Evaluation of mandibular growth rotation prediction methods based on lateral cephalogram measurements

M.S. Candidate: Eric C. Burgin, DDS, MPH

A Thesis submitted to the Department of Orthodontics and the Advanced Education Committee of the Oregon Health and Science University School of Dentistry
In partial fulfillment of the requirements for the degree of Master of Science

November 2008

Evaluation of mandibular growth rotation prediction methods based on lateral cephalogram measurements

A thesis presented by Eric C Burgin, DDS, MPH
In partial fulfillment for the degree of Master of Science

November 2008

[redacted]

Bruce Fiske, DMD
Clinical Professor
Department of Orthodontics

[redacted]

David Covell, PhD, DDS
Associate Professor, Chair
Department of Orthodontics

[redacted]

Larry Doyle, DDS
Assistant Professor and Graduate Program Director
Department of Orthodontics

[redacted]

Judah Garfinkle, DMD, MS
Director of Craniofacial Orthodontics
Assistant Professor of Plastic and Reconstructive Surgery
Assistant Professor of Orthodontics

ACKNOWLEDGEMENTS

I would like to thank the members of my thesis committee for providing ideas, guidance, and support throughout this process. Your help made this project more manageable and meaningful. Thank you to Dr. Bruce Fiske, Dr. David Covell, Dr. Larry Doyle, and Dr. Judah Garfinkle.

I would also like to thank my co-residents for their support and friendship.

TABLE OF CONTENTS **Page**

List of Figures

List of Tables

Abstract

Rotation of the mandible during growth can have an influence on treatment planning and its prediction could be a valuable diagnostic tool. This study aimed to evaluate several prediction methods including those described by Skieller et al. (1984), Jarabak (1972), and Lux et al. (1999) as well as the computerized growth forecast function of Quick Ceph Studio (Quick Ceph Systems) digital imaging software. An additional aim was to determine if the success of the methods was different for subgroups based on skeletal classification according to ANB. **Materials and Methods:** Pre-adolescent growth records from untreated subjects selected from the Oregon Child Study Clinic data collection were used to evaluate the prediction methods by making predictions of mandibular rotation and comparing the predictions to the actual growth measured from post-adolescent growth records. **Results:** The regression analysis described by Skieller et al. performed poorly in this sample as in previous studies of this method. Quick Ceph Studio's growth forecast predicted no mandibular rotation for all but 4 of the subjects. The computerized prediction method was not individualized enough to accurately predict mandibular rotation in individual patients. Of the ranges for prediction described by Jarabak (1972) and Lux et al. (1999), the predictive range using upper gonial angle (UGA) described by Jarabak was the most accurate at predicting the direction of mandibular growth, with 79.2% of the predictions made being correct. There was insufficient evidence to determine that differences in prediction accuracy between the subgroups existed. **Conclusions:** The mandibular growth rotation prediction methods evaluated are not accurate or reliable enough to make definitive predictions. However, a clinician may decide to use the ranges specified by Jarabak (1972) for UGA

to add to the overall assessment of a patient, with the limitations of the method considered.

Introduction

Growth amount and direction can be highly variable among patients and can have an impact on an orthodontic treatment plan and the ultimate outcome and stability of treatment. Insight into how an individual will grow could allow orthodontists to select the most appropriate treatment plan in order to achieve an optimal and stable result. When serial lateral cephalograms are not available, a tool that could allow the orthodontist to predict growth patterns based on a single lateral cephalogram would be beneficial.

Many prediction methods have been developed, and their interpretation and use have been a topic of debate for many years. Proposed methods have included anatomical measurements from lateral cephalograms (Jarabak, 1972; Lux et al., 1999), logistic regression equations (Skieller et al., 1984; Lee et al., 1987), predictions based on average growth patterns of a large group of patients (Ricketts, 1957; Hixon, 1968), as well as others (Johnston, 1975; Bhatia et al., 1979; Baumrind et al., 1989). These methods have been employed in various studies on several sample populations and have demonstrated a wide range of predictive values (Lee et al. 1987, Leslie et al. 1998). In this study, four of the methods that have been previously introduced were applied to a single population of untreated individuals in order to evaluate their predictive values. The sample was a random selection of adolescents that represent the general population of patients that might present for orthodontic evaluation.

Review of the Literature

Prediction of growth and the pubertal growth spurt has been a goal of many orthodontists in order to facilitate treatment planning. Many methods have been developed and assessed using a wide variety of indicators including peak growth velocity in standing height, pubertal markers (voice changes in males, menarche in females, breast development, appearance of pubic hair, and appearance of axillary hair), radiographic assessment of bone maturation, chronologic age, and staging of dental development (Johnston et al, 1965; Moore, 1997; Flores-Mir et al, 2004).

Hand/Wrist Films

Fishman (1979) investigated the comparisons that exist between chronologic and skeletal ages within a population to make some judgment as to the reliability of using cephalometric standards based on chronologic age, and to study the diagnostic value of using skeletal age for cephalometric evaluation. The sample consisted of 60 boys and 68 girls selected at random. Lateral cephalograms, left hand-wrist radiographs, and standing height measurements were recorded at 6-month intervals. Skeletal age determinations were established on the basis of the hand-wrist radiographs. Facial measurements were made from the lateral cephalograms to plot changes with both skeletal and chronologic ages. When the data were analyzed, it was concluded that the majority of individuals did not present concurrence between skeletal and chronologic ages at most developmental levels. The wide variation in the population of chronologic age at which skeletal maturation occurs lead Fishman to conclude that skeletal and not chronologic age would permit a more objective diagnostic evaluation to help develop a treatment plan.

Taking a skeptical approach to the clinical use of hand-wrist radiographs for predicting the pubertal growth spurt, Houston (1980) examined the roles of ossification events, bone stages, and bone ages in pubertal growth spurt prediction. The sample included 68 boys and 58 girls who took part in the Harpenden growth study (Harpenden, England). Records were collected every six months, and then every three months after the first signs of secondary sex characteristics were observed. The records included hand-wrist radiographs and standing height measurements. A number of methods described previously using ossification events, bone stages, and bone ages were tested and compared with the original data from the studies. After thorough analysis, Houston (1980) concluded that the information from hand-wrist radiographs is of limited value in predicting the timing of the peak height velocity and the growth spurt. He cited the need for frequent serial radiographs as a limiting factor for clinical use. Regression equations for males and females were presented as a method of more accurately predicting the timing of the peak height velocity.

Fishman (1982) presented a system for evaluating skeletal maturity based on hand-wrist radiographs. This system was based on the premise that the osseous changes seen in the hand and wrist are indicators of more general skeletal changes. This method used four ossification events including epiphyseal widening on selected phalanges, ossification of the adductor sesamoid of the thumb, the capping of selected epiphyses over their diaphyses, and the fusion of selected epiphyses and diaphyses. These events take place at 6 sites located on the thumb, third finger, fifth finger, and radius. The sites and stages combine to represent 11 Skeletal Maturity Indicators (SMI's). The sequence of occurrence of the 11 stages is very stable; the author reported only 3 deviations from

the sequence in over 2,000 observations (not part of this study). There were sample groups evaluated, a longitudinal group consisting of 170 females and 164 males, and a cross-sectional group consisting of 550 females and 550 males. In the longitudinal group, statural height was recorded semiannually during childhood through adulthood. Additional longitudinal records were obtained for 36 females and 32 males including lateral and P-A cephalometric radiographs and hand-wrist radiographs for the purpose of evaluating growth patterns. Two linear maxillary and two linear mandibular measurements were made to evaluate facial growth in relation to statural growth. In the cross-sectional group, hand-wrist radiographs were collected and SMI groups were formed to evaluate the relationship to chronologic age. It was found that there were significant differences in age of onset and progression of adolescent skeletal maturity in males and females. The difference was the greatest around the time of maximum growth velocity. Individuals studied demonstrated wide variation in maturational development; and patterns such as accelerated, average, or delayed maturation did not remain constant throughout maturation. A direct relationship was established between alterations in maturational development as observed on the hand-wrist film and growth velocity. Facial growth also demonstrated a close direct association with rates of growth and skeletal maturation. The maxilla and mandible reached their maximum growth rates later than statural height. The maxilla and mandible showed similar growth rates, but the maxilla showed more growth completed than the mandible until the final stage, when the mandible tended to catch up. Females demonstrated greater growth velocities and earlier maturation for the maxilla and for stature. Males demonstrated the highest growth velocities in the mandible. After the peak, growth velocities decreased more rapidly in

females than in males. Clinical use of the hand-wrist radiograph can provide a more useful estimate of growth completion than chronologic age. The SMI stage can be correlated with skeletal maturation, statural, and facial growth to assess how much of the total growth has occurred in a patient. The assessment cannot predict the amount of growth that will occur or how long growth will continue, but it gives clinicians an idea of how much of an individual's growth has been achieved and if additional growth can be anticipated.

Moore et al. (1990) attempted to compare specific craniofacial growth changes with statural growth as measured by changes in height and with skeletal maturation of the hand and wrist in order to assess the relevance of hand-wrist radiographs to clinical orthodontics. Annual records including statural height, lateral cephalograms, and hand-wrist radiographs were collected for a sample of 47 girls between the ages of 10 and 15, and of 39 boys between the ages of 11 and 16. Four skeletal linear measurements were made including SN, GoGn, SGo, and NMe. The hand-wrist radiographs were scored by the TW2 RUS assessment of skeletal maturity (Tanner et al., 1975). When analyzed, it was found that the maturity scores that immediately preceded the height velocity values were the most highly correlated, indicating that hand-wrist growth precedes changes in statural growth. The hand-wrist skeletal maturation was significantly related to statural height in both sexes. Children experienced a large variety of growth patterns, and craniofacial growth spurts could not be consistently demonstrated on an individual basis. The correlation coefficients were relatively small between height and facial dimension velocities as well as between skeletal maturity scores and changes in facial dimension. The authors concluded that the relationship between acceleration and deceleration in

growth of specific craniofacial dimensions and statural height or skeletal maturity is not clinically significant for prediction. They do, however acknowledge that the relationship may be a useful factor to consider in treatment planning.

Flores-Mir et al. (2004) evaluated the predictive value of hand-wrist radiographic assessment of skeletal maturity in estimating facial growth timing and velocity. The study was conducted in the standard method of systematic reviews beginning with a search of scientific literature databases. Articles were analyzed for the following inclusion criteria: 1) Use of hand-wrist radiographs for skeletal maturation determination, 2) Facial growth evaluation through cephalometric radiographs, and 3) Cross-sectional or longitudinal studies. Sixteen articles met the inclusion criteria, but five were rejected due to methodological issues. All of the articles indicated that overall facial growth velocity was well related to standing height growth velocity and skeletal maturity. Fishman (1982) and Moore et al (1990) developed growth curves that showed a rapid acceleration to peak growth velocity and a more gradual decline. The studies demonstrated significant correlations between skeletal maturity and mandibular growth velocity. The review found that skeletal maturity determined by hand-wrist radiographic analysis is well related to overall facial growth velocity. Maxillary and mandibular growth velocities are related to skeletal maturity, but the correlations are weaker than those for overall facial growth velocity. The relationship between cranial base growth velocity and skeletal maturity has not been sufficiently established. Skeletal maturity analysis of hand-wrist radiographs for use in predicting facial growth velocity should include bone staging as well as ossification events, as described by Fishman (1982).

In 2007, Hunter et al. evaluated the relationship between skeletal age and peak mandibular growth velocity (PMdV) by using skeletal age category at age 9 years (delayed or advanced) to predict whether PMdV would be delayed or advanced. The sample consisted of 94 boys from the Burlington Orthodontic Research Centre (Popovich & Thompson 1975) for whom annual lateral cephalograms, hand-wrist films, and height measurements had been collected from 4 to 18 years of age. Skeletal age was determined at several time points according to the methods described by Greulich and Pyle (1959), and predictions of PMdV were made based on these findings. Delayed and advanced skeletal age were defined as a skeletal age of greater than one year more and less, respectively, than chronologic age. Advanced and delayed PmdV were defined as PMdV occurring at or before age 12.7 years and at or after age 15.1 years, respectively. The authors reported that of the 30 boys who were classified as skeletally delayed, only 4 were classified as delayed in PMdV. Also, of the between 9 and 12 boys that were found to be skeletally advanced at the different evaluation ages, only 2 were classified as advanced in PMdV. When performing error analysis, the authors found that 35% of the determinations of PMdV that were re-analyzed were different from the first determinations, some being between 1 and 2 years older or younger than the initial determinations. The authors dismiss this increased error rate, stating that this error alone could not account for what they consider clear evidence of their conclusions. Hunter et al. concluded that skeletal age as determined from hand-wrist films at age 9, 10, or 11 years of age is not useful for predicting whether PMdV will be early, average, or late. The authors proposed that treating at the average age for PMdV, between the 13th and 15th birthdays for boys, is an effective way to exploit growth in 90% of the study

population without knowing exactly when PMdV will occur. It is concerning that the authors ignored a fairly large error rate that certainly raises the question: How can the study discount PMdV prediction from hand-wrist films when the authors could not accurately determine PMdV from actual mandibular measurements? Also, while the findings may question the use of hand-wrist films to predict when in the future PMdV will occur, they do not demonstrate that skeletal age is not useful for determining where the patient is currently on their individual skeletal or mandibular growth curve. Since a clinician can obtain current hand-wrist films easily to make this determination, predictions based on films made as young as 9 years of age are not necessary. Finally, the authors claim that 90% of their male subjects experienced substantial mandibular growth between ages 13 and 15 years, but this may include patients who were completing their growth spurts early in the time period or beginning their growth spurts very late in the time period. An individualized approach to evaluating growth seems much more appropriate than basing treatment timing on average values.

Cervical Vertebral Maturation

San Roman et al (2002) developed and tested a new method of assessment of cervical vertebral maturation against two previously described methods to determine the validity of cervical vertebral maturation (CVM) assessment to predict skeletal maturation. The other two methods tested were described by Lamparski (1972) and Hassel and Farman (1995). The sample included 958 Spanish children from 5 to 18 years of age. Lateral cephalograms and hand-wrist radiographs were collected. Skeletal maturation was evaluated on the hand-wrist radiographs according to the classification used by Grave and Brown (1976). The odontoid process and the body of the cervical

vertebrae were traced, and the stage of vertebral maturation defined by the methods of Lamparski (1972) and Hassel and Farman (1995) was assigned to each radiograph. The new method, which involves classification based on the concavity of the lower borders of the vertebrae, vertebral body height, and the shape of the vertebral body, was also used to evaluate vertebral maturation. Distributions of subjects based on maturation stage predicted by hand-wrist evaluation and the three CVM methods were compared using Pearson correlation coefficients. A good correlation was found between hand-wrist skeletal maturation and vertebral maturation as assessed by Hassel and Farman (1995) in females and males (r=0.84 and 0.77, respectively). A lower correlation was found between hand-wrist skeletal maturation and Lamparski's (1972) classification (r=0.79 for females and 0.69 for males). Concavity of the lower border tended to have the highest correlation with hand-wrist maturation (r=0.82 for females and 0.75 for males). Shape and height had lower correlations. The goal of the present study was to develop a simple system of maturation evaluation that does not require a hand-wrist radiograph in order to avoid extra radiation to the patient. The correlation between the hand-wrist maturation method and concavity was similar to that obtained when Hassel and Farman's classification was used, but higher than Lamparski's classification. Therefore the simpler method of only looking at the parameter of vertebral concavity is an adequate method of skeletal maturation assessment and avoids the added radiation exposure of a hand-wrist radiograph.

Flores-Mir et al. (2006) assessed the correlation between the Fishman maturation prediction (FMP) method (Fishman, 2000) and the CVM method (Baccetti et al, 2002) for skeletal maturation stage determination. The sample consisted of 79 subjects (52

females and 27 males) with hand-wrist radiographs and lateral cephalograms. Hand-wrist radiographs were evaluated using the FMP method to determine skeletal maturation level (advanced, average, or delayed) and stage (relative position of the individual in the pubertal growth curve) by a calibrated technician at the Growth Tek Company (Skaneateles, NY). Lateral cephalograms were evaluated for skeletal maturation stage according to CVM. The intraexaminer reliability correlation coefficient was 0.985 (0.959 to 0.996; P<.001) for FMP and 0.889 (0.723 to 0.968; P<.001) for CVM, demonstrating that at least in this study, the CVM method was less reproducible than FMP. A Spearman correlation value of 0.72 was found between the skeletal maturation stages of both methods. When the groups of skeletal maturation level according to FMP were evaluated individually with CVM, the correlation value was 0.73 for early maturing subjects, 0.70 for average maturing subjects, and 0.87 for late maturing subjects. The findings demonstrate that either method may be useful for research purposes, but not necessarily for the assessment of individual patients. The correlation values were highest in the late maturing subjects.

Baccetti et al. (2005) described a method of assessing skeletal maturity with CVM using only the second, third, and fourth cervical vertebrae. 30 subjects were included from the cephalometric files of the University of Michigan Elementary and Secondary School Growth Study. The peak in mandibular growth at puberty was defined as the maximum increase in Co-Gn between two consecutive annual cephalograms. These two annual cephalograms, the two immediately preceding, and the two immediately following comprised the six annual cephalograms used for each patient. The morphology of the bodies of C2-C4 was analyzed on each of these cephalograms. Chi squared tests,

ANOVA, and discriminant analysis were used to evaluate the significance of morphologic characteristics and to identify those characteristics mostly accounting for the differences between two consecutive observations. Cervical vertebral characteristics are described for each of the six stages proposed in this article. The appearance of a concavity at the lower border of the third cervical vertebra is the characteristic that mostly accounts for the identification of the stage immediately preceding the peak in mandibular growth (Cervical stage 3). Identification of Cervical stage 2 indicates that the peak in mandibular growth will occur on average 1 year after this stage. Identification of Cervical stage 4 indicates that the peak in mandibular growth has occurred within 1 or 2 years before this stage. A clinical example given in the article described a patient who experienced 2.5 mm of mandibular growth between CS2 and 3, and between CS 4 and 5. The patient experienced 5.4 mm of mandibular growth in the year following CS3. This method is proposed as advantageous over hand-wrist films because it only requires a film that is already routinely taken on orthodontic patients. It is also presented as a useful method because it does not require any cervical vertebrae past the fourth, as these are often covered on the film with the protective thyroid collar. Finally, it is presented as a useful way to predict the timing of the peak in mandibular growth in order to time treatment appropriately.

O'Reilly and Yanniello (1988) attempted to investigate the relationship of the stages of CVM to growth changes in the mandible. Annual lateral cephalograms of 13 girls from ages 9 to 15 years from the Bolton-Broadbent growth study in Cleveland were studied. Measurements of mandibular length (Ar-Pog), corpus length (Go-Pog), and ramus height (Ar-Go) were made in a previous study (Tofani, 1972), and maturational

changes in the cervical vertebrae were analyzed using the standards outlined by Lamparski (1972). Individual incremental curves were plotted for each subject and mandibular dimension, and average curves were derived by superimposing the individual curves on peak growth velocity. ANOVA was also performed. Cervical vertebral stages 1-3 (out of 6) were generally observed prior to peak velocity for all of the mandibular dimensions, with stages 2 and 3 occurring during the year immediately preceding the peak velocity. There was significant growth in mandibular length during stages 1-4, in corpus length during stages 1-3, and in ramus height during stages 1 and 2. Lamparski's (1972) study showed that cervical vertebral maturation was as reliable as hand-wrist analyses for assessing skeletal age. O'Reilly and Yanniello (1988) showed that the stages of cervical vertebral maturation are related to mandibular growth changes during puberty and can be used to assess timing of these mandibular growth changes

Mitani and Sato (1992) attempted to compare the growth characteristics of the mandible during puberty with growth characteristics of the hyoid bone, cervical vertebrae, hand bones, and standing height. The sample consisted of 33 Japanese girls and records collected included annual hand-wrist and lateral cephalometric radiographs between the ages of 9 and 14 years. The amount and timing of the maximum growth of the mandible did not correlate well with that of the other parameters investigated. The authors concluded that mandibular growth may show unpredictable, random variation in timing and amount, and that orthodontists should be careful about predicting mandibular growth from growth of other body parts.

In an attempt to assess morphological and incremental associations between the vertical development of the cervical spine and the face in subjects with varying facial

patterns, Karlsen (2004) longitudinally studied lateral cephalograms of 30 patients with low and high MP-SN angles. The children were selected from the Oslo Growth Material, University of Oslo, Department of Orthodontics. Lateral cephalograms were examined that were made at ages 6, 12, and 15 years. Karlsen had difficulty identifying 6-year olds with adequate variation in MP-SN, so for grouping patients he only used MP-SN measured at 12 years of age. The lower angle group had MP-SN of 25° or less, and the higher angle group had MP-SN of 35° or more. The lateral cephalograms were traced, and landmarks for the cervical vertebrae were defined as the lower anterior border of the body of the corresponding cervical vertebra. There were no morphological associations detected during the study. Children with long necks tended to have short, square faces, and children with short necks tended to have long faces. Vertical growth of the upper cervical spine and face were weakly correlated in the 6-to-12-year period, but strongly correlated later during puberty. An interesting finding was that the vertical distance between gonion and the body of the second cervical vertebra was constant during childhood and puberty, suggesting that a mutual relationship may exist between vertical growth of the upper cervical spine and the face, particularly the lower face. Discriminant analysis showed predictions of low- or high-angle subjects based on growth of the upper cervical spine were weak, only being correct 46.7% of the time in the 6-to-12 – year period and 53.3% in the 12-to-15-year period.

Developmental Factors

In 1966, Hunter evaluated the correlation of facial growth with body height and skeletal maturation during adolescence. The sample consisted of 25 males and 34 females from the Child Research Council, Denver, Colorado. Eighteen of the subjects

underwent orthodontic treatment while the rest were untreated. The chronologic age and skeletal age (determined using hand-wrist radiographs and the Greulich and Pyle (1950) standards) were analyzed using annual lateral cephalograms. In males, the mean age of onset of the adolescent growth spurt was 12.79 years, and in females, the mean age was 10.41 years. The mean duration of the pubertal growth period was the same in males and females. The results from this study indicate that maximum facial growth is coincident with maximum growth in height, which is different from findings of previous studies (Nanda, 1955; Bambha, 1961) which reported that the peak velocity of growth of the face is reached after the statural peak. Orthodontic treatment was found to have no effect on the time of maximum facial growth. The anteroposterior length of the mandible showed the most consistent relationship with growth in height through adolescence. The chronologic age range at the onset of the growth spurt was found to be much more variable than the skeletal age range at the onset of the growth spurt in males; but in females, the two age ranges demonstrated little difference. At the end of the year of peak facial growth, the female sample had completed a greater percentage of their total facial growth than the male sample. Final facial size was reached earlier in females than in males, and 88.3% of males experienced a small amount of facial growth after the skeletal age of 18 and probably after completion of skeletal maturation. In females, facial growth ceased late in the second decade and was more likely to be complete by the time final height was reached. In males, facial growth most often continued into the third decade and continued after final height was reached.

Baccetti et al. (2006) assessed the relationship between chronologic age and the individual skeletal maturity by means of the cervical vertebral method during the

circumpubertal period. The sample consisted of 600 subjects between the ages of 9 and 14. There were six groups of 100 subjects (50 male and 50 female) corresponding to each year of age between 9 and 14. Skeletal maturity was assessed for each individual using the CVM method and the relationship between the chronologic age and the most prevalent CVM stage at each age group was evaluated. It was found that in male subjects, the age 9 years +/- 6 months had a strong diagnostic power for identification of a pre-pubertal stage. In female subjects, the age 14 years +/- 6 months had a strong diagnostic power for identification of a post-pubertal stage. The relationships between the other ages and CVM stages were too weak to be considered diagnostic; therefore the study concluded that in both males and females, chronologic age cannot be used to identify the onset of the adolescent peak in skeletal maturation.

Bergersen (1972) analyzed the pubertal growth spurt for seven facial dimensions and standing height longitudinally on 23 males to evaluate the relationship of these spurts with skeletal maturity as determined by hand-wrist radiographs. Annual lateral cephalograms were obtained from the Child Research Council at the University of Colorado Medical School. Every six months from birth, standing height measurements were recorded and skeletal age was calculated from hand-wrist radiographs using the Greulich and Pyle (1959) technique. Seven linear facial dimensions were measured and plotted for velocity of growth on a yearly basis from 3 years of age until adulthood. Standing height was measured and plotted similarly. The findings of the study indicate that skeletal age is a more accurate indicator of the timing of the growth spurt than chronologic age. Prediction tables using the hand-wrist index of skeletal maturity were presented and claimed to eliminate 75% of the variation when compared with growth

spurt estimates based on chronologic age. Bergersen (1972) also concluded that the metacarpal sesamoid is significantly correlated with the onset of the male adolescent growth spurt in the face and in standing height.

Grezzi Galli Tassi et al. (2007) evaluated the possible relationship between the exfoliation of the primary second molars (Es) and the onset of the pubertal growth spurt assessed with the CVM method. The sample included 123 patients with exfoliation of the Es and a control group of 250 subjects in the late mixed dentition. The CVM stage was evaluated on the lateral cephalogram of all subjects in both groups. Baccetti et al. (2005) showed in a previous study that cervical stage 3 (CS3) corresponds to the onset of the growth spurt. The statistical analysis indicated a lack of diagnostic power of the exfoliation of the Es with regard to the onset of the pubertal growth spurt.

Baccetti et al. (2008) assessed the relationship between the eruption of the permanent maxillary canines and skeletal maturity. A sample of 152 patients was divided into pre-peak growth, peak growth, and post-peak growth based on CVM stages. The authors concluded that the eruption of the permanent maxillary canine can take place at any stage in skeletal maturation.

In 1972, Tofani et al. designed a retrospective study to investigate whether there is an association between puberty (as defined by menarche), skeletal age, spurt of statural growth, and the growth of the mandible. The sample consisted of 20 females enrolled in the Bolton Study of Western Reserve University. Menarche was recorded by interview, skeletal age was recorded as the onset of fusion in the distal phalanges of the fingers, and stature was recorded as standing height annually. Mandibular growth was recorded using lateral and posteroanterior cephalograms, and by measuring mandibular length (Ar-Pog),

ramus height (Ar-Go), corpus length (Go-Pog), and bigonial width (Go-Go). The study used graphic analysis of incremental growth curves of the mandible. Curves were constructed for each measurement on each individual, and then menarche, onset of fusion of the distal phalanges, and maximum increment in stature were marked on each curve. Average curves were derived from groups formed according to age at maximum growth increment. The data was also analyzed statistically using t-tests. The findings indicated that growth of the mandible does continue after menarche, but there is less growth after than before. Menarche most often occurred after the maximum increment of growth in the mandible in the early- and average-maturing girls, and before the maximum increment in the late-maturing girls (a very small number in this study). The statural growth spurt occurred before the maximum increment in the mandible in the majority of girls, and the onset of fusion in the distal phalanges was highly correlated with menarche. The mean age at menarche was 12 years and 7 months, while the mean age at onset of fusion of the distal phalanges was 12 years and 6 months. These results can be used to estimate whether a patient's mandible will continue to grow based on pubertal and skeletal maturation status.

In Hagg and Turanger's (1982) prospective longitudinal study of 212 randomly selected Swedish children, maturation level indicators suitable for use in clinical orthodontics were sought by investigation of dental, skeletal, and pubertal development. Annual records were collected including standing height, tooth emergence, pubertal development information (menarche and voice change), and a hand-wrist radiograph. Growth curves were created and evaluated for estimates of the beginning and the end of the pubertal growth spurt. It was found that there was a two-year sex difference in age at

the beginning, peak, and end of the pubertal growth spurt and the individual variation was approximately six years at each event in both sexes. Dental development was not useful as an indicator of the pubertal growth spurt. Dental development in relation to the pubertal growth spurt was more advanced in boys than in girls, but there was great individual variation in both sexes. The peak and end, but not the beginning, of the pubertal growth spurt could be determined using information from the hand-wrist radiograph and pubertal development indicators (menarche and voice change). Girls experienced menarche at or just after their peak height velocity (PHV), boys experienced the change to pubertal voice close to PHV, and boys achieved male voice at PHV or after. The study found that ossification of the ulnar sesamoid in boys and girls indicated that they were in the acceleration period of the growth spurt or at PHV.

Systemic Factors

Thomsen et al. (1986) examined the relationship between changes in testosterone concentration during puberty in males and hemoglobin concentration. Twenty boys whose mean age was 11.9 years (11.1-12.7) were examined every three months for 2-2.5 years. Blood samples were drawn and hemoglobin concentrations as well as serum testosterone were measured. A significant increase in serum testosterone during puberty was demonstrated and was followed approximately five months later by a significant increase in hemoglobin concentration. The authors concluded that the steep increase in serum testosterone during puberty produces a stimulation of erythropoietin leading to an increase in erythrocyte production a few months later. This increase in erythrocyte production is accompanied by a detectable increase in hemoglobin concentration. While these findings may not have a direct use for predicting facial growth, they certainly allude

to the concept that hormones and blood components are altered during male puberty and are possible avenues for predicting or detecting the adolescent growth spurt.

Anttila and Siimes (1996) studied serum transferrin and ferritin concentrations in relation to individual body growth, stage of puberty, blood hemoglobin, and red blood cell iron (RBCI). Transferrins bind iron reversibly and transport it between sites of absorption, storage, and utilization. Transferrin concentration increases in iron-deficiency anemia and during pregnancy, and decreases with iron overload or lack of protein. Ferritin is low when there is an iron deficiency and high when there is an iron overload. Rapid growth of the body and muscles at the end of puberty requires a great deal of iron, and physiologic demand may be misinterpreted as iron deficiency anemia. sixty males with a mean age of 11.7 years participated in the study. Data collections occurred at the beginning of the study and every three months for 18 months. Measurements included body weight, height, genital and pubic-hair stages (assessed according to the method of Tanner (1962)), testicular volume, serum hemoglobin, serum transferrin, serum ferritin, red blood cell mass, and RBCI. The mean ferritin concentration was higher in the prepubertal boys than in the pubertal boys, and the mean ferritin concentration for all boys decreased from 35 to 22μg/L during the study. There was a positive correlation between the increments in transferrin and hemoglobin and between the increments in transferrin and estimated RBCI. The authors concluded that during puberty there may be a physiologic increase in transferrin and decrease in ferritin that is likely related to stimulated erythropoiesis and is not necessarily an indication of iron deficiency.

Misaki et al. (1991) measured serum transferrin in healthy boys between the ages of 13-15 years to evaluate its relationship to serum alkaline phosphatase (ALP) levels and rate of growth in height. The serum concentration of ALP is a biochemical marker of bone formation in boys (Posen et al., 1977). Blood samples were collected from 149 healthy boys aged 13-15 years and the rate of growth in height was estimated over a 5 month period. The blood samples were tested for serum transferrin, serum albumin, serum ALP, and plasma insulin-like growth factor 1 (IGF-1). The samples and the growth rates were compared using a t-test and linear regression. Serum transferrin was significantly correlated with serum ALP levels ($r=0.31;P<0.0005$). The rate of growth in height was significantly correlated with serum ALP levels ($r=0.41;P<0.0005$), but not significantly correlated with serum transferrin levels ($r=0.12;P>0.05$). The authors state that serum transferrin is influenced by iron deficiency anemia and that a study eliminating subjects with latent iron deficiency anemia could show significant correlations between serum transferrin and rate of growth in height. The authors concluded that serum transferrin concentration could be a marker of skeletal growth in normal boys.

In 1984, Krabbe et al. studied the relationship between androgens and the mineralization process expressed as changes in bone mineral content (BMC) and serum concentrations of alkaline phosphatase (AP) during male puberty. BMC, AP, testosterone, dehydroepiandrosterone (DHEA), and andrestenedione (A-dione) were measured longitudinally for 20 boys. The times of maximal increase after the start of the investigation in months (T_m) were found for each of the variables using a best fit curve, and correlation coefficients and t-tests were used to evaluate the data. There was a

significant correlation between T_m-testosterone and T_m-BMC; between T_m-testosterone and T_m-AP; and between T_m-AP and T_m-BMC. The T_m of serum testosterone occurred less than one month after T_m-AP and 4-5 months before T_m-BMC. No significant correlations occurred in Tm between DHEA, A-dione, and the other variables. Although the associations do not prove causation, it would seem that the maximal increase in testosterone and AP occur at close to the same time, and this time is 4-5 months before maximal increase in BMC. These markers could potentially be used to anticipate growth spurts in adolescent boys seeking orthodontic treatment.

Familial Factors

Stein et al. (1956) analyzed correlations among relatives for a group of angles measured on tracings from lateral cephalograms. The subjects consisted of Mount Holyoke College students with sisters in college, other members of their families, and a group of families living within a 25 mile radius of the college. Photographs and lateral cephalograms were made as well as records of occlusion type and missing, transposed, or malformed teeth. 150 pairs of parents with 364 siblings were included in the study. The study found that there was significant correlation of facial angles, particularly between sisters. Superimposition of tracings from radiographs showed likenesses between related people, especially in three pairs of identical twins. Family pedigrees demonstrated that similar types of occlusion occur in families and that Angle's Class II occlusion may be due to recessive factors. Students with malocclusion had a higher percentage of relatives with malocclusion than those with a normal bite. Finally, no conclusive evidence was found for the influence of any particular environmental factor, such as sucking habits, for the causation of malocclusion.

Wasson (1963) attempted to predict facial growth in children based on cephalometric measurements from each child's parent. The sample consisted of lateral cephalograms from 33 children with a mean age of 11.1 years and lateral cephalograms of each child's parents. These were superimposed to find similarities and differences in facial patterns. Predictions of growth changes were made for profile, vertical height of the upper face, vertical height of the lower face, horizontal length of the maxilla, and horizontal length of the mandible. Lateral cephalograms taken at a mean age of 17.4 years were used to compare predictions to actual growth. The method was found to be very accurate in 58.9%, partially accurate in 32.5%, and completely inaccurate in 8.6% of the predictions. The measurement that could be predicted most accurately was the horizontal length of the mandible.

Hunter et al. (1970) attempted to determine whether the size of facial dimensions in parents can be used to predict the size of those facial dimensions in the adult offspring. Lateral cephalograms were collected from 31 families in which both parents and two or more children at least 21 years of age. Five facial dimensions were recorded from the tracings that were found in a previous study (Hunter, 1965) to be highly inherited relative to other measurements. Correlation coefficients were calculated within each group of parents and offspring, and multiple regression analysis was performed to evaluate each individual relationship between parent and offspring. The most significant correlations were found between the corresponding measures in fathers and offspring. The only dimension for which measurements from mothers were more predictive was Na-Me. Regression equations were developed for prediction using mother, father, and combined parent measurements. The combination approach proved better at prediction of offspring

measurements, and the range of reduction of the confidence interval (which is proportional to the standard deviation) was from 12.9% to 36%. Although the standard errors of estimate were reduced significantly, they were large from a clinical perspective. The authors concluded that while the relationship was apparent, using parental facial dimensions was of questionable clinical value for predicting the adult dimensions of offspring.

Byard et al. (1983) utilized measurements of recumbent length and statural height from participants in the Fels Longitudinal Growth Study (Kettering, Ohio) and their relatives recorded at the same ages to describe familial correlations. Pairs of relatives were compared at the same chronological ages from 1 to 18 years in one-year increments and again in adulthood. The correlation coefficients revealed that first-degree relatives were more similar than second- or third-degree relatives. Sibling correlations were significantly higher than parent-offspring correlations, except after the age of 15, when they became similar. The largest amount of variation in familial correlations is due to the degree of relationship. These data may indicate that if using familial growth patterns to estimate those of a patient, it might be better to look at sibling growth history to estimate timing of the growth spurt, but both sibling and parent data could be used to estimate final statural height.

Skeletal Factors from Lateral Cephalograms

Others attempted to make predictions of growth based on skeletal measurements from lateral cephalograms. In his early studies, Bjork attempted to correlate linear and angular measurements made from a lateral cephalogram with growth remaining up to adulthood (Bjork & Palling, 1954). He was unable at the time to establish strong

correlations, but found that roughly half of the actual rotation of the mandible during growth is masked by remodeling that occurs at the lower border of the mandible (Bjork, 1963). Odegaard agreed with Bjork that the prediction of mandibular growth must be made on the basis of mandibular morphology, not the relationship of the mandible to the rest of the skull (Odegaard, 1970; Lux et al., 1999). Multiple regression analysis used in the study produced an equation for determining the angle of condylar growth, and showed that the direction of condylar growth, when measured to the mandibular line, varies with the gonial angle. No significant correlation was found between the condylar growth direction and gonial angle when measured to SN. This supports the argument that it is mandibular morphology that is important for growth prediction (Odegaard, 1970). The relationship between mandibular symphysis morphology and mandibular growth rotation was evaluated and relationships were established (Aki et al., 1994). Durlak et al. determined, however, that the relationships were too weak for predictive purposes (Durlak & Witt, 1980; Lux et al., 1999).

Skieller et al.'s multiple regression analysis of growth rotation of the mandible produced encouraging results, identifying four variables that together could account for 86% of that rotation (Skieller et al., 1984). These variables included (as shown in Figure 1):

1) Mandibular inclination measured as:
    a. Posterior Face Height/Anterior Face Height ((S-tGo distance/N-Me distance) x 100)
    b. Angle SN to mandibular line 1 (SN-ML1)
2) Intermolar angle (MOLs-MOLi)

3) Shape of the lower border of the mandible (ML1-ML2) (Angle between the two mandibular lines)
4) Inclination of the symphysis (CTL-SN) (Angle between chin tangent line and SN line)

The authors included patients with extreme growth patterns, which likely skewed the results and limited their applicability to a general orthodontic population. However, exaggerated findings in extreme cases can be helpful in identifying more subtle morphologic indicators in normal patients. Skieller et al.'s method was not held out as a reliable growth prediction method for all patients, but rather as a way to identify extreme growth rotation patterns by observing certain variables whose measurements lie outside of a normal range (Skieller et al., 1984). Implants were used in the subjects, increasing the validity of the findings, but limiting the current ethical and legal ability to reproduce the methods. Limitations of the study were echoed by authors claiming that the sample size was inadequate for the number of variables tested, and the inclusion of patients with extreme growth rotation altered the method's reliability and applicability to a more normal population (Lee et al., 1984; Leslie et al., 1998). These studies applied Skieller et al.'s 4-variable regression equation to a more normal sample, and were not able to confirm the predictive significance of the variables.

Ricketts (1957) described a method of estimating facial growth based on adding growth increments to existing craniofacial morphology based on chronologic age. The sequential addition of growth increments (for example, 1mm per year increase in SN during the pubertal growth spurt) from the cranial base through the facial structures leading to the mandible was used to predict where the mandible will be at the end of

growth. These growth increments were based on average values obtained from a growth study. Ricketts (1957) reported that "the technique appeared to be sensibly accurate in more than ninety percent of routine clinical cases to date," but offered no data confirming this at the time.

In 1972, Ricketts described the growth of the mandible as occurring in an archial fashion and proposed a supplement to his method of facial growth prediction. The Xi point was defined in order to represent the center of the ramus. The Pm (protuberance menti) point and Dc (a point found by bisecting the condylar neck) were used with the Xi point to form the condylar axis upon which mandibular growth was predicted. Several other points were defined and an average growth increment based on chronologic age produced a prediction of mandibular growth using the archial method. The method was presented with the caution that it was not useful for predicting growth in patients who had any disruption of the neurologic equilibrium, abnormal growth, or true mandibular prognathism.

Ricketts et al. (1972) provided the orthodontic community with an overview of the development and use of computerized cephalometrics. Long before the time where computer ownership was feasible or widespread among private practitioners, a service was developed where clinicians could send lateral and postero-anterior cephalograms to a centralized processing center to have them traced and analyzed using a computer program. The service provided clinicians with an analysis of the patient based on norm values established through research of the literature and published scientific data. The analysis included not only a value for each of the cephalometric measurements, but also included an evaluation of the variation from the norm using an asterisk system

representing standard deviations. The analysis considered age, sex, ethnic type, and size differences to more closely predict individual growth patterns. The program also computed predictions of growth probabilities with and without treatment. Johnson (1968) criticized this program for its incapability of prediction certainty. The authors argue that the forecasts are treatment planning tools that are not meant to provide an absolute prediction due to the difficulty if predicting the variation of growth and treatment effects. The Ricketts arc method of growth prediction (Ricketts, 1972) was used in addition to information from records of over 2,000 treated patients in order to predict growth and treatment effects. He reported a high accuracy in prediction of the size and form of the mandible, claiming approximately 90% or better accuracy in 90% of the predictions. No study data was reported in this article to support this claim. The authors present the computerized cephalometrics service as useful for treatment planning, patient education, treatment plan presentation, monitoring treatment and results, and as a centralized clearinghouse for information that could be used for research purposes. The computerized growth prediction program has been updated many times and is currently available on some commercially available digital imaging programs.

In order to evaluate the clinical acceptability of the arcial growth prediction method of the mandible, Mitchell et al. (1975) selected 8 patients, with gold implants from the Emory University Orthodontic Clinic files, to have evaluated by Ricketts. The authors requested a 6-year growth prediction using the arcial method. The predictions were superimposed on the actual cephalogram tracings on the gold implants to compare predicted to actual growth. No statistical analysis was completed, the authors simply described the predictions as an overestimation of growth, and underestimation of growth,

or a clinically acceptable prediction. Five of the eight patients' predictions were clinically acceptable, two were overestimated, and one was underestimated. In this study, the majority of predictions were clinically acceptable, but the study does not identify acceptability criteria or any analysis other than the author's opinion on acceptability. An objective measure of predictive capability would be much more useful.

Schulhof and Bagha (1975) evaluated the predictive capabilities of the Ricketts and Johnston forecasting methods. Fifty untreated subjects were selected from the University of Michigan growth study and growth forecasts were made using the Johnston (1974) forecast grid, average increments from sella-nasion (a method devised by Schulhof and Bagha), the Ricketts (1972) short-range prediction, and the Rocky Mountain Data Systems (RMDS) computer program based on Ricketts' methods. The average age of the subjects at the initial record was 6.25 years, and 16 years at the final record. The forecasts were compared to the tracings of the actual growth of the subjects and the root-mean-square error was calculated for the predictions of each method. The Johnston forecast grid, which uses average increments of growth per year for various cephalometric points, was found to be the least accurate (70%) method of prediction of mandibular growth measured at pogonion. The method using average increments from sella-nasion was more accurate (73%), and the authors felt that this was due to using growth rates more applicable to the 10-year prediction period and directly predicting the position of pogonion rather than constructing pogonion from point B. The Ricketts short-range prediction had similar accuracy to the average increment method (73%), but was much more accurate than the average increment method when facial patterns were considered. The RMDS predictions took individual growth rates and facial patterns into

consideration and were more accurate than the other methods (78%), and were even more so in patients with abnormal growth patterns including long face patterns and Class III tendencies. The authors concluded that prediction methods that consider an individual's facial growth pattern as well as growth curve will be more accurate than those based solely on population averages.

Thames et al. (1985) examined the accuracy of the RMDS computerized forecasting system in predicting the effects of growth and orthodontic treatment. The study included lateral cephalograms and wax bites from 33 Class II patients with high mandibular plane angles that were sent to RMDS for prediction of the outcome of growth and orthodontic treatment. All patients were treated without extractions and with high-pull facebow headgear. The measurement error was found to be 0.35 mm (range, 0.07 to 0.90 mm) for linear measurements, and 0.73° (range, 0.15° to 1.59°) for angular measurements. The post-treatment predictions were then compared to the actual post-treatment lateral cephalograms using a t test for statistically significant differences ($P<0.01$). The prediction was accurate for maxillary position and rotation, mandibular length, upper face height, and incisor positions. It was found to be inaccurate in predicting maxillary length, mandibular rotation, lower anterior and posterior face heights, the horizontal and vertical positions of the molars, and over half of the soft tissue parameters. Although the author completed a questionnaire from RMDS outlining planned treatment mechanics and techniques, it seems that there are many variables that cannot be accounted for during treatment such as patient cooperation, force level and recommended hours of wear of the headgear. The predictions were particularly inaccurate when estimating soft tissue profile, which is one of the most important

considerations during treatment planning. RMDS requested posteroanterior head films and wrist films for processing, but these were not provided by the authors. Therefore it is difficult to consider the study's results accurate because additional diagnostic information such as the skeletal age of the patient could have influenced the accuracy of the prediction. Perhaps the predictions would have been more accurate given complete diagnostic information, but the limitations of predicting the outcome of both growth and orthodontic treatment combined seem apparent.

Hixon also adopted the approach of adding average growth from a group to childhood dimensions to predict overall adult dimensions (Hixon, 1968). While the basis of population averages makes these methods fairly predictive in a large portion of the general population, they have been criticized for their inability to accurately predict growth in patients with normal (Greenberg & Johnston, 1975) and divergent growth patterns (Skieller et al., 1984).

Bhatia et al. developed a multivariate method of growth prediction using factor analysis, cluster analysis, and discriminant function analysis (Bhatia et al., 1979). The multivariate approach was seen as an improvement in prediction methods since subgroup growth increments gave a more accurate individual prediction than mean growth values of a population (Lux et al., 1999).

Jarabak found that several measurements on the lateral cephalogram of a patient at least 10 years of age and with remaining growth pointed to growth direction and future facial form (Jarabak, 1972). Focusing on the saddle, articular, and gonial angles as well as posterior to anterior face height ratio, mandibular body length, and cranial base lengths, he felt that predictions could be made with a high degree of accuracy.

Measurement and ratio ranges were given so that direct measurements could be interpreted into future growth patterns. Jarabak's growth prediction method was based on a study of 200 patients 5 years or more after treatment (Jarabak, 1972). Having an upper gonial angle greater than 55 degrees indicated counterclockwise growth, while having an upper gonial angle less than 48 degrees indicated clockwise growth. The sum of three angles including the Saddle, Articular, and Gonial angles had a mean of 396. Patients with sums greater than 402 could be expected to grow in a clockwise direction, while those with sums less than 390 could be expected to grow in a counterclockwise direction. The average for the posterior to anterior face height percentage was given as 62% with those with measurements 2-4% above and below the mean, growing in a normal pattern (Jarabak, 1972). Other variables were mentioned, but ranges of normal for prediction purposes were not given.

Many of the variables described by Jarabak (1972) were later tested in a sample of patients with Class II malocclusions. The upper and lower parts of the gonial angle (N-Go-Ar and N-Go-Me) were the only measurements that demonstrated predictive value, even though this was of limited value (Lux et al., 1999). This study only tested prediction of direction, not magnitude of mandibular rotation, but the results indicated that the predictive potential of vertical mandibular changes based on information from one lateral cephalogram seems to be limited (Lux et al., 1999). Lux et al. used the change in SN-MeGo to evaluate the direction of mandibular growth rotation (Lux et al., 1999). The variables studied were: 1) SN-MeGo (Sella-Nasion/Mandibular plane angle); 2) S-Go/N-Me (facial height ratio, according to Jarabak, 1972); 3) Spp-Spa-MeGo (maxillary/mandibular plane angle); 4) Ar-Go-Me (gonial angle); 5) N-Go-Ar (Upper

part of gonial angle); 6) N-Go-Me (Lower part of gonial angle). The study population consisted of 30 untreated males with Class II malocclusions, ANB angle greater than or equal to 4 degrees, and a distal occlusion of at least ¼ premolar width (Lux et al., 1999). Logistic regression models only showed a predictive impact of the upper and lower parts of the gonial angle, although only the upper part was statistically significant ($p<0.05$). ROC (Receiver Operating Characteristics) curves were used to graphically evaluate the predictive value of the variables, and the relationships were confirmed (Lux et al., 1999). The use of the Youdin index converted their findings into clinically useful cut-off points for cephalometric analysis. However, the authors caution users that the usefulness of the ranges given by the Youdin index is limited due to the relative lack of strength of the predictive variables tested. It was found that values for the upper gonial angle above a range of 50-54 degrees indicated a higher probability of horizontal (or counterclockwise) growth, and values below this range indicated a higher probability of vertical (or clockwise) growth. Values for the lower part of the gonial angle above the range of 68-75 degrees indicates a higher probability of vertical growth and values below this range indicate a higher probability of horizontal growth (Lux et al., 1999). The relative weakness of the predictive value of the lower part of the gonial angle is reflected in the wider range of values for which prediction of mandibular growth direction cannot be confidently predicted. The limitation of the predictive potential of vertical mandibular changes based on information from one lateral cephalogram is acknowledged by the authors (Lux et al., 1999).

Moorrees and Efstratiadis (1991) analyzed the utility of the mesh diagram for predicting facial growth in orthodontic patients. Moorrees et al (1976) described the

mesh diagram analysis as a "proportionate analysis of the position of conventional landmarks in the face, within a rectilinear coordinate system whereby the horizontal and vertical coordinates are distorted to reveal deviations in the location of landmarks from those in a norm." Lateral cephalograms from 148 males and 128 females enrolled in a longitudinal study of twins conducted at the Forsyth Dental Center in Boston were used in this study. Radiographs collected at ages 8 and 16 years were analyzed using the mesh diagram method (Moorrees et al, 1976). Using landmarks on the lateral cephalogram, a rectilinear coordinate system composed of 24 small rectangles was computed. Scatter plots were computed for the relation of various landmarks at ages 8 and 16 years for each individual studied. The findings showed that the configurations of most facial landmarks were relatively consistent between ages 8 and 16 years, which would include the adolescent growth spurt for most subjects. The median face showed little change in the location of hard and soft tissues except for a small advancement of the chin and a downward and backward movement of Gonion. Individual variation, however, was great enough to indicate that predictions based on average increments may not be able to predict facial changes within the precise framework that orthodontists need for treatment planning.

In an attempt to evaluate the ability of clinicians to predict the direction of mandibular growth rotation, Baumrind et al. tested five clinicians, who were considered experts, and found that their assessments of direction were no better than chance (Baumrind et al., 1989). They concluded that prediction of mandibular growth direction by use of lateral cephalograms was inaccurate.

Turchetta et al. (2007) evaluated methods of facial growth prediction by comparing actual growth to predicted growth of subjects from the Burlington Growth Center study of the University of Toronto, Toronto, Ontario, Canada. The three methods tested included the Ricketts analysis (1957, 1972), the Johnston grid analysis (1975), and the Fishman maturational analysis (1982, 1987, 2000). The Ricketts and Johnston methods are based on chronologic age, while the Fishman method is based on maturation as evaluated on a hand-wrist radiograph. Lateral cephalograms and hand-wrist radiographs from 50 untreated patients were analyzed at T1 (approximately 9 years of age), T2 (approximately 13 years of age), and T3 (approximately 20 years of age). The sample was subdivided by sex and skeletal classification. Each prediction method was applied to the T1 and T2 records to predict the maxillary and mandibular positions at T2 and T3. The comparative measurements were both linear and angular. The predicted positions and the actual positions were compared using a paired *t* test. Also, "positional prediction envelopes" were developed to graphically represent the results and prediction accuracy. The article did not report any *t* or *P* values, but reported which prediction methods were statistically significant ($P < .05$) for each subgroup (males, females, all sexes; and Angle Classes I, II, and III). The Fishman analysis produced a statistically significant prediction in more of the subgroups and time periods than both the Johnston and Ricketts methods. Unfortunately, the article does not statistically or even numerically quantify this difference. Also, since the article fails to report *t* or *P* values, it is impossible to compare the predictive abilities of the methods in any other way than based on their individual predictive significance. The article concludes that the Fishman maturational method of facial prediction is superior to other methods that are based on

chronologic age. The superiority of skeletal age over chronologic age for growth prediction has been established in several studies (Fishman, 1979; Fishman 1987; Baccetti et al., 2006), but this study does not quantify the claimed difference between methods based on chronologic age and skeletal maturity.

Treatment effects on mandibular plane

In 1997, Ngan et al. assessed the treatment response to maxillary expansion and protraction. Twenty subjects with skeletal Class III malocclusions were treated with palatal expansion and a protraction facemask. Pre-treatment, post-treatment, and retention records were made and measurements from lateral cephalograms were compared. It was determined that the positive overjet was attributable to forward movement of the maxilla, backward and downward rotation of the mandible, proclination of the maxillary incisors, and retroclination of the mandibular incisors. The authors concluded that maxillary expansion and protraction facemask treatment was best used with Class III patients with a retrusive maxilla and a hypodivergent growth pattern.

Park et al. (2005) attempted to quantify the treatment effects of distalization of the maxillary and mandibular molars using TADs. Thirteen subjects who had undergone distalization of the posterior teeth were evaluated. The authors did not find a significant change in mandibular plane from pre-treatment to post-treatment. Distalization with TADs did not increase the mandibular plane angle as expected, but instead reduced it slightly. The authors attribute this to an intrusive component of the force applied to the posterior teeth. The mandibular plane angle could be influenced by distalization using TADs for anchorage, but if the force system is carefully planned, this change can be avoided.

In 2004, Haralabakis and Sifakakis compared the amount of posterior mandibular rotation during orthodontic treatment with edgewise appliances and cervical headgear in patients with high or low Frankfort-mandibular plane angles (FMA). Twenty-nine subjects with low FMA and 31 subjects with high FMA were evaluated. All had Class II Division I malocclusions and were treated without extractions. Cervical headgear and Class II elastics were used and an anterior biteplane was used in several patients for short periods. Pre- and Post- treatment cephalograms were superimposed and comparisons were made. The authors found no difference in FMA changes between the two groups and no statistically significant differences in changes for the other cephalometric variables evaluated during treatment. Both groups showed a counterclockwise mandibular rotation in relation to the Frankfort plane, with the high angle group rotating a little less. The authors concluded that vertical skeletal relationships could not be altered predictably by controlling the direction of extraoral force.

Haralabakis and Sifakakis's (2004) study confirmed Hubbard et al.'s (1994) findings. Hubbard et al. (1994) evaluated the effects of orthodontic treatment with the use of cervical pull headgear in patients with Class II malocclusions. Eighty-five subjects treated with cervical pull headgear were evaluated, and it was found that the mandibular plane angle did not increase appreciably with treatment. The pre-treatment mandibular plane angle did not affect this lack of significant change.

Ciger et al. (2005) evaluated post-treatment changes in Class II division 1 patients treated without extractions. All patients were treated with a combination of cervical headgear, Class II elastics, and edgewise appliances. Pre-treatment, post-treatment, and postretention records were made, and dental and skeletal changes were measured. Like

Haralabakis and Sifakakis (2004), Ciger et al. found that there was a slight mandibular posterior rotation at the end of treatment. The postretention records showed that the treatment-induced mandibular rotations tended to return to their original patterns.

In 2008, Sivakumar and Valiathan cephalometrically assessed the vertical changes in Class I subjects treated with and without extractions. There were 31 subjects in the treatment group who were treated with maxillary and mandibular first premolar extractions. The nonextraction control group consisted of 29 patients. The authors found increases in linear vertical dimension in both groups. Extrusion occurred with the mesial movement of the maxillary and mandibular posterior teeth, and the vertical dimension was increased. The mandibular plane angle, however, remained unchanged during treatment. The authors concluded that extraction solely for the purpose of increasing the overbite or decreasing the mandibular plane angle may not be justified.

Barnett et al. (2008) evaluated the skeletal and dental changes produced by the Herbst appliance in growing patients with Class II division 1 malocclusions. This was a systematic review of other articles assessing the skeletal and dental changes associated with this functional appliance. While most of the changes occurring were dental changes, two skeletal changes occurred: the ANB angle and the mandibular plane angle. ANB was found to be reduced and the mandibular plane angle was found to increase in patients treated with the Herbst appliance.

In 2000, Nelson et al. compared the treatment effects of Class II correction using the Herbst appliance and Class II elastics. Skeletal and dental measurements were made from the lateral cephalograms of 18 subject pairs. These measurements were compared, and it was found that the average change in mandibular plane angle was 0° for the

subjects treated with the Herbst appliance and +1.3° for the subjects treated with Class II elastics. The findings for the change in mandibular plane angle for subjects treated with the Herbst appliance do not agree with Barnett et al's (2008) findings. There is minimal rotation of the mandible reported for those patients treated with Class II elastics.

Error in use of Lateral Cephalograms

The distortion of measurements of the gonial angle in lateral cephalograms was studied in 1977 by Slagsvold and Pedersen. They postulated that since the two halves of the mandibular corpus are angulated to the median plane (and therefore the plane of the film), there would be distortion in the gonial angle as measured from the lateral cephalogram. They made craniometric and cephalometric measurements on 30 adult male skulls and compared them. The mean of the cephalometric observations was larger than that of the craniometric observations for all three angles measured (right, left, and intermediate gonial angle), and the differences were statistically significant ($P<0.001$). The distortion varied from side to side and on average, was larger on the side closest to the film. In extreme cases, the distortion was 15 to 20 degrees. No correlations were found between the distortion and the magnitude of the gonial angle. At certain ramal inclinations, cephalometric measurements approached craniometric measurements. These cases, however, were few, and there was a significant amount of individual variation. The mean differences between the cephalometric and craniometric measurements of the gonial angle were 8.48, 5.15, and 6.65 degrees for the side closer to the film, the side farther from the film, and the intermediate gonial angle, respectively. The authors concluded that in general, lateral head films do not permit reliable registrations of the gonial angle (Slagsvold & Pedersen, 1977).

Summary

Many studies have been completed that have attempted to elucidate the underlying mechanisms of growth to take some of the mystery out of individual growth variation. Studies of the hand-wrist film helped determine that chronologic age and skeletal age are not synonymous. The hand-wrist film and the cervical vertebral maturation method were found to be fairly reliable ways to determine a patient's skeletal age since discrete developmental changes occur in sync with skeletal development. Other factors such as standing height, growth of the mandible, secondary sex characteristics, exfoliation of primary molars, and familial patterns were not shown to be successful at predicting skeletal maturity. Systemic factors as measured in blood samples were correlated with ongoing developmental effects and could be used in the future to predict when the pubertal growth spurt will begin, if it is ongoing, or if it is over. Skeletal factors measured from lateral cephalograms were tested in many ways to attempt to predict the skeletal changes that occur during the adolescent growth spurt. Mixed results were found, but no method has been demonstrated to be extraordinarily accurate or reliable. Orthodontic treatment effects on mandibular rotation were evaluated and there is evidence that maxillary expansion and protraction facemask as well as the Herbst appliance cause clockwise rotation of the mandible. Problems with the mandibular rotation prediction methods either result from, or are compounded by errors in making measurements from lateral cephalograms.

This study evaluated four of the methods using lateral cephalogram measurements to attempt to predict mandibular growth rotation. The Skieller et al. (1984) method was chosen due to both its historical relevance and its ease of use in clinical practice. The

Quick Ceph Studio growth forecast function was chosen to represent the computerized prediction methods because of its availability in the OHSU Orthodontic department. The Jarabak (1972) ranges were chosen as a classic example of easy-to-use clinical guidelines based on experience and expert opinion. The Lux et al. (1999) ranges were selected because the concept was similar to Jarabak's ranges, but these were based on scientific evidence and statistical analysis. These four methods were also selected because their use was clearly outlined and could easily be incorporated into clinical evaluations.

Materials and Methods

Sample

The sample consisted of 61 subjects with no history of orthodontic treatment selected at random from the Oregon Child Study Clinic (CSC) data collection. This collection consists of radiographic, photographic, nutritional, statural, social, and behavioral data as well as dental study models collected on a semi-annual basis from the time of enrollment in the study through adolescence and then annually as long as the patient continued to participate. If available, this information was also collected for parents of the patients. The study was collected in the late 1950s through the early 1970s and the collected data is housed at Oregon Health and Science University.

To be included in this study, subjects must have had lateral cephalograms and hand-wrist radiographs corresponding with SMI 3 (T1) and SMI 9 (T2). If the exact desired SMI level was not represented in the data for each patient, the SMI level immediately preceding SMI 3 was used for T1 and the SMI level immediately following SMI 9 was used for T2. There were 10 Class III patients, 25 Class II patients, and 26 Class I patients as determined by the Angle dental classification noted in the chart. For additional analysis, the subjects were divided into skeletal classification subgroups based on their ANB measurements.

The Fishman (1982) hand-wrist maturation prediction method is the most appropriate method for skeletal maturation evaluation (Flores-Mir et al., 2004) and was used in this study. SMI 3 was chosen as T1 because it occurs just prior to the adolescent growth spurt, and SMI 9 was chosen as T2 because it occurs just after the growth spurt (Fishman, 1982).

Analysis

All lateral cephalograms were scanned (Epson Perfection 4990, Epson America, Long Beach, CA) and digitally traced by the author using Quick Ceph Studio (Quick Ceph Systems, San Diego, CA) digital imaging software. All T1 cephalograms were traced before beginning T2 tracings to reduce bias in landmark selection. The variables measured are defined in Table I.

For evaluation purposes, mandibular rotation was defined as the change, measured in direction and degrees, in SN-MeGo. Counterclockwise (forward) rotation was defined as negative (-) and clockwise (backward) rotation was defined as positive (+) (Leslie, 1998).

Variables identified by Skieller et al. (1984) were measured on T1 cephalograms and regression equations developed were used to predict the direction and amount of mandibular growth rotation. Measurements from T2 cephalograms were used to check the accuracy of the prediction. Each variable was also tested using simple linear regression and stepwise multivariate regression as described by Skieller et al. (1984).

The computerized growth prediction method developed by Ricketts (1972) is currently available on some digital imaging systems. The growth forecast function of the Quick Ceph Studio (Quick Ceph Systems) digital imaging system is based on the Ricketts method, and has been modified based on the Bolton-Broadbent growth study. The Bolton-Broadbent growth study examined normal dentofacial growth and development in 4,309 subjects, and records are currently housed at Case Western Reserve University and available for scientific research (Hans, 1994). The predicted changes vary based on the measurements from the lateral cephalogram, the sex, and the age of the

subject. The Quick Ceph Studio growth forecast function was used to predict mandibular growth rotation direction and amount based on the T1 cephalogram tracings. These predictions were then compared to the changes observed from the T2 cephalogram tracings.

The predictive variables described by Jarabak (1972) were measured on the T1 lateral cephalograms, and their predictions of growth direction were compared with the actual mandibular growth rotation observed on the T2 lateral cephalogram. Clockwise (positive) growth rotation was predicted in subjects with upper gonial angles measuring less than 48 degrees; sums of the three angles Saddle, Articular, and Gonial greater than 402; and posterior to anterior face height percentages less than 59. Counterclockwise (negative) growth rotation was predicted in subjects with upper gonial angles measuring greater than 55 degrees; sums of the three angles Saddle, Articular, and Gonial less than 390; and posterior to anterior face height percentages greater than 65.

The predictive variables described by Lux et al. (1999) were measured on the T1 lateral cephalograms, and their predictions of growth direction were compared with the actual mandibular growth rotation observed on the T2 lateral cephalogram. Clockwise growth rotation of the mandible was predicted in subjects with upper gonial angles measuring less than 50 degrees and lower gonial angles greater than 75 degrees. Counterclockwise growth rotation of the mandible was predicted in subjects with upper gonial angles measuring greater than 54 degrees, and lower gonial angles less than 68 degrees.

After evaluating the entire sample, it was divided into skeletal class subgroups to determine if the predictive methods tested in the present study worked differently in

patients with different skeletal classifications. The subgroups were selected based on ANB angle. Subjects with ANB less than or equal to zero were considered Class III, subjects with ANB greater than zero and less than four were considered Class I, and subjects with ANB of 4 or greater were considered Class II.

Method error was checked by selecting 10 subjects at random, re-selecting their T1 lateral cephalograms, and digitizing and retracing them at least two weeks after the initial tracing. The method error was calculated using the equation:

$$S_x^2 = \frac{\Sigma D^2}{2N}$$

where S_x is the error for the measurement, D is the difference between duplicated measurements, and N is the number of double measurements (Dahlberg, 1940).

Results

The sample demographics from the Skieller et al (1984), Lee et al (1987), Leslie et al (1998), and present studies are presented in Table III. The sample size in the present study is larger than in the previous studies, which should improve the statistical validity of the findings. Skieller et al (1984), Leslie et al (1998), and the present study used an untreated sample, while Lee et al's (1987) sample was composed of a mixture of treated and untreated individuals. The means, standard deviations, and ranges of the independent variables for the three cited studies and the present study are shown in Table IV. The ranges were not reported by Lee et al (1987). The means are similar for each variable except for variable number 4 (Chin Tangent Line-SN) for which Lee et al's (1987) sample exhibited a larger mean measurement than the other studies. The standard deviations are greater in the Skieller et al (1984) study for variables 1 (Post/Ant face height) and 4 (CTL-SN) than in the other studies. This is consistent with the previous discussion of Skieller et al's sample which included subjects with extreme growth rotation patterns. For most variables, the subjects used by Skieller et al (1984) demonstrated a wider range, which is also consistent with the extreme growth patterns observed in their sample. The present study, however, had 13 subjects with a measurement of variable 2, Intermolar angle, where the maximum value was larger than any of the subjects in the other two studies for which ranges were reported.

Table V shows the measurement means, standard deviations, and ranges of mandibular rotation for each study. The range was not reported in the Lee et al (1987) study. The present study's mean and standard deviation were similar to those found by

Leslie et al. (1998), whereas those for the Skieller et al (1984) and Lee et al (1987) studies were larger, with the values reported by Skieller et al being the largest. The range reported by Skieller et al (1984) was much larger than that reported by Leslie et al (1998) and the present study.

The means, standard deviations, and ranges of the predicted mandibular rotation with Skieller et al's (1984) regression equation are shown in Table VI. Table VI also includes the means, standard deviations, and ranges of the differences between predicted mandibular rotation and what was actually observed. There is a large difference between the predicted rotation and the actual rotation for this sample.

The simple linear regression analysis results are shown in Table VII. The R^2 values reported by Leslie et al (1998) and the present study for each independent variable are much smaller than those reported by Skieller et al (1984). Variable 1, Posterior face height/Anterior face height, demonstrated the highest predictive value in Skieller et al's (1984) results with R^2=0.62. Leslie et al's (1998) study found the highest predictive value in variable 2 (Intermolar angle) with R^2=0.056. Variable 4, CTL-SN, gave the highest predictive value in the current study with R^2=0.06.

The results of stepwise regression analysis are reported in Table VIII. This analysis aimed to determine the combined predictive ability of the four independent variables. The variables are added in the order of their predictive ability to explain the variance in mandibular rotation. In each step, an additional independent variable is added to determine the combined predictive ability using multiple regression. Skieller et al (1984) demonstrated an R^2 value of 0.86, indicating that the four variables accounted for 86% of the variability in mandibular rotation. Lee et al (1987) could only account for 8%

and Leslie et al (1998) could only account for 7% of the variability. In the present study, all four variables when combined accounted for 18% of the observed mandibular rotation, which was more than Lee et al (1987) and Leslie et al (1998), but still much less than Skieller et al (1984). (86%).

For completeness, Table IX shows the simple linear regression analysis of several of the variables used in other sections of the present study as well as the gonial angle. The R^2 values for these variables are comparable to those found for the other variables reported by Leslie et al (1998) and the present study. The variable with the highest R^2 value was the sum of the saddle, articular, and gonial angles, however this only accounted for 3.5% of the variability in mandibular rotation.

The demographics of the subgroups are shown in Table X. The three subgroups are similar in composition, but there are much fewer Class III patients than Class I or II. The means, standard deviations, and ranges of the predicted mandibular rotation with the Skieller et al (1984) regression equation as well as for the differences between predicted and actual rotation are shown in Table XI. The differences between the predicted and actual rotation are large for all three subgroups and similar to the differences for the entire sample. The Class III subgroup's measurements were closer to the predicted values, but the difference was still -5.24° on average.

The results of the simple linear regression analysis are shown in Table XII. Most of the R^2 values are very low, as in the Leslie et al (1998) study, except for a few outliers. The highest R^2 value for an individual variable was R^2=0.38 for Variable 4 in the Class I subgroup. Table XIII shows the results of the stepwise regression analysis for each

subgroup. The R^2 values for each of the three subgroups were larger than those found by Lee et al (1987), Leslie et al (1998), and even the present study for the entire sample.

Table XIV shows the results of the predictions made with the Quick Ceph Studio growth forecast function. The mean predicted mandibular rotation was very small at -0.0016° with a very narrow range of predictions. The differences between the predicted and actual mandibular rotations are small on average, much smaller than those found in the analysis of Skieller et al's (1984) regression equations. It is interesting to note, however, that out of 61 subjects, the prediction for mandibular rotation was 0° for 57 of them. The predictions for the 4 subjects ranged from -0.3° to 0.2°.

The results of the mandibular rotation predictions using the ranges specified by Jarabak are shown in Table XV. With this method, a large portion of the subjects fell into the middle range where no direction of mandibular rotation could be confidently predicted. More subjects fell into the ranges that provided directional predictions with the Posterior/Anterior face height ratio (63.7%), while the other variables made predictions for less than half of the sample. Upper gonial angle was the variable with the most correct directional predictions, and 79.2% of the predictions that were made were correct. The sum of the angles and Posterior/Anterior face height ratio performed only slightly better than half correct with 58.8% and 61.8% correct respectively. Table XVI shows the subjects who fell into the range that gave no prediction of mandibular rotation, but experienced more than 3° of rotation at T2. The upper gonial angle ranges had fewer false negatives than the other two variables (13.5%), although the sum of the angles was close behind (15.9%).

Table XVII shows the results of Jarabak's (1972) predictive ranges when applied to the subgroups based on skeletal classification. In all but three scenarios, less than half of the subjects' measurements placed them in ranges that would provide predictions of mandibular rotation. The three with the largest proportion of subjects with predictions were the Posterior/Anterior face height in Class I and II subjects, and the upper gonial angle in Class III subjects. The UGA in Class III subjects was also the only scenario with no false negatives (as shown in Table XVIII); and it is one of the two scenarios with the highest percentage of correct predictions (80%). The scenario with the highest percentage of correct predictions was the UGA in Class I subjects (81.8%). The sum of the angles and Posterior/Anterior face height in Class I subjects, and the UGA in Class II subjects also had higher percentages of correct predictions with 72.7%, 71.4%, and 75%, respectively. Although the percentages of correct predictions were high overall for Class I subjects, this group also demonstrated the highest percentage of false negatives among the other classes. Scenarios with poor predictive value included the sum of the angles and post/ant face height in Class II subjects as well as Posterior/Anterior face height in Class III subjects. Interestingly, all of the measurements of the sum of the angles for Class III subjects fell into the "no prediction" range, but in fact 2 subjects (25%) experienced mandibular growth rotation greater than 3^{o}.

The results of the mandibular rotation predictions using the ranges specified by Lux et al (1999) are shown in Table XIX. The UGA measurements led to correct predictions in 64.9% of the subjects for which predictions were made, while the LGA measurements led to correct predictions in less than half of the subjects with predictions (44.4%). While the UGA predictions were more correct than those made from LGA

measurements, Table XX shows that UGA gave a much higher percentage of false negatives.

Table XXI shows the results of Lux et al's (1999) predictive ranges when applied to the subgroups based on skeletal classification. UGA measurements for Class I and III subjects gave relatively, but not extremely, high percentages of correct predictions (78.6% and 71.4%, respectively). The other scenarios had weak to poor predictive abilities. While UGA measurements for Class I subjects gave the highest percentage of correct predictions, Table XXII shows that they also gave the highest percentage of false negatives (30%). The percentage of false negatives was 0% for UGA in Class III subjects, but there was only one subject for whom no prediction was given.

The error analysis results are shown in Table XXIII. For most of the variables, the mean difference between the two measurements was within one to two degrees. MOLs-MOLi and CTL-SN had the largest mean difference at 5.07° and 3.34°, respectively. The Dahlberg equation (1940) evaluates the method for differences between the measurements as well as the variance of the differences. The method error for MOLs-MOLi and CTL-SN were high, 4.02 and 2.76, respectively, because of one or more outlier subjects for whom the measurements differed by a large amount. Method errors for LGA, GA, and articular angle were also higher than the others, but to a lesser degree.

Discussion

Optimal treatment is the goal for all patients and orthodontists. Occasionally, treatment decisions are made when one or more pieces of information, such as growth amount and direction, are unknown. Investigators continue to search for the "crystal ball" that will allow orthodontists to accurately predict how a patient is going to grow. The use of maxillary expansion and protraction facemask as well as the use of the Herbst appliance cause clockwise rotation of the mandible. If an orthodontist can predict that the mandible is already going to rotate clockwise and this additional rotation is undesirable, an alternative treatment method might be sought.

This study aimed to evaluate several of these methods of predicting mandibular growth rotation. The sample was selected from the Child Study Clinic (CSC) data at random when possible. Since there were a limited number of untreated Class II and III patients, most or all of the qualifying subjects were included in the study. Class I untreated subjects could be considered randomly selected as there were many subjects to choose from. Untreated subjects were selected for inclusion in the study to avoid any influence orthodontic treatment could have on the rotation of the mandible. Selecting untreated subjects, however, could have excluded subjects with extreme growth rotation as these patients would have been more likely to seek orthodontic treatment. It is possible that reduced severity of growth pattern could weaken the predictive relationships evaluated.

There are several reasons that the results of this and other studies have varied. Skieller et al. (1984) attempted to analyze patients with extreme growth patterns to identify measurements that would give clues to a more normal patient's growth pattern.

The authors acknowledged that the regression equation they developed was based on an abnormal sample and could have limited application to a more normal population.

The baseline age of the samples differ, as different selection methods were used among the studies. Skieller et al. (1984) selected lateral cephalograms that corresponded with the onset of puberty in patients for analysis, while Lee et al. (1984) and Leslie et al. (1988) selected lateral cephalograms that corresponded with chronologic ages. The present study used hand wrist radiographs to attempt to more accurately determine the beginning and ending of the pubertal growth spurt for each individual patient. Fishman (1984) outlined this method of determining where an individual fell on the pubertal growth curve. SMI 3 was selected in this study for T1, and SMI 9 was selected for T2. In Fishman's study (1984), females had completed 25% and males had completed 19.5% of their total adolescent growth from Sella to Gnathion at SMI 3. At SMI 9, females had completed 84% and males had completed 84.6% of their total adolescent growth from Sella to Gnathion. These time points were selected to ensure that the bulk of the adolescent growth spurt was included in each individual's evaluation.

The means of the independent variables (Table IV) are similar among the studies, but the standard deviations are larger in the Skieller et al (1984) study. This is consistent with the inclusion of subjects with extreme mandibular rotation in that sample. One difference of note is that the standard deviation of the intermolar angle in the present study is larger than all previous studies. The ranges shown in Table IV reflect the differences between the previous studies and the present study, as the maximum measurement of intermolar angle is much larger than even Skieller et al.'s sample (1984). The differences between the studies for this particular independent variable could be

attributed to measurement error. The intermolar angle was difficult to measure on the lateral cephalograms used in the present study due to overlap of right and left molars and occasional slight overlap of upper and lower molars. Baumrind and Frantz (1971) found that identification error of molars on a lateral cephalogram was higher than many other cephalometric variables. Thirteen of the 61 subjects in the present study had intermolar angle measurements that fell outside the ranges of the previous studies. Blurred margins and overlap between bilateral structures introduce difficulty in measurement and could be considered a weakness of using a lateral cephalogram for growth prediction.

The measurements of the dependent variable (mandibular rotation) were smaller in the present study than in all of the previous studies. The mean and standard deviation were similar to those reported by Leslie et al (1998), and both were less than those reported by Skieller et al (1984) and Lee et al (1987). The differences could lie in the sample selection criteria. Skieller et al (1984) included patients with an extreme growth pattern, which explains the increased mean and standard deviation of the observed mandibular rotation. While Lee et al's (1987) sample included patients with less extreme growth patterns, it also included some patients who underwent orthodontic treatment. Orthodontic treatment mechanics may influence the rotation of the mandible (Ngan, 1997; Barnett, 2008); therefore a sample that includes treated patients does not evaluate rotation solely due to growth. It is possible that the increase in observed mean and standard deviation of mandibular rotation was caused, at least in part, by orthodontic treatment. Leslie et al (1998) and the present study used an untreated sample with less extreme growth patterns. The means and standard deviations of mandibular rotation are similar between these two studies.

Another possible explanation for the differences in observed mandibular rotations is the use of implants as reference points by Skieller et al (1984). Roughly half of the actual rotation of the mandible during growth is masked by remodeling that occurs at the lower border of the mandible (Bjork, 1963). Although implants are not used by Lee et al (1987), Leslie et al (1998), or the present study, implants are not routinely placed in orthodontic patients, and a prediction method that relies on their use would have limited application in clinical practice.

The large differences between the mandibular rotation predicted by the Skieller et al (1984) regression equation and that observed in the present study raise serious doubts that this equation can be used clinically to evaluate the growth patterns of individual patients (Table VI). In one patient, for whom the predicted and actual rotation difference was the greatest, the equation predicted a rotation of -16.21°. The patient experienced a mandibular rotation of 0.4°, for a difference of -16.61°. A difference of this size could lead a clinician to choose a different course of treatment if the regression equation were used in clinical practice.

Unlike in Skieller et al's (1984) study, the results of the simple linear regression analysis of individual independent variables reported by Leslie et al (1998) and the present study demonstrate limited ability to predict growth rotation of the mandible. The R^2 value of 0.62 reported for Posterior face height/Anterior face height (Variable 1) means that this variable accounted for 62% of the variability observed in the dependent variable (mandibular rotation) in the Skieller et al (1984) sample. The variable with the highest predictive value in the present study is variable 4 (CTL-SN), which accounted for only 6% of the variability in mandibular rotation. This is in contrast to Leslie et al

(1998), who reported that variable 4 only accounted for 0.5% of the variability in mandibular rotation.

When the independent variables were combined in the stepwise multiple regression analysis, the predictability was significantly lower in the Lee et al (1987) and Leslie et al (1998) studies as well as the present study. The best predictive ability any study other than Skieller et al (1984) could report was R^2=0.18 for all four variables in the present study. This predictive value is too small for clinical use in orthodontic treatment planning. Perhaps in a sample with extreme growth patterns, the extreme measurements exaggerated the predictive ability for mandibular rotation; and it appears from the results of the other three studies with subjects with more normal growth patterns that the relationships are much more subtle.

The simple linear regression analyses of the additional independent variables were included to determine if these variables commonly used in other prediction methods had been overlooked in the original Skieller et al (1984) study, or if regression analysis could provide more insight into their clinical utility. The gonial angle was included because although Jarabak (1972) did not provide ranges for mandibular rotation prediction using this variable, it was discussed as being useful and contributing to the overall diagnosis of the patient. Table IX shows that the R^2 values of the variables were very low, comparable to those previously found by Leslie et al (1998) and the present study.

Subjects in the study were divided into skeletal classification subgroups in order to determine if there was a difference in predictive abilities of the prediction methods tested between the skeletal classes. Several classification methods are available, and all have their pros and cons. Dental classification would be inappropriate in this study as

this is a study of skeletal and cephalometric measurements. The Wits analysis is commonly used in clinical practice, but it has several drawbacks. Accurate identification of the occlusal plane is not always easy or reproducible (Haynes and Chau, 1995) due to the presence of open bites, canted occlusal planes, mixed dentition, or steep curves of Spee in some patients (Baik and Ververidou, 2004). The Beta angle was introduced by Baik and Ververidou (2004), and uses points A, B, and the center of the condyle to determine skeletal classification. This method seems useful, but has not been thoroughly tested for accuracy. Using ANB has its problems as well. Del Santo (2006) reports that the measurement of ANB "varies according to the extension and inclination of the anterior cranial base." ANB can also be influenced by the patient's age, the vertical and anteroposterior position of the Nasion, the upward or downward rotation of the jaws, and the degree of facial prognathism (Del Santo, 2006). ANB was selected for use in the present study due to its historical and common clinical use and its use in the Lux et al (1999) study method evaluated here.

There were only 8 subjects that fell into the Class III subgroup due to the limited number of untreated Class III patients for which records were available. The subgroups were similar in age at T1, as shown in Table X. All of the subgroups had large average differences between the predicted and actual mandibular rotation, but the Class III subgroup was less different that the others. The simple linear regression analysis showed results consistent with previous studies (other than Skieller et al (1984)) except for a few outlier measurements. Variable 4 in the Class I subgroup gave the highest R^2 value at 0.38. When stepwise regression was completed for the subgroups, the R2 values were much larger than those found by Lee et al (1987), Leslie et al (1998), and even the entire

sample of the present study. The reduced difference in predicted and actual mandibular rotation, the outlier R^2 values in some of the subgroups with simple linear regression, and the higher R^2 values for all three subgroups in the stepwise regression analysis could all be explained by the small size of the subgroups. Leslie et al (1998) stated that "in cases where the number of subjects is small relative to the pool of possible predictor variables, the forward stepwise selection procedure is unreliable because the R^2 statistic will be quite high, even when the independent variables have no predictive power whatsoever." There should be a minimum of 10 subjects for each independent variable tested (Leslie et al, 1998). There were fewer than 40 subjects in each of the subgroups, with only 8 in the Class III subgroup. This could mean that the R^2 values obtained for the subgroups are inflated and cannot be considered useful. Perhaps with a much larger sample size for all 3 subgroups, a clearer picture of the differences could be obtained.

When using the growth forecast function of QuickCeph Studio (Quick Ceph Systems), no change was predicted in the vast majority of subjects. Only 4 of the 61 subjects received a prediction of any mandibular rotation, and this prediction was minimal, ranging from -0.03 to 0.02 degrees. It appears that the mandibular plane is altered minimally if at all when growth predictions are made. The mean difference between predicted and actual rotation is small, but that could be due to the mean mandibular rotation observed in this sample being very small (and close to 0°) as well. The few subjects for whom predictions were made were not even the most extreme of the rotators, and the four subjects whose mandibles rotated the most were among the subjects with 0° predicted rotation. It seems that Quick Ceph Studio's growth forecast function alters the mandibular plane angle very minimally if at all, and its accuracy is dependent

on the fact that most patients rotate minimally. This is a common critique of prediction methods that are based on population averages. They work well when considered as a group, but on the individual level, the most important level for treatment planning, they can be inaccurate.

The Jarabak (1972) and Lux et al (1999) analyses differ from the Skieller et al (1984) and Quick Ceph Studio growth forcast analyses in that they predict only the direction of mandibular rotation, not the amount. Measurements of variables made from lateral cephalograms fall into ranges that can be used to make predictions as to what direction the mandible will rotate with growth. Jarabak's (1972) ranges were tested and the variable with the highest percentage of correct predictions (of those where predictions were made) was the upper gonial angle. The ranges for this angle correctly predicted the direction of mandibular growth rotation in 79.2% of subjects whose measurements fell into the predictive ranges. The other two variables did not perform as well, with predictive abilities little better than chance. A large portion of the subjects, up to 72.1% with the sum of the angles, had measurements that fell into the range where no prediction could be made. This could be viewed as a limitation of the method since it cannot be applied to all patients, or perhaps those subjects who fell in this range experienced so little rotation of the mandible that it would not significantly affect their treatment. In fact 80% of the subjects experienced mandibular rotation that was less than 3^{o} in either direction at T2. Of those subjects who had upper gonial angle measurements that placed them in the "no prediction" category, 86.5% were found to have rotated less than 3^{o}. The incorrect predictions, whether incorrect direction or false negatives, add up to 52.7% and 49.7% for the sum of the angles and the posterior/anterior face height ratio, respectively.

This precludes their use in clinical practice, as roughly half of the predictions made will be incorrect. The upper gonial angle ranges performed much better than the other two variables, but still had a significant portion of incorrect predictions (29% of the total sample). While this is certainly not strong evidence that Jarabak's (1972) ranges for mandibular rotation prediction are accurate for treatment planning purposes, perhaps when considered with other factors, the upper gonial angle could contribute to the clinician's overall picture of the patient when considering treatment options.

In consideration of the lack of false negatives and the higher percentage of correct predictions of mandibular rotation direction, it would seem that in the sample presently tested, the most predictive scenario is UGA measurements in Class III subjects. UGA was also relatively useful in making predictions in Class I and II subjects. Although the UGA measurement provided no prediction for over half of the Class I and II subjects, this is not necessarily a negative, as many of these subjects experienced mandibular rotation that was less than 3° in either direction. The percentage of false negatives was very low (4.8%) for Class II subjects and close to average (23.1%) in Class I subjects using UGA. The other two variables (sum of the angles and post/ant face height) were only relatively predictive in Class I subjects, however the percentages of false negatives were the highest in these two scenarios. The predictive abilities of the other scenarios were so low that clinical use would not be helpful in predicting mandibular growth rotation.

In 1999, Lux et al published a study attempting to predict mandibular growth rotation. Statistical methods including receiver operating characteristic curves to determine the predictive value of cephalometric variables and the Youden index to determine appropriate cut-points for growth prediction were used. Using these ranges

and measurements of the cephalometric variables, predictions for mandibular growth rotation were made for the current sample. The UGA measurements led to correct predictions in 64.9% of the subjects for which predictions were made. LGA measurements led to correct predictions in only 44.4% of the subjects falling into the predictive ranges. The low percentage of correct predictions combined with the high percentage of false negatives for UGA (37.5%) make Lux et al's (1999) ranges for prediction based on UGA very weak. The predictions for LGA measurements based on the Lux et al (1999) ranges were worse than chance. In the total sample, Lux et al's (1999) ranges did not prove to be clinically useful.

When the sample was divided into subgroups based on skeletal classification, the UGA measurements did better in Class I and III subjects than they did in the entire sample. The percentages of correct predictions were comparable to those of the more successful predictions made with Jarabak's ranges. Oddly, the ranges given by Lux et al (1999) did not work well for UGA in Class II subjects. Perhaps this is a result of such a small subgroup sample, as only 16 predictions were made for this scenario. As with the entire sample, LGA measurements did not produce adequate percentages of correct predictions in the subgroups. The results of the Lux et al (1999) analysis confirm those from the Jarabak (1972) analysis that UGA is the most predictive of the tested cephalometric variables. Even though the connection may not be as strong as orthodontists would like, these analyses may be used as an adjunctive tool in order to get a clear picture of the patient for treatment planning purposes.

When considering these evaluations of scenarios involving independent variables and skeletal classifications, it must be remembered that the sample sizes of the subgroups

are greatly reduced from the analysis involving the entire study sample. There were only 8 subjects in the Class III subgroup due to a limited number of Class III subjects in the CSC data collection. With such a small sample of Class III subjects, as well as a reduced sample of Class I and II subjects, it is difficult to make solid, confident conclusions. Another source of error was the measurement of the independent variables themselves. Slagsvold & Pedersen (1977) found significant differences between craniometric and cephalometric measurements of the gonial angle when measured on human skulls. Baumrind & Frantz (1971) found that orthodontic residents tracing lateral cephalograms experienced nearly twice the amount of error in identifying the UGA and LGA than any other variable.

The measurement error for most of the variables measured in this study was within acceptable limits of 1-2°. MOLs-MOLi and CTL-SN had large mean differences between the measurements and large method errors as well. This could be due to the difficulty in tracing the molars and chin tangent line on the films. On many of the lateral cephalograms, the molars were overlapped with both the opposing and contralateral molars. The chin tangent line is also difficult to reproduce because it is made of two points located on curves. Baumrind and Frantz (1971) noted that points on curves were more difficult to identify than landmark points. These error values are also inflated due to a few outliers with very large differences between measurements. This could be due to overlap of structures. It is also possible that if there was error in time point selection from the hand-wrist films, the measurements could have been made from different films. If this occurred, growth or patient positioning could have caused the large differences in measurements. Method errors for LGA, GA, and articular angle were also higher than

most of the other variables, but to a lesser degree. It is likely that these errors are due to the same problems of overlapping structures and they all involve the gonial angle. The gonial angle is another point on a curve, and it was shown by Baumrind & Frantz (1971) and Slagsvold & Pederson (1977) to be an unreliable landmark. It is interesting, however that the UGA demonstrated relatively little error in this study, even though it also involved the gonial angle.

The average difference in measurement for SN-MPA, the dependent variable, was relatively low at 1.32°. It is a bit discouraging, though, that the mean mandibular rotation for the subjects in this study was 1.73° (Standard deviation = 1.48). It is possible that the rotation that occurs in most patients is so minimal that measurements made from lateral cephalograms are not accurate enough to correctly detect them.

Conclusions

Although many authors and clinicians have sought to predict growth changes based on measurements from lateral cephalograms, a reliable method has still not been found. The results of this study agree with past evaluations of mandibular growth rotation prediction methods that these methods are weak and often inaccurate.

Skieller et al's (1984) regression equation did not work well on this sample, but there was also a significant amount of error associated with some of the variables, most notably the intermolar angle. The results of this study agree, however, with the previous evaluations of the same method. When simple regression was used to evaluate the independent variables and then stepwise multiple regression was used to evaluate their combined predictive ability, the R^2 values were too low for clinical use. When subgroups of subjects with similar skeletal classifications were evaluated, all predictive values were still poor, although some were slightly better than the overall group. This difference however could have been attributable to the small sizes of the subgroups leading to inflated R^2 values.

The growth forecast function of Quick Ceph Studio (Quick Ceph Systems) digital imaging software did very little to predict mandibular growth rotation. While the mean of the predictions was close to the mean of the actual mandibular rotations, the predictions seemed to be generalized and may not be useful for individual patients.

The evaluation of Jarabak's (1972) ranges for prediction of mandibular rotation direction demonstrated that the Upper Gonial Angle (UGA) performed much better than the other variables tested. When the skeletal classification subgroups were evaluated, the UGA had the highest R^2 value for Class III subjects. Here again, the small size of the

subgroup (8 subjects) could be the reason for the difference in R^2 value. Lux et al's (1999) ranges for prediction of mandibular rotation direction were less successful than Jarabak's (1972) in this sample. When the subjects were divided into skeletal classification subgroups, the predictions with Lux et al.'s (1999) method were also weak. The UGA, as in the results using Jarabak's ranges (1972), was the most predictive variable, although the predictions were weaker than those found in Jarabak's study.

In this study, the UGA was the most predictive variable when evaluated using Jarabak's (1972) ranges. The use of these ranges does not give an extremely accurate prediction, and some clinicians may feel that it is of no use. Some may recognize its limitations and use it as a small part of their diagnostic procedure to get an overall picture of the patient. Its clinical application is limited because it only predicts the direction, not the amount of rotation, and therefore would not distinguish between a patient whose mandible rotates 1° and a patient whose mandible rotates 8°.

There is a lot of error associated with identifying landmarks on a lateral cephalogram. It is possible that the measurements themselves are not accurate enough for the prediction methods to work adequately. Also, in this sample, actual mandibular rotation was minimal. Perhaps in the majority of patients, knowledge of future mandibular growth rotation would not influence the treatment plan because it is so small. After evaluating the sample in the present study, it appears that the methods tested here are not accurate enough to confidently predict mandibular growth rotation.

Future research in this area might include a larger sample that could provide larger numbers of subjects in each of the subgroups based on skeletal classification. Also, prediction of additional dependent variables such as length of the mandible or

vertical and horizontal position of the chin could be explored. These measures may be of more clinical value when planning treatment on skeletal class II and III patients. Continued research into linking growth and the pubertal growth spurt to systemic factors could lead to innovative and more accurate ways to make growth predictions.

References

Aki T, Nanda RS, Currier GF, Nanda SK. Assessment of symphysis morphology as a predictor of the direction of mandibular growth. Am J Orthod Dentofac Orthop 1994;106:60-9

Anttila R, Siimes MA. Serum transferrin and ferritin in pubertal boys: relations to body growth, pubertal stage, erythropoiesis, and iron deficiency. Am J Clin Nutr 1996;63:179-183.

Baccetti T, Franchi L, McNamara JA Jr. An improved version of the cervical vertebral maturation (CVM) method for the assessment of mandibular growth. Angle Orthod. 2002;72:316-323.

Baccetti T, Franchi L, McNamera JA Jr. The cervical vertebral maturation (CVM) method for the assessment of optimal treatment timing in dentofacial orthopedics. Semin Orthod 2005;11:119-29.

Baccetti T, Franchi L, De Toffol L, Ghiozzi B, Cozza P. The diagnostic performance of chronological age in the assessment of skeletal maturity. Prog Orthod 2006;7(2):176-88.

Baccetti T, Franchi L, De Lisa S, Giuntini. Eruption of the maxillary canines in relation to skeletal maturity. Am J Orthod Dentofac Orthop 2008;133:748-51.

Baik CY, Ververidou M. A new approach of assessing sagittal discrepancies: The Beta angle. Am J Orthod Dentofac Orthop 2004;126:100-105.

Bambha JK. Longitudinal cephalometric roentgenographic study of face and cranium in relation to body height. JADA 1961;63:776-779.

Barnett G, Duncan H, Major P, Flores-Mir C. Immediate skeletal and dental effects of the crown- or banded type Herbst appliance on Class II division 1 malocclusion. Angle Orthod 2008;78:361-9.

Baumrind S, Frantz RC. The reliability of head film measurements: landmark identification. AJO 1971;60:111-27.

Baumrind S, Korn EL, West EL. Prediction of mandibular rotation: an ampirical test of clinical performance. Am J Orthod Dentofac Orthop 1989;96:371-85.

Bergersen, E O. The male adolescent facial growth spurt: Its prediction and relation to skeletal maturation. Angle Orthod 1972;42:319-336.

Bhatia SN, Wright GW, Leighton BC. A proposed multivariate model for prediction of facial growth. Am J Orthod 1979; 75:264-81.

Bjork A, Palling M. Adolescent age changes in saggital jaw relation, alveolar prognathy, and incisal inclination. Acta Odontol Scand 1954; 12:201-32.

Bjork A. Variations in the growth pattern of the human mandible: longitudinal radiographic study by the implant method. J Dent Res 1963;42:400-11.

Byard PJ, Siervogel RM, Roche AF. Familial correlations for serial measurements of recumbent length and stature. Ann Hum Biol 1983;10:281-93.

Ciger S, Aksu M, Germec D. Evaluation of post-treatment changes in Class II Division 1 patients after nonextraction orthodontic treatment: Cephalometric and model analysis. Am J Orthod Dentofac Orthop 2005;127:219-23.

Dahlberg G. Statistical methods for medical and biological students. London: George Allen & Unwin Ltd; 1940. p. 122-32.

Del Santo M. Influence of occlusal plane inclination on ANB and Wits assessments of anteroposterior jaw relationships. Am J Orthod Dentofac Orthop 2006;129:641-648.

Durlak C, Witt E. Der Stellenwert der Symphyse fur die Wachstumsprognose des Unterkiefers. Fortschr Kieferorthop 1980;41:18-30.

Fishman LS. Chronological versus skeletal age, an evaluation of craniofacial growth. Angle Orthod 1979;49:181-189.

Fishman LS. Radiographic evaluation of skeletal maturation. A clinically oriented method based on hand-wrist films. Angle Orthod. 1982;52:88-112.

Fishman LS. Maturational patterns and prediction during adolescence. Angle Orthod 1987;57:178-93.

Fishman L. Maturational development and facial form relative to treatment timing. In: Subtenly J, ed. Early Orthodontic Treatment. Chicago, Ill: Quintessence Publishing; 2000: 265-285.

Flores-Mir C, Nebbe B, Major P. Use of skeletal maturation based on hand-wrist radiographic analysis as a predictor of facial growth: A systematic review. Angle Orthod 2004;74:118-124.

Flores-Mir C, Burgess C, Champney M, Jensen R, Pitcher M, Major P. Correlation of skeletal maturation stages determined by cervical vertebrae and hand-wrist evaluations. Angle Orthod 2006;76:1-5.

Grave K C, Brown T. Skeletal ossification and the adolescent growth spurt. Am J Orthod 1976;69:611-619.

Greenberg LZ, Johnston LE. Computerized prediction: The accuracy of a contemporary long-range forecast. Am J Orthod 1975;67:243-52.

Greulich WW, Pyle SI. *Radiographic Atlas of Skeletal Development of the Hand and Wrist*, Stanford, CA: Stanford University Press, 1950.

Greulich WW, Pyle SI. *Radiographic Atlas of Skeletal Development of the Hand and Wrist, Ed. 2*. Stanford, CA: Stanford University Press, 1959.

Grezzi Galli Tassi N, Franchi L, Baccetti T, Barbato E. Diagnostic performance study on the relationship between the exfoliation of the deciduous second molars and the pubertal growth spurt. Am J Orthod Dentofac Orthop.2007;131:769-771.

Hagg U, Taranger J. Maturation indicators and the pubertal growth spurt. Am J Orthod 1982;82:299-309.

Hans MG, Broadbent BH, Nelson SS. The Broadbent-Bolton Growth Study – past, present, and future. Am J Orthod Dentofac Orthop. 1994;105:598-603.

Haralabakis N, Sifakakis I. The effect of cervical headgear on patients with high or low mandibular plane angles and the "myth" of posterior mandibular rotation. Am J Orthod Dentofac Orthop 2004;126: 310-7

Hassel B, Farman A G. Skeletal maturation evaluation using cervical vertebrae. Am J Orthod Dentofac Orthop 1995;107:58-66.

Hixon EH. Prediction of facial growth. Trans Eur Orthod Soc 1968;44:127-139.

Houston, WJB. Relationships between skeletal maturity estimated from hand-wrist radiographs and the timing of the adolescent growth spurt. Europ J Orthod 1980;2:81-93.

Houston WJB. The analysis of errors in orthodontic measurements. Am J Orthod 1983;83:382-90.

Hubbard GW, Nanda RS, Currier GF. A cephalometric evaluation of nonextraction cervical headgear treatment in Class II malocclusions. Angle Orthod 1994;64:359-370.

Hunter, CJ: The correlation of facial growth with body height and skeletal maturation at adolescence. Angle Orthod 1966;36:44-53.

Hunter WS. A study of the inheritance of craniofacial characteristics. Trans Europ Orthod Soc 1965: 59-70.

Hunter WS, Balbach DR, Lamphiear DE. The heritability of attained growth in the

human face. Am J Orthod 1970;58:128-134.

Hunter WS, Baumrind S, Popovich F, Jorgensen G. Forecasting the timing of peak mandibular growth in males by using skeletal age. Am J Orthod Dentofac Orthop 2007;131:327-33.

Jarabak JR, Fizzell JA. Technique and treatment with light wire edgewise appliances. St. Louis: Mosby,1972:113-205.

Jacobson A, Jacobson R. Radiographic cephalometry; From basics to 3-D imaging, 2nd ed. Illinois: Quintessence, 2006:49-51.

Johnston L. A statistical evaluation of cephalometric prediction. Angle Orthod 1968;38:284-304.

Johnston, L. Lecture presented at Great Lakes Society of Orthodontics, French Lick, Ind., 1974.

Johnston L E. A simplified approach to prediction. Am J Orthod 1975;67:253-7.

Karlsen A T. Association between vertical development of the cervical spine and the face in subjects with varying vertical facial patterns. Am J Orthod Dentofac Orthop 2004;125:597-606.

Krabbe S, Hummer L, Christiansen C. Longitudinal study of calcium metabolism in male puberty II: relationship between mineralization and serum testosterone. Acta Paediatr Scand 1984;73:750-5.

Lamparski, D G. Skeletal age assessment utilizing cervical vertebrae. 1972; Master of Science Thesis, University of Pittsburgh, Pennsylvania

Lee RS, Daniel FJ, Swartz M, Baumrind S, Korn EL. Assessment of a method for the prediction of mandibular rotation. AJODO 1987;91:395-402.

Leslie LR, Southard TE, Southard KA, Casko JS, Jakobsen JR, Tolley EA, Hillis SL, Carolan C, Logue M. Prediction of mandibular growth rotation: Assessment of the Skieller, Bjork, and Linde-Hansen method. AJODO 1998;114:659-67.

Lux CJ, Conradt C, Stellzig A, Komposch G. Evaluation of the predictive impact of cephalometric variables. J Orofac Orthop 1999;60:95-107.

Misaki M, Shima T, Yano Y, Okazaki T. Serum transferrin as a marker of bone growth in boys: correlation with serum alkaline phosphatase activity, plasma insulin-like growth factor 1 and rate of growth in height. Horm Metab Res 1991;23:230-232.

Mitani H, Sato K. Comparison of mandibular growth with other variables during puberty. Angle Orthod 1992;62:217-222.

Mitchell DL, Jordan JF, Ricketts RM. Arcial growth with metallic implants in mandibular growth prediction. Am J Orthod 1975;68:655-9.

Moore RN, Moyer BA, DuBois LM. Skeletal maturation and craniofacial growth. Am J Orthod Dentofacial Orthop. 1990;98:33-40.

Moorrees C F A et al. New norms for the mesh diagram analysis. Am J Orthod 1976;69:57-71.

Moorrees C F A, Efstratiadis S, Kent R L Jr. The mesh diagram for analysis of facial growth. Proc Finn Dent Soc 1991;87:33-41.

Nanda, RS. The rates of growth of several facial components measured from serial cephalometric roengenograms. Am J Orthod 1955;41:658-673.

Nelson B, Hansen K, Hagg U. Class II correction in patients treated with Class II elastics and with fixed functional appliances: A comparative study. Am J Orthod Dentofacial Orthop 2000;118:142-9.

Ngan P, Hagg U, Yiu C, Wei S. Treatment response and long-term dentofacial adaptations to maxillary expansion and protraction. Semin Orthod 1997;3:225-264.

O'Reilly M, Yanniello G. Mandibular growth changes and maturation of the cervical vertebrae. Angle Orthod 1988;58:179-184.

Odegaard J. Growth of the mandible studied with the aid of metal implants. Am J Orthod 1970;57:145-57.

Park H-S, Lee S-K, Kwon O-W. Group distal movement of teeth using microscrew implant anchorage. Angle Orthod 2005;75:602-609.

Posen S, Cornish C, Kleerekoper M. Alkaline phosphatase and metabolic bone disorders. Metabolic bone disease; Avioli and Krane, Ed. Academic Press, New York 1977, vol. 1,

pp.141.

Popovich F, Thompson GW. Evaluation of preventive and interceptive orthodontic treatment between three and eighteen years of age. In: Cook JT, editor. Transactions of the 3rd International Orthodontic Congress; August 13-18, 1973, London, UK. St. Louis: Mosby; 1975. p.260-81.

Ricketts RM. Planning treatment on the basis of the facial pattern and an estimate of its growth. Angle Orthod 1957;27:14-37.

Ricketts RM. The value of cephalometrics and computerized technology. Angle Orthod 1972;42:179-99

Ricketts RM. A principle of archial growth of the mandible. Angle Orthod 1972;42:368-86.

Ricketts RM, Bench RW, Hilgers JJ, Schulhof RJ. An overview of computerized cephalometrics. Am J Orthod 1972;61:1-28.

Ricketts RM, Roth RH, Chaconas SJ, Schulhof RJ, Engle GA. Orthodontic diagnosis and planning, 1982, Rocky Mountain Data Systems.

San Roman P, Palma JC, Oteo MD, Nevado E. Skeletal maturation determined by cervical vertebrae development. Euro J Orthod 2002;24:303-311.

Schulhof RJ, Bagha L. A statistical evaluation of the Ricketts and Johnston growth-forecasting methods. Am J Orthod 1975;67:258-276.

Sivakumar A, Valiathan A. Cephalometric assessment of dentofacial vertical changes in Class I subjects treated with and without extraction. Am J Orthod Dentofac Orthop 2008;133:869-75.

Skieller V, Bjork A, Linde-Hansen T. Prediction of mandibular growth rotation evaluated from a longitudinal implant sample. Am J Orthod 1984;86:359-70.

Slagsvold O, Petersen K. Gonial angle distortion in lateral head films: A methodologic study. Am J Orthod 1977;71:554-564.

Stein KF, Kelley TJ, Wood E. Influence of heredity in the etiology of malocclusion. Am J Orthod 1956;42:125-141.

Tanner JM. Growth at adolescence. 2nd ed. Oxford, United Kingdom: Blackwell Scientific Publications, 1962.

Tanner JM, Whitehouse RH, Marshall WA, Healy MJ, Goldstein H. Assessment of skeletal maturity and prediction of adult height (TW2 method). London: Academic Press, 1975.

Thames T, Sinclair PM, Alexander RG. The accuracy of computerized growth prediction in Class II high-angle cases. Am J Orthod 1985;87:398-405.

Thomsen K, Riis B, Krabbe S, Christiansen C. Testosterone regulates the haemoglobin concentration in male puberty. Acta Paediatr Scand 1986;75:793-6.

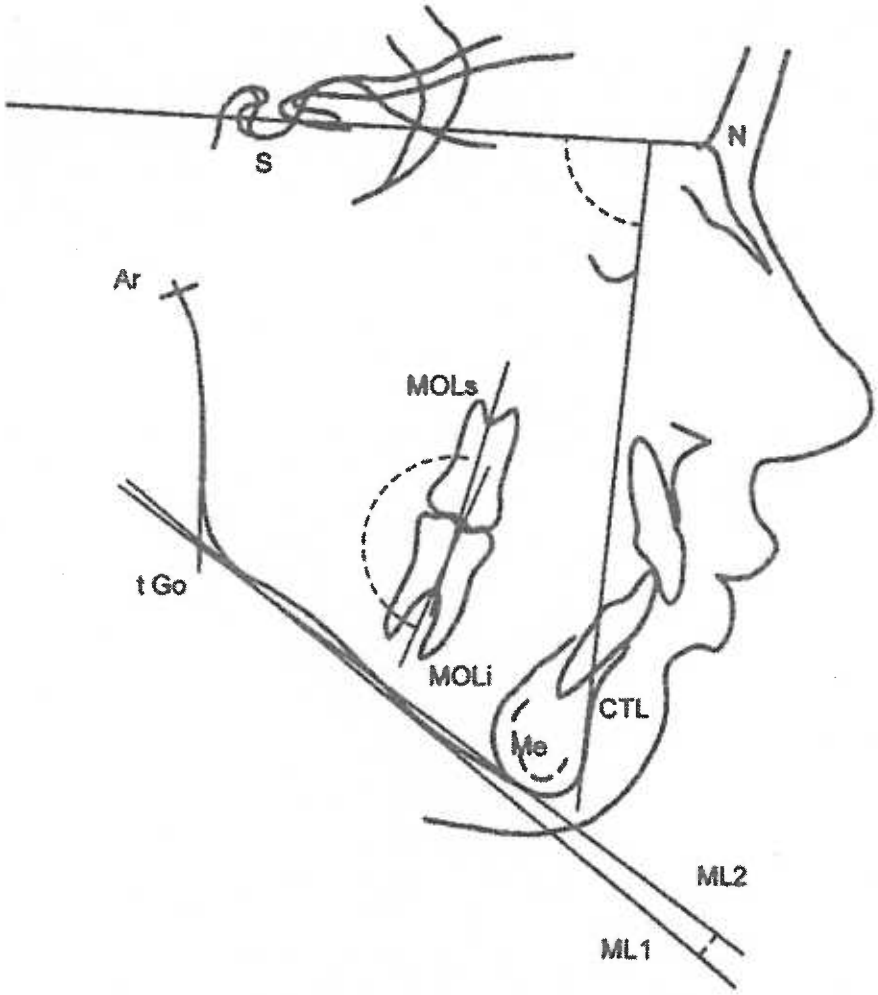
Tofani MI. Mandibular growth at puberty. Am J Ortho 1972;62:176-95

Turchetta B, Fishman LS, Subtelny JD. Facial growth prediction: A comparison of methodologies. Am J Orthod Dentofac Orthop 2007;132:439-449.

Wasson JL. Evaluation of a method of predicting craniofacial growth that compares cephalometric roentgenograms of children and parents. Am J Orthod 1963;49:864.

Figures

Figure 1. Location of landmarks, lines, and independent variables 2 (intermolar angle: MOLs-MOLi), 3 (Shape of the lower border of the mandible: ML1-ML2), and 4 (inclination of the symphysis: CTL-SN). (Figure taken from Leslie et al. (1998))



Tables

Table I. Definition of variables

Nasion (N) – The most anterior point on the frontonasal suture in the midsagittal plane (Jacobson and Jacobson, 2006).

Sella (S) – The geometric center of the pituitary fossa.

Menton (Me) – The lowest point on the symphyseal shadow of the mandible seen on a lateral cephalogram.

Articulare (Ar) – A point at the junction of the posterior border of the ramus and the inferior border of the posterior cranial base.

Tangential gonion (tGo) – A point found by bisecting the angle formed by a line tangent to the averaged inferior borders of the mandible and a line through articulare tangent to the averaged posterior borders of the mandibular rami (Leslie, 1998).

SN – The line connecting Sella and Nasion

Mandibular line 1 (ML1) – The tangential line formed by the lower border of the mandible (Leslie, 1998).

Mandibular line 2 (ML2) – The line formed tangent to the lower gonial border and passing through menton (Leslie, 1998).

Molar long axis inferior (MOLi) – The mandibular first molar long axis (Leslie, 1998).

Molar long axis superior (MOLs) – The maxillary first molar long axis (Leslie, 1998).

Chin tangent line (CTL) – The line formed tangent to the anterior border of the chin (Leslie, 1998). The line formed between soft tissue B-point and soft tissue pogonion used in this study.

Saddle angle (SN-Ar) – The angle formed by a line drawn between Sella and Nasion, and a line drawn between Sella and Articulare.

Articular angle (S-Ar-Go)– The angle formed by a line drawn between Sella and Articulare and a line drawn between Articulare and Gonion. (tGo used here)

Gonial angle (Ar-Go-Me) – The angle formed by a line drawn between Articulare and Gonion and a line drawn between Gonion and Menton. (tGo used here)

Upper part of Gonial angle (N-Go-Ar) – The angle formed by a line drawn between Nasion and Gonion and a line drawn between Gonion and Articulare. (tGo used here)

Lower part of Gonial angle (N-Go-Me) – The angle formed by a line drawn between Nasion and Gonion and a line drawn between Gonion and Menton. (tGo used here)

Posterior-Anterior face height percentage (S-Go/N-Me x 100%) – The distance between Sella and Gonion divided by the distance between Nasion and Menton multiplied by 100%. (tGo used here)

Sella-Nasion/Mandibular plane angle (SN-MeGo) – The angle formed by a line drawn between Sella and Nasion and a line drawn between Menton and Gonion. (tGo used here)

Table II. Skieller et al regression equation

75.6 -	0.59	(variable 1)	-
	0.32	(variable 2)	-
	0.98	(variable 3)	+
	0.15	(variable 4)	=
	Predicted rotation		
R^2=	0.8612		

Table III. Comparison of sample demographics

	Skieller et al	*Lee et al*	*Leslie et al*	*Present study*
Sample size (n)	21	25	40	61
Sex distribution				
Males	12	11	20	24
Females	9	14	20	37
Baseline age	11.3 +/- 1.00	8.5 +/- 0.0	9 +/- 0.0	11 +/- 1.38
Treatment status	Untreated	Mixed	Untreated	Untreated

Table IV. Independent variables: mean +/- standard deviation

Independent variables	*Skieller et al*		*Lee et al**	*Leslie et al*		*Present study*	
	Mean (S.D.)	*Range*	*Mean(S.D.)*	*Mean(S.D.)*	*Range*	*Mean(S.D.)*	*Range*
1 Post face height / Ant face height	63.6 (6.4)	54.4-76.8	63.4 (2.8)	63.5 (4.1)	57.1-74	64.8 (3.9)	55.2-72.2
2 (Intermolar angle)	173.6 (5.6)	159.8-180.1	177.7 (3.5)	173.3 (4.2)	163-181.5	176.6 (5.9)	162.8-191.6
3 (ML1-ML2)	2.4 (1.8)	0-5.5	1.1 (0.9)	1.4 (0.9)	0-4.5	2.4 (1.3)	0-5.2
4 (CTL-SN)	87.4 (12.2)	65-116	98.7 (7.4)	83.6 (8.4)	65.5-104.5	86 (7.1)	72.6-99.9

*Ranges not reported by Lee et al.

Table V. Predicted and actual measurements for mandibular rotation

Observed mandibular rotation	*Skieller et al*	*Lee et al*	*Leslie et al*	*Present study*
Mean +/- standard deviation	-6.0° +/- 4.5	-4.9° +/- 3.0	-1.9° +/- 2.1	-1.7° +/- 1.5
Actual range: Minimum	+5.3°	NA	+3.3°	+1.2°
Maximum	-16.4°	NA	-5.8°	-6.3°

Table VI. Predicted mandibular rotation with Skieller et al method versus actual

	Mean +/- standard deviation	*Range*	
		Minimum	*Maximum*
Predicted rotation	-8.6° +/- 3.17	-1.56°	-16.21°
Difference from observed rotation	-7.03° +/- 4.04	-0.02°	-16.6°

Table VII. Simple linear regression analysis: R^2

Independent variables	*Skieller et al* R^2	*Skieller et al* *Level of significance*	*Leslie et al* R^2	*Leslie et al* *Level of significance*	*Present study* R^2	*Present study* *Level of significance*
1 Post face height Ant face height	0.62	P<0.001	0.0075	P<0.59	0.041	P<0.12
2 (Intermolar angle)	0.39	P<0.005	0.0558	P<0.14	0.00025	P<0.9
3 (ML1-ML2)	0.27	P<0.025	0.0012	P<0.83	0.0049	P<0.59
4 (CTL-SN)	0.38	P<0.005	0.0007	P<0.87	0.06	P<0.057

Table VIII. Stepwise regression analysis

Skieller et al *Independent variable*	R^2	*Lee et al* *Independent variable*	R^2	*Leslie et al* *Independent variable*	R^2	*Present study* *Independent variable*	R^2
1	0.62	1	0.05	2	0.06	4	0.06
2	0.76	2	0.08	4	0.06	1	0.07
3	0.81	3	0.08	1	0.07	3	0.12
4	0.86	4	0.08	3	0.07	2	0.18

*Variables are listed in order of entry and R^2 values are cumulative for all variables included in the model.

Table IX. Simple linear regression analysis for additional variables

Independent variables	R^2	*Level of significance*
Upper gonial angle	0.0012	P<0.78
Lower gonial angle	0.014	P<0.37
Sum of saddle, articular and gonial angles	0.035	P<0.15
Gonial angle	0.0011	P<0.8

Table X. Subgroup demographics

	Class I	*Class II*	*Class III*
Sample size (n)	24	29	8
Sex distribution			
Males	9	11	4
Females	15	17	4
Baseline age	10.7 +/- 1.6	11.3 +/- 1.2	10.9 +/- 1.1

Table XI. Predicted mandibular rotation with regression equation for sample divided into skeletal class

	Mean +/- standard deviation		
	Class I	*Class II*	*Class III*
Predicted rotation	-8.57° +/- 3.31	-8.97° +/- 3.39	-7.36° +/- 1.35
Observed rotation	-1.86° +/- 1.9	-1.17° +/- 1.27	-2.11° +/- 1.97
Difference from observed rotation	-6.7° +/- 4.17	-7.81° +/- 4.13	-5.24° +/- 2.82

Table XII. Simple linear regression analysis: R^2

	Class I		*Class II*		*Class III*	
Independent variables	R^2	*Level of significance*	R^2	*Level of significance*	R^2	*Level of significance*
1 Post face height / Ant face height	0.09	P<0.15	0.06	P<0.20	0.035	P<0.66
2 (Intermolar angle)	0.04	P<0.34	0.17	P<0.024	0.00059	P<0.95
3 (ML1-ML2)	0.07	P<0.22	0.071	P<0.16	0.16	P<0.33
4 (CTL-SN)	0.38	P<0.001	0.064	P<0.18	0.023	P<0.72

Table XIII. Stepwise regression analysis

Class I		Class II		Class III	
Independent variable	R^2	*Independent variable*	R^2	*Independent variable*	R^2
4	0.38	2	0.17	3	0.16
1	0.39	3	0.21	1	0.32
3	0.39	4	0.21	4	0.32
2	0.43	1	0.24	2	0.32

*Variables are listed in order of entry and R^2 values are cumulative for all variables included in the model.

Table XIV. Predicted mandibular rotation with QuickCeph Studio growth forecast function

	Mean +/- standard deviation	*Range* *Minimum*	*Maximum*
Predicted rotation	-0.0016° +/- 0.05	-0.3°	0.2°
Difference from observed rotation	1.56° +/- 1.65	-1.2°	6.3°

Table XV. Jarabak analysis

	Upper gonial angle			*Sum of saddle, articular and gonial angles*			*Post/Ant face height*		
	Number	*% of total*	*% of predicted*	*Number*	*% of total*	*% of predicted*	*Number*	*% of total*	*% of predicted*
No prediction	37	60.7		44	72.1		27	44.3	
Incorrect prediction	5	8.2	20.8	7	11.5	41.2	13	21.3	38.2
Correct prediction	19	31.1	79.2	10	16.4	58.8	21	34.4	61.8

Table XVI. Subjects with no predicted direction of mandibular rotation who actually rotated >3°

Upper gonial angle		*Sum of saddle, articular and gonial angles*		*Post/Ant face height*	
Number	*% of No predictions*	*Number*	*% of No prediction*	*Number*	*% of No prediction*
5	13.5	7	15.9	7	25.9

Table XVII. Jarabak analysis by subgroup

	Upper gonial angle			*Sum of saddle, articular and gonial angles*			*Post/Ant face height*		
	Number	*% of total*	*% of predicted*	*Number*	*% of total*	*% of predicted*	*Number*	*% of total*	*% of predicted*
Class I									
No prediction	13	54.2		13	54.2		10	41.7	
Incorrect prediction	2	8.3	18.2	3	12.5	27.3	4	16.7	28.6
Correct prediction	9	37.5	81.8	8	33.3	72.7	10	41.7	71.4
Class II									
No prediction	21	72.4		20	69		11	37.9	
Incorrect prediction	2	6.9	25	4	13.8	44.4	8	27.6	44.4
Correct prediction	6	20.7	75	5	17.2	55.6	10	34.5	55.6
Class III									
No prediction	3	37.5		8	100		6	75	
Incorrect prediction	1	12.5	20	0	0	0	1	12.5	50
Correct prediction	4	50	80	0	0	0	1	12.5	50

Table XVIII. Subjects with no predicted direction of mandibular rotation who actually rotated >3° (By subgroup)

Upper gonial angle		*Sum of saddle, articular and gonial angles*		*Post/Ant face height*	
Number	*% of No predictions*	*Number*	*% of No prediction*	*Number*	*% of No prediction*
Class I					
3	23.1	4	30.8	4	40
Class II					
1	4.8	2	10	3	27.3
Class III					
0	0	2	25	1	12.5

Table XIX. Lux analysis

	Upper gonial angle			*Lower gonial angle*		
	Number	*% of total*	*% of predicted*	*Number*	*% of total*	*% of predicted*
No prediction	24	39.3		43	70.5	
Incorrect prediction	13	21.3	35.1	10	16.4	55.6
Correct prediction	24	39.3	64.9	8	13.1	44.4

Table XX. Subjects with no predicted direction of mandibular rotation who actually rotated >3°

Upper gonial angle		*Lower gonial angle*	
Number	*% of No predictions*	*Number*	*% of No prediction*
9	37.5	4	9.3

Table XXI. Lux analysis by subgroup

	Upper gonial angle			Lower gonial angle		
	Number	*% of total*	*% of predicted*	*Number*	*% of total*	*% of predicted*
Class I						
No prediction	10	41.7		16	68	
Incorrect prediction	3	12.5	21.4	5	12	37.5
Correct prediction	11	45.8	78.6	3	20	62.5
Class II						
No prediction	13	44.8		21	72.4	
Incorrect prediction	9	31	56.3	4	13.8	50
Correct prediction	7	24.1	43.8	4	13.8	50
Class III						
No prediction	1	12.5		6	75	
Incorrect prediction	2	25	28.6	1	12.5	50
Correct prediction	5	62.5	71.4	1	12.5	50

Table XXII. Subjects with no predicted direction of mandibular rotation who actually rotated >3° (By subgroup)

	Upper gonial angle		Lower gonial angle	
	Number	*% of No predictions*	*Number*	*% of No prediction*
Class I	3	30	4	25
Class II	1	7.7	2	9.5
Class III	0	0	2	25

Table XXIII. Error analysis

Variables	*Difference between 1st and 2nd measurements*		*Error*
	Mean	*St Dev*	
Posterior face height Anterior face height	1.48	1.27	1.34
SN-MPA	1.32	0.94	1.13
MOLs-MOLi	5.07	2.71	4.02
ML1-ML2	0.45	0.49	0.46
CTL-SN	3.34	2.13	2.76
UGA	1.47	1.13	1.29
LGA	1.93	2.33	2.08
GA	2.09	1.77	1.9
Articular angle	1.98	1.69	1.8
Saddle angle	1.55	0.87	1.24
ANB	1.02	1.01	0.99