Sella just below the clinoid process.
- The cribriform plate and ethmoidal crest.
- The planum sphenoidale, where some apposition may occur up to the age of 14 years.

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- Cerebral surface of orbital part of the frontal bone.

The average of values measured for the 28 subjects was used as the Gold Standard to compare the differences predicted by the Bolton and Ricketts algorithms in the Dolphin © Program.

Bolton Prediction

When testing the prediction algorithms only the T1 radiographs for each subject were used. The digitized version of each T1 radiograph was used as the input for the algorithm. Once input, the T1 tracings were each "grown" by two years resulting in a prediction of the growth that would potentially occur in two years i.e. when the subject was 14-years-old.

Each Bolton prediction was saved in the subject's time point in Dolphin © identifiable by the letter B and a set of four numbers.

Ricketts' prediction

When testing the prediction algorithms only the T1 radiographs for each subject were used. The digitized version of each T1 radiograph was used as the input for the algorithm. Once input, the T1 tracings were each "grown" by two years resulting in a prediction of the growth that would potentially occur in two

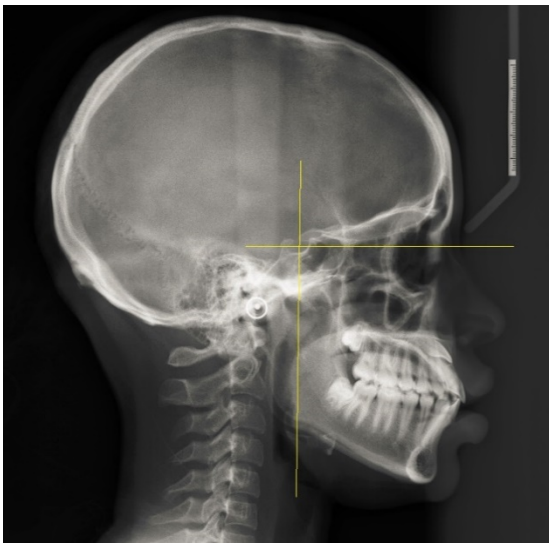
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years i.e., when the subject was 14 years old. Each Ricketts prediction was saved in the subject's time point in Dolphin © identifiable by the letter R and a set of four numbers. One important difference between these methods is that the Ricketts method does not take into account skeletal age or gender.

Statistical analysis

For statistical purposes the embedded functions in Excel were used and an open-source program called Statistics Kingdom available on the internet. The Kolmogorov-Smirnoff test was performed to establish whether the data set was distributed in a normal fashion. After the normality of the distribution was confirmed, a student's t- test was performed to investigate statistically significant differences between the sample and the predictions. The coordinate center being Sella and hence 0 on the X and Y axis, all measured landmarks were in the same quadrant except for Nasion.

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Example of a cephalometric x-ray with imaginary lines to represent Sella and the coordinate center.

Any growth in the actual patient population and any growth in a growth prediction in the antero-posterior direction would be registered as a positive number, including Nasion. Any downward or vertical growth in the actual patient sample and any predicted vertical growth would be registered as a negative variable on the Y-axis.

In accordance with Baumrind's paper published in 1971, some of the landmarks were only investigated either on the x- or y-axis.[1] For example, A-point is an AP-measurement that was proven to be found likewise by experienced and inexperienced operators consistently on the x-axis. Yet a scattergram showed that on the Y-axis the operators were not as consistent in identifying the landmark.[1] The

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error for the tips and roots of maxillary and mandibular incisors (U1; L1) occurred in a more circular fashion and they are the only landmarks investigated in both the x- and y-axis.

The investigated axis for each landmark were:

- Nasion: AP/x-axis
- A-Point: AP/x-axis
- ANS: Vertical/y-axis
- PNS: Vertical/y-axis
- U1 Tip: Vertical and AP/x- and y- axis
- U1 Root: Vertical and AP/x- and y- axis
- B-Point: AP/x-axis
- Pogonion: AP/x-axis
- Menton: Vertical/ y-axis
- L1 Tip: Vertical and AP/x- and y- axis
- L1 Root: Vertical and AP/x- and y- axis

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Results

The tracings of the actual Bolton sample revealed a range of growth, potential tracing error and magnification errors.

Most samples were relatively consistent, but others revealed a sudden increase in growth in the lower regions of the face, especially around Menton and Pogonion, while other structures closer to Sella or A-point remained within a more intuitive range.

ANS as a comparatively radiolucent structure might present one of the higher risks of tracing error especially on the x-axis.

Further we investigated the Mean, Median and Standard Deviation of all landmarks of interest in the axis of interest according to the envelops of error identified in the 1971 Baumrind paper.

The general direction of growth was always correct for both the Bolton and Ricketts predictions.

Downward growth along the y-axis is represented by numbers with a negative sign although it might initially seem counterintuitive. Nasion, the only landmark lying above the Sella coordinate, and therefore located in the second quadrant, grows upwards and has a positive sign.

PNS is a landmark that elongates and grows backwards towards Sella as the palate and floor of the nose grow, which is represented by a negative number along

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the x-axis. We can see that the mean actual growth in the Bolton Subjects for most landmarks was within the range of 1-2 mm but with a wider range of standard deviation.

	Actual		Bolton Prediction		Ricketts Prediction	
	Dx Mean ± SD	Dy Mean ± SD	Dx Mean ± SD	Dy Mean ± SD	Dx Mean ± SD	Dy Mean ± SD
Nasion	1.19 ± 0.49	1.11 ± 0.49	0.51 ± .09 ***	0.02 ± 0.03	1.84 ± 0.10***	0.05 ± 0.08
A-Point	1.8 ± 0.67	-0.9 ± 0.72	2.49 ± 0.27 ***	-2.04 ± 0.38	1.54 ± 0.28 NS	-1.64 ± 0.28
ANS	1.89 ± 0.93	-1.19 ± 0.56	3.09 ± 1.64	-1.87 ± 0.45**	1.44 ± 0.33	-1.59 ± 0.36*
PNS	-0.11 ± 1.28	-1.15 ± 0.95	1.06 ± 0.42	-1.71 ± 0.13 *	1.37 ± 0.42	-1.75 ± 0.17*
U1 Tip	2.41 ± 1.12	-1.74 ± 0.94	2.85 ± 0.41 NS	-2.78 ± 0.48**	1.66 ± 0.35 *	-3.74 ± 0.24***
U1 Root	2.3 ± 1.10	-2.08 ± 0.80	2.46 ± 0.23 NS	-2.19 ± 0.30 NS	1.91 ± 0.28 NS	-3.69 ± 0.22***
B-Point	2.54 ± 1.20	-2.78 ± 1.48	2.29 ± 1.04 NS	-4.43 ± 1.35***	1.19 ± 0.51***	-5.29 ± 0.46***
Pogonion	3.16 ± 1.22	-3.58 ± 1.26	1.96 ± 1.04 *	-4.53 ± 0.95	1.04 ± 0.42***	-5.43 ± 0.21
Menton	3.04 ± 1.52	-3.75 ± 1.39	1.18 ± 0.67	-5.01 ± 0.36***	0.98 ± 0.45	-5.37 ± 0.20***
L1 Tip	2.30 ± 1.13	-1.85 ± 1.19	2.51 ± 0.32 NS	-3.12 ± 0.44***	1.69 ± 0.33 NS	-3.73 ± 0.21***
L1 Root	2.71 ± 1.24	-2.00 ± 1.26	2.79 ± 0.39 NS	-3.33 ± 0.35***	1.38 ± 0.53***	-3.60 ± 0.16***

Statistically Significant Actual to Predicted *P≤ 0.05 **P≤ 0.005 *** P≤ 0.0005

Table of Means and SD for all variables studied

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Discussion

While the general direction of growth is accurate in both predictions on the x- and y-axis, the accuracy of the numbers is not satisfactory leading to us having to reject our null hypothesis that the predictions are accurate for treatment planning.

Some of the reasons that might lead to this outcome are:

- Growth of the individual human being might be unpredictable after all if all one is given are two timepoints.
- The algorithms are not taking into account all variables necessary to create a useful prediction.

This seems to be especially the case for the Ricketts' prediction on the y-axis, which seems to just generically add about 5mm of growth in Menton. While the actual patient sample has some outliers (Menton Max Dx = 8.3mm), the median growth observed in this sample along the y-axis was 3.58mm. This means that Ricketts overestimates the growth on average by approximately 1.5 mm.

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Conclusion

The Bolton and Ricketts' growth predictions embedded in Dolphin Imaging © software are not accurate enough to predict individual growth in males between the ages of 12 and 14.

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Appendices

Appendix 1: IRB exemption

IRB Administration Offices

UH IRB Phone: 216.844.1529
CWRU IRB Phone: 216.368.6925

Principal Investigator:	Juan Palomo
Title:	Evaluation of the accuracy of the Bolton and Rickett's growth prediction algorithms embedded in the Dolphin imaging software.
IRB Number:	STUDY20190730
IRB Office:	CWRU IRB
Approval Date:	7/8/2019
Exemption Category:	(4) Secondary research on data or specimens (no consent required)
Documents Reviewed:	• 2nd correction Exemption Protocol CWRU Banasik Hans.pdf, Category: IRB Protocol;

EXEMPT DETERMINATION

The IRB determined that this protocol meets the criteria for exemption from IRB review.

Ongoing IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If you wish to make changes to this protocol, please submit a modification.

The UH IRB operates under HHS Federalwide Assurance (FWA) number 00003937 and IRB registration numbers 00000684, 00001691 and 00008600. The CWRU IRB operates under DHHS FWA00004428 and IRB registration number 00000683.

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Appendix 2: Hard tissue point definitions

1. Glabella: Most prominent point on the outline of the fontal bone in the supraorbital and sinus region. BC Leighton 1993
2. Nasion: Junction of the nasal and frontal bones. Graber 1975
3. ANS: Apex of spina nasalis anterior. Björk 1947
4. A point (Subspinale): Deepest midline point on the premaxilla between the anterior nasal spine and prosthion (transition between crown of most prominent tooth and alveolar ridge) Downs 1948
5. B point (Supramentale): Deepest midline point on the mandible between infradentale and pogonion. Downs 1948
6. Pogonion: Most anterior point on the symphysis of the mandible in the median plane when the head is viewed in Frankfurt relation. Broadbent 1975
7. Gnathion: Most everted and outward point on the profile curvature of the symphysis of the mandible. Graber 1952
8. Menton: Lowermost point of the contour of the mandibular symphysis. Sassouni 1971
9. Gonion: Posterior-inferior point on the ramus. Cephalometric go at the intersection of mandibular plane and ramus plane. Ricketts
10. Upper molar mesial cups tip – Riolo 1974
11. Lower molar mesial cups tip – Riolo
12. Sigmoid notch: Deepest point on sigmoid notch of mandible. Ricketts 1989
13. Porion: The top of the ear rod's shadow, the external auditory meati. Moyers 1973
14. Sella: Center of Sella turcica. Björk 1947
15. UIA (upper incisor apex): Tip of root of upper 1. Riolo 1974

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16. Incision superius: Midpoint of the incisal edge of the most prominent upper central incisor. Björk 1960
17. Incision inferius: incisal point of the most prominent medial mandibular incisor. Björk 1947
18. LIA (Lower incisor apex): Root apex of the most prominent lower incisor. Leighton 1993
19. Floor of Sella / dorsum sellae – Sassouni 1971
20. Sphenoidale: Point of intersection between the greater wings of the sphenoid and the anterior cranial base Leighton 1993
21. Ethmoidale: Deepest median point of the anterior cranial fossa, corresponding to the cribriform plate of the ethmoid bone. Björk 1947
22. Temporale: Intersection of the shadows of the ethmoid and the anterior wall of the infratemporal fossa. Sassouni 1971
23. R1: Mid-point on anterior border of the mandibular ramus.
24. R2: Most convex point on posterior border of the ramus.
25. R3: Most inferior point in sigmoid notch.
26. R4: Most superior point on lower border of the mandibular ramus.

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Appendix 3

Raw Data

Patient Age at Visit for cephalometric record

Patient Age	12	14
B1224	12	14
B1240	11.9	14.3
B2066	11.9	14
B2065	12.1	13.8
B2055	12	14
B2013	12	14.1
B1984	12.3	14.1
B1836	12	14
B1892	12.1	14
B2094	12	14
B2102	12	14
B2131	11.9	14
B2205	12	14.1
B2207	12	14.1
B2216	12	14
B2224	12	14
B2285	12.1	14.1
B2319	12	14.3
B2326	12	14.1
B2378	12	14.3
B2444	12	14
B2553	12	14
B2615	12	14
B2471	12	14
B2426	12	14
B2070	12	14.3
B2019	12.3	13.5
B2009	12.2	14.1
B2321	12.7	14

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Appendix 4

Raw Data for landmarks

1. Raw Data Nasion

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	0.6	0.4	0.5	0	1.9	0
B1240	0.5	1.7	0.5	0	1.9	-0.1
B2066	0.4	1.2	0.7	0.1	1.9	0.2
B2065	2	0.5	0.7	0.1	1.8	0.1
B2055	0.3	1.5	0.5	0	1.8	0
B2013	1.2	1.4	0.5	0	1.8	0.1
B1984	1.5	2.1	0.5	0	1.8	0
B1836	0.8	0.8	0.9	0	2.2	0.1
B1892	0.9	1.4	0.1	0	1.3	-0.1
B2094	0.9	1.8	0.5	0	1.8	0
B2102	1.5	1.9	0.5	0	1.8	0
B2131	1	0.2	0.5	0	1.9	0
B2205	1.1	0.9	0.5	0	1.9	0
B2207	1.7	1.3	1	0	1.9	0.1
B2216	2	1	0.5	0	1.9	0
B2224	1.6	0.3	0.5	0.1	1.9	0.2
B2285	1.7	0.9	0.5	0	1.9	0.1
B2326	1.1	1.4	0.5	0	1.9	0
B2378	1.4	0.5	0.5	0	1.9	0
B2444	2.3	1.4	0.5	0	1.9	0
B2553	1.8	0.2	0.5	0	1.9	0.1
B2615	1.6	0.8	-0.1	0	1.2	0.1
B2471	0.5	2.5	0.5	0	1.9	0
B2426	1.8	1.4	0.5	0.1	1.9	0.2
B2070	0.4	1	0.5	0	1.9	-0.1
B2019	1	1.1	0.5	0	1.9	0
B2009	0.3	1.5	0.5	0.1	1.9	0.4
B2321	1.3	0.1	0.5	0	1.9	0.1

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2. Raw Data A-point

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2.6	-1.6	2.6	-2	1.6	-1.8
B1240	0.9	-0.1	2.4	-2.3	1.6	-1.9
B2066	0.8	-1.2	2.6	-2	1.5	-1.6
B2065	0.9	-1.4	2.5	-2	1.6	-1.7
B2055	0.8	-0.5	2.7	-2.3	1.5	-1.8
B2013	2.3	-1.4	2.7	-2.3	1.5	-1.8
B1984	1.3	-1.5	2.6	-2.2	1.4	-2
B1836	1.9	-1.3	2.9	0.5	2.1	0.9
B1892	3.1	0.4	0.2	-0.5	-1.3	-0.4
B2094	2.5	-1.1	2.6	-2.1	1.6	-1.9
B2102	1.9	-1.2	2.6	-2.1	1.5	-1.9
B2131	1.6	-0.1	2.6	-2.1	1.6	-1.8
B2205	1.1	-0.3	2.6	-2.1	1.6	-1.8
B2207	2.8	-0.7	2.3	-2.1	1.9	-1.7
B2216	0.9	-0.9	2.6	-2	1.6	-1.8
B2224	3.2	-0.7	2.8	-1.8	1.7	-1.6
B2285	1.5	-0.1	2.7	-1.9	1.6	-1.7
B2326	1.6	-1.2	2.6	-2.1	1.6	-1.8
B2378	2.9	-2.1	2.6	-2.1	2.6	-1.8
B2444	3	-1.2	2.6	-2.2	1.6	-1.8
B2553	2.2	-3.2	2.8	-2.1	1.7	-1.7
B2615	1.9	-1.5	1.9	-2	0.7	-1.9
B2471	0.9	2.4	2.7	-2.1	1.7	-1.8
B2426	1.5	0.5	2.8	-1.8	1.8	-1.6
B2070	1.3	-0.6	2.5	-2.2	1.6	-1.9
B2019	0.8	-0.9	2.5	-2.3	1.7	-1.8
B2009	2.1	-1.8	2.9	-1.6	1.8	-1.6
B2321	2.2	-2	1.8	-5.2	1.6	-1.8

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3. Raw Data ANS

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2	-1.5	2.5	-2	1.6	-1.8
B1240	0.1	-0.5	2.2	-2.3	1.6	-1.9
B2066	0.1	-1.6	2.5	-1.7	1.6	-1.6
B2065	1	-0.3	2.4	-1.8	1.6	-1.7
B2055	0.1	-2	2.4	-2	1.5	-1.8
B2013	2.6	-1.4	2.4	-2	1.5	-1.8
B1984	1.3	-1	2.4	-2.1	1.4	-2
B1836	1.8	-1.7	1.9	0.8	1.3	1.2
B1892	3.9	-2.3	0.8	-1.9	-0.5	-1.9
B2094	1.1	-2.6	2.4	-2	1.6	-1.9
B2102	0.7	-1.3	2.4	-2	1.5	-1.9
B2131	1.7	0	2.4	-2	1.6	-1.8
B2205	0.9	-1.1	2.4	-2	1.6	-1.8
B2207	2.5	-2.2	2.2	-1.8	1.8	-1.7
B2216	1.5	-0.9	2.5	-2	1.6	-1.8
B2224	6.2	-1.1	2.6	-1.8	1.7	-1.6
B2285	2.4	-0.9	2.5	-1.9	1.6	-1.7
B2326	2.7	-1.5	2.4	-2	1.6	-1.8
B2378	2.7	-2.4	2.4	-2	1.6	-1.8
B2444	4.2	-0.8	2.4	-2.1	1.6	-1.8
B2553	2.3	-1.3	2.6	-1.8	1.7	-1.7
B2615	1.2	-0.6	0.1	0.8	-1	0.7
B2471	1.8	-0.4	2.4	-2	1.7	-1.8
B2426	2.2	0.7	2.6	-1.8	1.8	-1.6
B2070	1.6	-1	2.4	-2.1	1.6	-1.9
B2019	1	-1.2	2.4	-2.1	1.7	-1.8
B2009	1.3	-0.9	2.8	-1.5	1.8	-1.6
B2321	2	-1.5	1.7	-5.3	1.6	-1.8

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4. Raw Data PNS

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	-0.3	-1.1	1.3	-1.8	1.6	-1.9
B1240	-2	-0.5	0.7	-1.9	1.5	-2
B2066	-0.5	-1.1	1.4	-1.6	1.6	-1.5
B2065	-0.8	2.2	1.3	-1.6	1.6	-1.7
B2055	-0.4	-1.6	1.2	-1.8	1.5	-1.7
B2013	-1.4	-1.7	1.2	-1.8	1.5	-1.7
B1984	-1.6	-2.2	1.2	-1.8	1.4	-1.9
B1836	-2.9	-3	0.1	-1.4	0.7	-1.4
B1892	0.6	-0.6	0.2	-1.4	0.1	-1.4
B2094	1.5	-1.2	1.3	-1.8	1.6	-2
B2102	1.3	-1.3	1.3	-1.8	1.5	-1.9
B2131	0.4	-0.3	1.3	-1.8	1.6	-1.8
B2205	0.4	-1	1.3	-1.8	1.6	-1.8
B2207	1.2	-1.1	1.1	-1.6	1.8	-1.9
B2216	-1.7	-1.3	1.3	-1.8	1.6	-1.9
B2224	3.4	-3.2	1.4	-1.7	1.7	-1.5
B2285	0.2	-1.5	1.4	-1.8	1.6	-1.7
B2326	1.6	0.8	1.3	-1.8	1.6	-1.8
B2378	-2.9	-3	1.3	-1.8	1.6	-1.8
B2444	1.5	0.1	1.2	-1.8	1.6	-1.9
B2553	-1.9	-2.7	1.4	-1.7	1.7	-1.9
B2615	-2.1	-0.7	-2.6	-0.9	-2.6	-1
B2471	0.1	-0.3	1.3	-1.8	1.7	-1.9
B2426	2.5	1.1	1.4	-1.7	1.6	-1.7
B2070	1.2	-3.9	1.2	-1.9	1.6	-2
B2019	-0.4	-0.3	1.2	-1.9	1.7	-2.1
B2009	-0.5	-1.3	1.6	-1.6	1.7	-1.6
B2321	0.4	-1.4	1.4	-1.7	1.6	-1.7

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5. Raw Data Maxillary Incisor Tip (U1Tip)

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2.8	-1.4	3.1	-2.4	1.7	-3.9
B1240	0.4	0.7	2.9	-2.7	1.7	-3.8
B2066	1.5	-0.3	2.8	-2.8	1.6	-3.5
B2065	1	-0.5	2.8	-2.8	1.9	-3.8
B2055	2.1	-0.6	2.8	-3.1	1.5	-3.7
B2013	0.5	-2.4	2.8	-3.1	1.5	-3.7
B1984	3.2	-3.4	2.6	-3	1.3	-4.1
B1836	1.9	-2	4.8	-0.7	4.1	-1.4
B1892	5.4	-1.6	0.3	-3	-1.5	-4.2
B2094	2.7	-3.5	3	-2.7	1.6	-4.1
B2102	3.9	-2.3	3	-2.6	1.6	-4
B2131	0.9	0.9	3.1	-2.5	1.7	-3.7
B2205	3	-1.8	3.1	-2.5	1.7	-3.7
B2207	3.5	-1.4	2.6	-2.8	2	-3.6
B2216	1.5	-2.6	3.3	-2.2	1.7	-3.8
B2224	6.3	-2	3.2	-2.2	1.9	-3.6
B2285	3	-3.2	3.2	-2.3	1.7	-3.8
B2326	2.1	-3.7	3	-2.6	1.7	-3.8
B2378	2.7	-2	3	-2.6	1.7	-3.8
B2444	3.3	-1.6	2.7	-3.3	1.6	-3.8
B2553	2.4	-2.8	1.5	-5.8	1.8	-3.9
B2615	1.5	-1.6	2.5	-3.2	1	-4.4
B2471	0.9	1.2	3.1	-2.5	1.9	-3.8
B2426	0.7	-1.6	3.2	-2.1	2.1	-3.5
B2070	4	-2.6	3	-2.5	1.7	-3.9
B2019	1.2	-2	2.7	-3.2	1.9	-3.9
B2009	2	-2	3.3	-2.6	1.9	-3.6
B2321	3.2	-2.7	2.4	-4	1.6	-3.8

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6. Raw Data Maxillary Incisor Root (U1Root)

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2.4	-0.8	2.5	-2.1	1.9	-3.8
B1240	-0.4	0.7	2.4	-2.3	1.9	-3.7
B2066	1.6	-2.3	2.5	-1.9	1.8	-3.4
B2065	1.3	-2.5	2.4	-2	2.1	-3.7
B2055	1.6	-2.7	2.5	-2.2	1.8	-3.6
B2013	-1	-2.5	2.5	-2.2	1.8	-3.6
B1984	2.6	-2.8	2.5	-2.2	1.6	-4.1
B1836	2.2	-1.5	3.9	-0.7	3.9	-1.9
B1892	4.1	-2.9	0.7	-2.4	-0.6	-4.4
B2094	4.5	-3.5	2.5	-2.1	1.9	-4
B2102	3.9	-2.3	2.5	-2.1	1.8	-3.9
B2131	2	-2.5	2.5	-2.1	1.9	-3.6
B2205	1.7	-2.8	2.5	-2.1	1.9	-3.6
B2207	4.9	-1.1	2.1	-2.2	2.2	-3.6
B2216	1.1	-1.8	2.5	-2.1	2	-3.8
B2224	4.6	-3	2.7	-1.9	2.1	-3.5
B2285	2.8	-3.2	2.6	-2	2	-3.7
B2326	1.3	-4.1	2.5	-2.1	1.9	-3.7
B2378	3.4	-1.9	2.5	-2.1	1.9	-3.7
B2444	3.6	-1.6	2.5	-2.2	1.9	-3.7
B2553	2.4	-2.1	2.6	-2	2.1	-3.8
B2615	1.4	-1.8	2.4	-2.2	1.3	-4.3
B2471	0.8	0.3	2.5	-2.1	2.1	-3.7
B2426	1.9	-0.6	2.7	-1.9	2.3	-3.4
B2070	3.1	-3.1	2.4	-2.2	1.9	-3.9
B2019	1.9	-1.9	2.4	-2.2	2.1	-3.8
B2009	1.5	-2.1	2.9	-1.7	2.1	-3.6
B2321	3.2	-1.8	1.6	-5.9	1.9	-3.8

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7. Raw Data Mandibular Incisor Tip (L1Tip)

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	3.2	-0.7	2.7	-2.8	1.7	-3.9
B1240	0.2	-0.2	2.5	-3.1	1.7	-3.8
B2066	1.4	-0.4	2.7	-2.9	1.6	-3.5
B2065	1	-0.7	2.6	-2.9	1.9	-3.8
B2055	1.5	0.9	2.5	-3.3	1.6	-3.7
B2013	2.7	-1.8	2.5	-3.3	1.6	-3.7
B1984	2.3	-2.7	2.4	-3.3	1.3	-4.1
B1836	1.1	-2.4	4.2	-1.6	3.8	-1.9
B1892	3	-2.7	0.2	-3.2	-1.5	-4.2
B2094	2.7	-5.3	2.6	-2.1	1.7	-4
B2102	4.9	-2.9	2.6	-3	1.6	-3.9
B2131	2	-3.3	2.6	-3	1.7	-3.7
B2205	2.1	-1.8	2.6	-3	1.7	-3.7
B2207	3	-3.9	2.2	-2.9	2.1	-3.6
B2216	0.3	-0.3	2.7	-2.9	1.8	-3.8
B2224	6.7	-2.4	2.9	-2.8	1.9	-3.5
B2285	1.9	-1	2.7	-2.8	1.8	-3.8
B2326	2	-3.8	2.6	-3	1.7	-3.7
B2378	4	-3.4	2.6	-3	1.7	-3.7
B2444	3.4	-2.3	2.5	-3.3	1.7	-3.8
B2553	1.7	-0.9	2.2	-5.3	1.9	-3.8
B2615	1.8	-1	2.3	-3.3	1	-4.3
B2471	0.3	0.2	2.6	-2.9	1.9	-3.8
B2426	0.8	-0.5	2.9	-2.8	2.1	-3.5
B2070	4.8	-2.4	2.5	-3	1.7	-3.9
B2019	1.1	-1	2.4	-3.3	1.9	-3.8
B2009	1.9	-1.8	3	-2.7	1.9	-3.6
B2321	2.7	-3.2	1.5	-5.9	1.7	-3.8

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8. Raw Data Mandibular Incisor Root (L1Root)

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2.9	-1.3	3.1	-3.1	1.5	-3.7
B1240	1.1	-1.2	2.9	-3.3	1.5	-3.6
B2066	2.7	0.2	2.9	-3.1	1.4	-3.4
B2065	2.3	0	2.9	-3.1	1.7	-3.6
B2055	3.4	1.1	2.7	-3.4	1.4	-3.6
B2013	1.7	-1.4	2.7	-3.4	1.4	-3.6
B1984	2.4	-3.4	2.7	-3.4	1.1	-4
B1836	1.9	-2.5	4.7	-1.9	4	-2.1
B1892	3.1	-2.4	0.3	-2.9	-1.8	-3.6
B2094	1.7	-4.7	2.9	-3.3	1.5	-3.9
B2102	4.8	-2.5	2.9	-3.3	1.4	-3.8
B2131	2	-3.7	2.9	-3.3	1.6	-3.6
B2205	3.7	-2.6	2.9	-3.3	1.6	-3.6
B2207	4.5	-3.5	2.6	-3.2	-2	-3.5
B2216	0.2	-0.9	3	-3.1	1.6	-3.7
B2224	8.3	-3.1	3.2	-2.9	1.8	-3.4
B2285	2	-1.2	3.2	-3.1	1.6	-3.6
B2326	2.8	-4.1	2.9	-3.2	1.5	-3.6
B2378	4.2	-4.2	2.9	-3.2	1.5	-3.6
B2444	3.1	-2.1	2.7	-3.5	1.5	-3.6
B2553	1.2	-1.2	1.7	-4.9	1.7	-3.7
B2615	3.5	-1.4	2.6	-3.5	0.8	-4.1
B2471	1	0.5	3	-3.3	1.8	-3.7
B2426	0.4	-0.7	3.2	-2.9	1.9	-3.4
B2070	5.5	-2.9	2.9	-3.3	1.5	-3.8
B2019	0.8	-0.9	2.7	-3.5	1.8	-3.7
B2009	2.3	-2.1	3.4	-2.9	1.8	-3.5
B2321	2.3	-3.8	1.7	-6	1.5	-3.7

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9. Raw Data B-Point

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2.7	-1.4	3.2	-3.6	1	-5.6
B1240	1.2	-1.3	2.8	-3.6	1	-5.4
B2066	1.9	-1.1	1.7	-6	1.1	-5.2
B2065	1.4	-1.3	1.4	-6	1.5	-5.6
B2055	3.4	1	1	-5.9	1.1	-5.4
B2013	2.9	-0.7	1	-5.9	1.1	-5.4
B1984	0.1	-0.5	1.1	-6.2	0.7	-6
B1836	1.6	-4.4	6.7	2.6	5.9	0.9
B1892	3.7	-1.5	-2.2	-5.3	-2.9	-5.8
B2094	1.9	-5.2	2.9	-3.6	1.1	-5.8
B2102	5	-6.6	3	-3.8	1	-5.7
B2131	2.6	-3.6	3	-3.8	1.2	-5.3
B2205	3.1	-3.8	3	-3.8	1.2	-5.3
B2207	4.2	-3.6	2.6	-3.4	1.5	-5.2
B2216	1.1	-2.4	3	-3.5	1.1	-5.5
B2224	7.6	-4.8	3.2	-3.3	1.7	-5.3
B2285	0.6	-2.6	3.2	-3.7	1.3	-5.5
B2326	2.4	-5.9	2.8	-3.7	1.1	-5.4
B2378	4.8	-3	2.8	-3.7	1.1	-5.4
B2444	3.9	-2.8	1.1	-6.2	1	-5.4
B2553	1.9	-2.8	1.7	-6.1	1.3	-5.6
B2615	1.7	-2.2	1.2	-6.4	0.3	-6.2
B2471	1.1	-3.2	3	-3.8	1.3	-5.5
B2426	1.1	-1.3	3.2	-3.3	1.7	-5.2
B2070	3.1	-5.8	2.8	-3.9	1	-5.6
B2019	1.4	-0.1	1	-6.2	1.2	-5.5
B2009	1.9	-3.4	2.3	-5.8	1.6	-5.5
B2321	2.9	-3.6	1.6	-6	1.2	-5.6

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10. Raw Data Pogonion

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	3.1	-4.7	3.3	-4.1	1	-5.6
B1240	2	-4.8	3.6	-4.1	0.9	-5.4
B2066	2.6	-1.8	1.1	-5.6	1	-5.2
B2065	2.1	-2	1.3	-5.9	1.3	-5.5
B2055	2.9	-3.3	0.8	-5.6	1	-5.4
B2013	3.8	-3.8	0.8	-5.6	1	-5.4
B1984	2.9	-5	0.8	-5.7	0.6	-6
B1836	1.1	-0.9	5.2	-3.1	4.4	-3.6
B1892	4.9	-3.6	-2.1	-4.5	-2.6	-5.4
B2094	3.6	-4.4	2.5	-4.2	0.9	-5.8
B2102	6.6	-4.5	2	-4.6	0.9	-5.7
B2131	3.1	-4.1	2.3	-4.4	1.1	-5.4
B2205	4.7	-4.5	2.3	-4.4	1.1	-5.4
B2207	4.4	-2.7	1.4	-4.8	1.4	-5.2
B2216	0.8	-2.1	3.5	4.1	1	-5.5
B2224	9	-4.9	1.8	-4.6	1.5	-5.3
B2285	2	-3.3	3.6	-4	1.1	-5.4
B2326	3.1	-7.8	3	-4.2	1	-5.4
B2378	4.2	-6.3	3	-4.2	1	-5.4
B2444	3.1	-4.3	0.9	-5.9	0.9	-5.4
B2553	3.5	-1.9	1.4	-5.7	1.1	-5.5
B2615	2.3	-3.4	0.8	-5.9	0.1	-6.2
B2471	0.5	-2.8	2.5	-4.4	1.2	-5.5
B2426	1.6	-0.8	3	-4.1	1.6	-5.2
B2070	3.8	-4.2	1.8	-4.5	0.9	-5.6
B2019	0.7	-1	0.8	-5.7	1.1	-5.5
B2009	2.7	-2.8	2.2	-5.6	1.4	-5.5
B2321	3.3	-4.4	1.3	-5.6	1.1	-5.6

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11. Raw Data Menton

BOLTON #	Dx	Dy	Bolton Dx	Bolton Dy	Ricketts Dx	Ricketts Dy
B1224	2.9	-4.1	1.7	-4.6	0.9	-5.5
B1240	3.5	-3.1	2.1	-4.4	0.8	-5.3
B2066	3.8	-1	0.7	-5.3	1	-5.1
B2065	3.3	-1.2	0.9	-5.6	1.2	-5.5
B2055	2.4	-1.9	0.5	-5.1	0.9	-5.4
B2013	4.4	-3.6	0.5	-5.1	0.9	-5.4
B1984	3	-5.4	0.6	-5.5	0.5	-5.9
B1836	3.4	-3.7	3.7	-4	4.5	-3.8
B1892	2.3	-3.8	-2.3	-4.1	-2.7	-5.2
B2094	5	-5.2	1.2	-4.9	0.9	-5.7
B2102	5	-6.2	1.1	-4.9	0.9	-5.6
B2131	1.4	-6.6	1.1	-5	1	-5.3
B2205	5.7	-3.9	1.1	-5	1	-5.3
B2207	4.8	-3	0.4	-5.6	1.4	-5.1
B2216	0.3	-2.1	1.3	-4.9	0.9	-5.4
B2224	8.3	-5.5	1.5	-5.3	1.5	-5.2
B2285	2.1	-4.1	2.6	-4.5	1.1	-5.4
B2326	-3.4	-6	2.3	-4.7	0.9	-5.4
B2378	4.6	-7.3	2.3	-4.7	0.9	-5.4
B2444	3.6	-4.3	0.7	-5.6	0.8	-5.4
B2553	2.1	-2.6	1.1	-5.5	1.1	-5.5
B2615	2	-2.9	0.6	-5.7	0	-6.1
B2471	0.7	-1.8	1.1	-4.9	1.2	-5.4
B2426	2.2	-1.3	1.6	-4.7	1.5	-5.2
B2070	4.3	-5	1	-4.9	0.9	-5.5
B2019	0.2	-1.1	0.5	-5.3	1.1	-5.4
B2009	3.6	-3.7	2	-5.3	1.4	-5.4
B2321	3.5	-4.6	1	-5.3	1	-5.6

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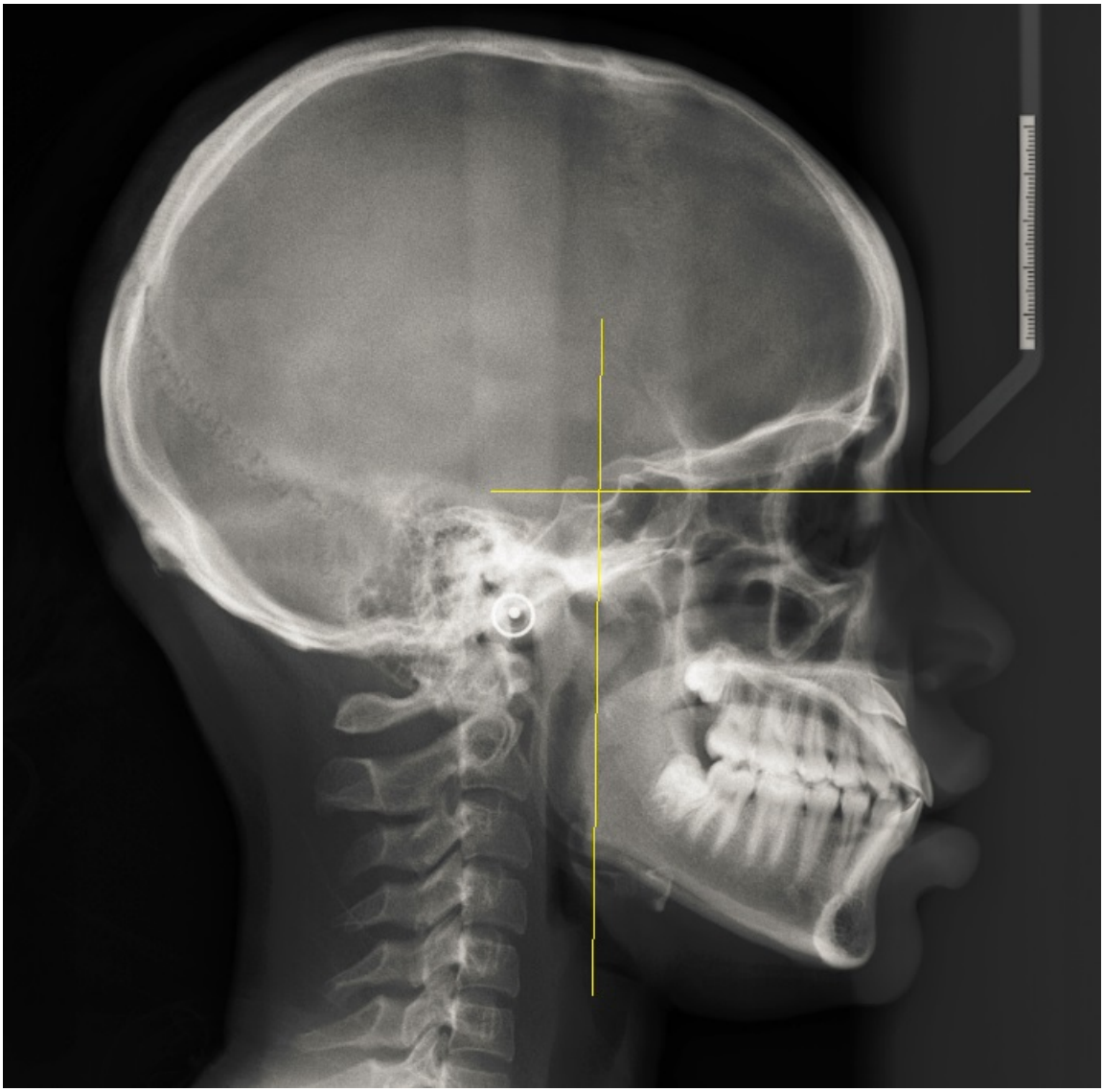
Appendix 5

Raw Data ML12 and ML14 – Film-Object distance

BOLTON #	ML 12	ML 14	ML12/ML14
B1224	88.2	90.6	1.0
B1240	86.2	88.5	1.0
B2066	91.6	95.2	1.0
B2065	87.1	85.8	1.0
B2055	84.2	91	0.9
B2013	89.6	83.2	1.1
B1984	86.5	85	1.0
B1836	82.6	85	1.0
B1892	85.5	82.6	1.0
B2094	84.8	88.8	1.0
B2102	88.5	89.1	1.0
B2131	90.6	94.5	1.0
B2205	87.6	85.4	1.0
B2207	84.6	90.5	0.9
B2216	83.5	84.7	1.0
B2224	87.8	82.5	1.1
B2285	88	85.8	1.0
B2326	87.4	83.7	1.0
B2378	86.3	89.6	1.0
B2444	97.7	93.4	1.0
B2553	88	89	1.0
B2615	75	81	0.9
B2471	89.4	94	1.0
B2426	87.3	94.4	0.9
B2070	84.8	83	1.0
B2019	84.2	81	1.0
B2009	84	89	0.9
B2321	81.4	88.5	0.9

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Appendix 6



Source:

http://3d-cdds.com/Our-Services/Dental-Photography/2D-Imaging/Cephalometric-Radiograph

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Appendix 7

Table representing the range of each landmark; Minimum and maximum for each variable

Variable	Max Dx	Min Dx	Max Dy	Min Dy	Max Dx	Min Dx	Max Dy	Min Dy	Max Dx	Min Dx	Max Dy	Min Dy
Nasion	2.3	0.3	2.5	0.1	1.0	-0.1	0.1	0.0	2.2	1.2	0.4	-0.1
A-Point	3.2	0.8	2.4	-3.2	2.9	0.2	0.5	-5.2	2.6	-1.3	0.9	-2.0
ANS	6.2	0.1	0.7	-2.6	2.8	0.1	0.8	-5.3	1.8	-1.0	1.2	-2.0
PNS	3.4	-2.9	2.2	-3.9	1.6	-2.6	-0.9	-1.9	1.8	-2.6	-1.0	-2.1
U1 Tip	6.3	0.4	1.2	-3.7	4.8	0.3	-0.7	-5.8	4.1	-1.5	-1.4	-4.4
U1 Root	4.9	-1.0	0.7	-4.1	3.9	0.7	-0.7	-5.9	3.9	-0.6	-1.9	-4.4
B-Point	7.6	0.1	1.0	-6.6	6.7	-2.2	2.6	-6.4	5.9	-2.9	0.9	-6.2
Pogonion	9.0	0.5	-0.8	-7.8	5.2	-2.1	4.1	-5.9	4.4	-2.6	-3.6	-6.2
Menton	8.3	-3.4	-1.0	-7.3	3.7	-2.3	-4.0	-5.7	4.5	-2.7	-3.8	-6.1
L1 Tip	6.7	0.2	0.9	-5.3	4.2	0.2	-1.6	-5.9	3.8	-1.5	-1.9	-4.3
L1 Root	8.3	0.2	1.1	-4.7	4.7	0.3	-1.9	-6.0	4.0	-2.0	-2.1	-4.1
	Actual Patient				Bolton Prediction				Rickett's Prediction			

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Appendix 8

Table representing the Mean and Standard Deviation for each landmark studied and along the x- and y-axis

Variable	Dx Mean ± SD	Dy Mean ± SD	Dx Mean ± SD	Dy Mean ± SD	Dx Mean ± SD	Dy Mean ± SD
Nasion	1.19 ± 0.49	1.11 ± 0.49	0.51 ± .09 ***	0.02 ± 0.03	1.84 ± 0.10***	0.05 ± 0.08
A-Point	1.8 ± 0.67	-0.9 ± 0.72	2.49 ± 0.27 ***	-2.04 ± 0.38	1.54 ± 0.28NS	-1.64 ± 0.28
ANS	1.89 ± 0.93	-1.19 ± 0.56	3.09 ± 1.64	-1.87 ± 0.45***	1.44 ± 0.33	-1.59 ± 0.36***
PNS	-0.11 ± 1.28	-1.15 ± 0.95	1.06 ± 0.42	-1.71 ± 0.13 ***	1.37 ± 0.42	-1.75 ± 0.17***
U1 Tip	2.41 ± 1.12	-1.74 ± 0.94	2.85 ± 0.41***	-2.78 ± 0.48***	1.66 ± 0.35***	-3.74 ± 0.24***
U1 Root	2.3 ± 1.10	-2.08 ± 0.80	2.46 ± 0.23***	-2.19 ± 0.30***	1.91 ± 0.28***	-3.69 ± 0.22***
B-Point	2.54 ± 1.20	-2.78 ± 1.48	2.29 ± 1.04***	-4.43 ± 1.35***	1.19 ± 0.51	-5.29 ± 0.46
Pogonion	3.16 ± 1.22	-3.58 ± 1.26	1.96 ± 1.04***	-4.53 ± 0.95	1.04 ± 0.42***	-5.43 ± 0.21
Menton	3.04 ± 1.52	-3.75 ± 1.39	1.18 ± 0.67	-5.01 ± 0.36***	0.98 ± 0.45	-5.37 ± 0.20***
L1 Tip	2.30 ± 1.13	-1.85 ± 1.19	2.51 ± 0.32***	-3.12 ± 0.44***	1.69 ± 0.33***	-3.73 ± 0.21***
L1 Root	2.71 ± 1.24	-2.00 ± 1.26	2.79 ± 0.39***	-3.33 ± 0.35***	1.38 ± 0.53***	-3.60 ± 0.16***

Actual Patient Bolton Prediction Rickett's Prediction

Statistically Significant

Actual to Predicted *P≤ 0.05 ** P≤ 0.005 *** P≤ 0.0005

DS MH DocuSigned by: J Martin Palomo 425B082644AD404... DS ML