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THE CORRELATION OF CERVICAL VERTEBRAE MATURATION WITH HAND-WRIST MATURATION AND STATURE INCREMENTS IN ADOLESCENT GIRLS

BY ©

AMAN DHILLON B.D.S., D.M.D.

A THESIS
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THE DEGREE OF MASTER OF SCIENCE IN CLINICAL SCIENCES

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The undersigned certify that they have read, and recommend to the faculty of Graduate Studies and Research for acceptance, a thesis entitled "The Correlation of Cervical Vertebrae Maturation With Hand-Wrist Maturation and Stature Increments in Adolescent Girls," submitted by Aman Dhillon in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Dentistry (Orthodontics).

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ABSTRACT

The purpose of this study was to evaluate the reliability of cervical vertebrae as maturation indicators for the assessment of skeletal age in adolescence females. This was determined by correlating cervical vertebral maturation to both hand-wrist assessments and to stature increments.

The sample for this longitudinal study consisted of 35 Caucasian females aged 10 through 15 years selected from the Burlington Growth Centre, Toronto. The independent variables for the serial sample were the Greulich and Pyle assessment of hand-wrist maturation and standing height increments, while the dependant variable was the shape and form of the cervical vertebral bodies from C2 through to C6.

The vertebral skeletal age was assessed using the maturity indicators described by Lamparaski (1972) for each of the 210 (35x6) tracings which then were subjected to statistical analysis to determine if any relationship exists between these different measures of physiologic maturity.

Double determinations were made for all 210 cervical vertebrae tracings for intra-investigator error studies. The 95% confidence interval was 0.67 years for cervical vertebral skeletal age assessments. The results of statistical tests conducted on double determination error studies for vertebral age all indicate that skeletal age assessments made from the cervical vertebrae are reliable and reproducible.

The reliability and validity of using vertebral age was further tested by evaluating its association with skeletal age assessments made from hand-wrists films. Scatter diagrams, correlation coefficients ($r=0.91$), Student 't' values for paired tests ($p=0.05$) all showed that a significant relationship exists between these two assessments of skeletal age.

Finally, the relationship between vertebral age and stature increments was tested by means of scatter diagrams and correlation coefficients (r=0.82). These results indicate that a fairly strong relationship exists between these two parameters.

The results of this longitudinal study indicate that skeletal age assessments made from the cervical vertebrae maturational changes are reliable and valid. Vertebral age could be a valuable adjunct in clinical orthodontics for assessment of the maturity status of an individual during adolescence. However, further studies are required to refine and possibly quantify the changes seen in the cervical vertebrae before their clinical use can be recommended.

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CHAPTER 1

1.1 INTRODUCTION

Successful treatment of certain malocclusions with skeletal manifestations may be optimally treated during the period of rapid facial growth. Thus, orthodontic diagnosis and treatment planning for the adolescent usually requires an evaluation of the physical growth status achieved, and prediction of the potential for future growth. Individuals show a great variation in the timing and duration of the adolescent growth spurt when related to chronologic age. Thus, methods which measure the biologic age of an individual may be better applied when attempting to assess the developmental status of a child.

Numerous investigations have shown that a close relationship exists between craniofacial growth, skeletal maturation, and general body growth. The rate of growth of the face and body shows a distinct development paradigm of rapid growth during infancy, a deceleration in early childhood, followed by a rapid acceleration to a maximum at adolescence after which it decelerates rapidly and subsequently ceases.

Physiologic parameters used to assess biologic age include: skeletal age assessment; growth spurt in stature; dental development; and secondary sexual characteristics. The assessment of skeletal age is based on radiographic findings of one or more areas of the body (hand-wrist, elbow, knee, foot). The hand-wrist radiograph has, to date, been most extensively studied, and has been found to have a strong correlation with the timing of pubertal growth spurt in stature and to mandibular maturation. However, controversies still exist as to the reliability of using skeletal age for the prediction of the onset and duration of the craniofacial growth spurt.

The timing of the adolescent growth spurt in stature has been demonstrated to hold a fairly strong relationship with the timing of maximum increment in facial dimensions.

The majority of investigators have concluded that the pubertal peak for craniofacial dimensions occurs slightly later than that for maximum increment in stature. The female adolescent growth spurt in height generally commences between 10 and 11 years, peaks at around 12 years and is virtually completed by 15 years.

The correlations between dental development and craniofacial growth as well as other indicators of maturation at puberty are poor and not considered to be a reliable indicator for assessment of the developmental status of the facial complex.

Physical examination for secondary sexual characteristics is not appropriate in orthodontic practice, hence investigators have limited the assessment of pubertal development to menarche in girls and voice change in boys. Menarche is considered to be fairly reliable, but not an absolute indicator of peak height velocity in girls. Due to the difficulty in determining the timing of voice change in boys, there is little conclusive evidence in the use of this maturity indicator in growth predictions.

At present no one maturity indicator is considered definitive in evaluating the maturity status of an individual during adolescence. There are still limitations in using indicators of maturity to predict the onset, timing and duration of craniofacial growth, and in particular mandibular growth. Hence, any investigation which may provide a better understanding of these relationships would be of great benefit to the orthodontist in treatment planning for the adolescent individual.

An area of the skeleton readily visible on the lateral cephalogram film are the cervical vertebrae. Research of the literature shows that this area may be a potential source of information in growth prediction. The cervical vertebrae have been shown to grow in a manner similar to other long bones in the body. Lamparaski (1972) found the cervical vertebrae to be as reliable and valid as the hand-wrist film in assessing skeletal age. Lamparaski developed maturity indicators for males and females based on the changes seen in the cervical vertebrae from ages 10 through 15 years.

1.2 STATEMENT OF THE PROBLEM

Orthodontic diagnosis and treatment planning for the growing individual with skeletal manifestations usually requires estimation of the biologic age. If the growth potential in the dentofacial bones is to be utilized to obtain the treatment objectives, the clinician also needs to predict the future growth potential. Individuals show a great variation in the timing and duration of the adolescent growth when related to chronologic age. Hence, several physiologic maturity indicators are used to assess the developmental status and future growth potential of the individual.

Although, facial growth shows a close relationship with several commonly used parameters of physiologic maturity (hand-wrist skeletal age, menarche, height and weight increments), the correlation is not perfect. At present no one maturity indicator is considered definitive in evaluating the maturity status achieved by a individual. Further research is thus indicated to improve upon the methods that are currently available for use in clinical orthodontics.

The cervical vertebrae have been shown to grow and mature in the same manner as long bones; however, this area which is readily discernable from lateral cephalograms has received little attention in orthodontic investigations. Lamparaski (1972) using cross-sectional data was the first to describe maturational changes seen in the cervical vertebral bodies 2 to 6 for assessment of skeletal age. Since gender differences exist with regard to the timing and duration of the pubertal growth spurt, Lamparaski has described separate maturity indicators for males and females from ages 10 through 15 years.

Skeletal age assessments utilizing the cervical vertebrae may prove to be a useful and accurate adjunct in evaluating the adolescent's maturational level. However, further investigations are first required on longitudinal samples to determine the reliability and validity of using vertebral maturational changes for assessment of skeletal age and mandibular maturation in clinical orthodontics. The validity of vertebral skeletal age assessments could be tested by determining if any significant relationship exists between vertebral age and skeletal age assessments made from conventional hand-wrist radiographs. A further test for the validity of using vertebral age would be to determine the correlation between vertebral age and stature increments.

Orthodontic therapy is considered optimally timed coincident with the adolescent growth spurt which in females usually ranges between ages 10 through 15 years. The cervical vertebral maturity indicators described by Lamparaski are also limited to this age range. Although racial differences have been reported for maturation of other skeletal areas of the body the current longitudinal study is limited to assessing the cervical vertebrae of Caucasian females who were reported to be free of any known medical disease and who were healthy.

1.3 PURPOSE OF THE STUDY

The purpose of the first part of this study is to determine the reliability of using cervical vertebrae maturity indicators for skeletal age assessment. The second component utilizes longitudinal serial cephalometric data for 10 to 15 year old females to compare the reliability and validity of the vertebral skeletal age assessment against conventional hand-wrist assessments. A third component is to investigate the relationship between increments in stature and cervical vertebrae maturation at puberty.

1.4 RESEARCH QUESTIONS

Can the maturity indicators for cervical vertebrae 2 through 6 provide accurate and reliable assessments of adolescent female skeletal age?

Is there a significant difference in adolescent females between skeletal age assessments using cervical vertebrae and conventional hand-wrist radiographs?

Is there a significant relationship in adolescent females between increments in stature and cervical vertebral maturation assessments?

1.5 HYPOTHESES

H_1 The reliability of skeletal age assessments of adolescent females utilizing the maturity indicators for cervical vertebrae 2 through 6.

- H_o There is no significant difference between first and second determinations of cervical vertebral skeletal age assessments.
- H_a There is a significant difference between first and second determinations of cervical vertebral skeletal age assessments.

H_2 The relationship between skeletal age assessments utilizing the hand-wrist film and cervical vertebrae.

- H_o There is no significant difference between skeletal age assessments utilizing the hand-wrist film and cervical vertebrae.
- H_a There is a significant difference between skeletal age assessments utilizing the hand-wrist film and cervical vertebrae.

H_3 The relationship between increase in stature and cervical vertebrae maturation.

- H_o There is no significant difference between timing of stature increments and cervical vertebrae maturation.
- H_a There is a significant difference between the timing of stature increments and cervical vertebrae maturation.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1 INTRODUCTION

The time of onset, direction, intensity and duration of the adolescent growth spurt seen in the craniofacial complex is of importance to the orthodontist in treatment planning. Early intervention and utilization of the growth differential observed between the maxilla and mandible at puberty may improve prognosis for certain class II malocclusions with skeletal discrepancies (Krogman 1958, Thurow 1982). Growth considerations are also of importance in treatment planning in class III malocclusions, surgical orthodontics, and retention and post-retention prognosis of a growing child (Nanda 1992, Graber and Swain 1985, Thurow 1982). Thus, estimations of the growth status achieved and predictions of the remaining growth potential are often required in orthodontic treatment planning.

Individuals show a great variation in the timing and duration of the adolescent growth spurt, hence chronologic age is considered to be an unreliable method for assessment of the stage of maturation of an individual. Some of the physiologic parameters used to assess the developmental status of a child include: assessment of skeletal age from hand-wrist radiographs; growth spurt in stature; weight increments; dental development; menarche in girls; voice change in boys; and development of secondary sexual characteristics.

Growth **is** defined as a normal change in quantity of living substance and may result in increase or decrease in size, change in form or proportion and complexity (Moyers 1984). Growth is a dynamic, complex process that is controlled by endocrine and metabolic mechanisms that encompass both genetic and environmental factors. Growth of body mass is reflected by progressively greater weight measurements and increase in height of an individual, and is measured in units of increase per units of time (for example, height increments would be in centimetres per year). Moyers (1984) defines *development* as "all the normal sequential series of events between fertilization of the ovum and the adult size." Development includes differentiation of various parts of the body to perform different functions and implies an increase in skill and complexity of functions.

Maturation encompasses both growth and development, and refers to the process of development toward completion of growth of the skeleton. Any tissue which undergoes specific and easily identifiable changes that occur in all individuals and which have a specific end maturational state (the adult size) may be utilized for assessment of biologic age.

Burstone (1963) suggested that any predictions of growth must consider the "maturation level" and the "rate of maturation". The level of maturation refers to the status of the individual relative to the end or completed maturational state. The level of maturity reached at a particular stage of development describes how far along the individual is on the road to completion of his/her growth (Tanner, 1962). Physical growth of an individual may be demonstrated graphically as height or weight achieved by a certain period of time (distance curves), or a rate of height or weight change in a specific period of time (velocity curves using incremental changes).

Since individuals of the same chronological age show a great degree of variation in the timing and rate of growth, the assessment of skeletal development is considered to be a more accurate method of assessing the skeletal maturity level that has been achieved by an individual.

2.2 STANDARDS OF GROWTH

Standards of growth have been developed to assist in the clinical evaluation of physical growth of an individual. Charts and tables of height and weight standards based on data collected on large numbers of the population, provide objective data to which the growth of an individual or group may be compared. Growth data collection used to describe a population may be of two types: *cross-sectional data*, where measurements are made on a large number of children at different ages; and *longitudinal data* where measurements of the same individual are made over the entire course of their growth. In cross-sectional studies the wide variation between individuals dampens the true appearance of the individual growth spurt. Longitudinal data better describes the changes at puberty, since longitudinal measurements tend to preserve and define the individual changes in growth.

The data such as height chart standards collected to describe normal populations, may be expressed as percentiles where mean values are represented by the 50th percentile with a range from the 3rd to 97th percentile. All data between the 3rd and 97th percentile would include 94% of all the measurements made. Another method of describing the range of a normal population is to construct growth charts from mean values and describe the range as standard deviations. Plus or minus 2 standard deviations (2SD) includes 95% of the measurements, and corresponds to the 3rd and 97th percentiles.

Tanner (1962) suggested that when collecting data on a population for construction of growth charts or standards the following factors must be taken into consideration. Firstly, the growth standard should be representative of the group with wnom they are to be compared, and secondly the study sample should be sufficiently large so that the variability about the mean is expressed in the data collected. His third condition was that the norms be from healthy, well nourished children who are free of any known disease; and, lastly, that the measurements be made accurately utilizing a standardized measurement technique.

2.3 SKELETAL AGE ASSESSMENT

At present, the most commonly used method for estimation of biologic age is skeletal age assessments based on the maturational changes seen in 30 bones of the hand and wrist. The skeleton is considered to be a reliable measure of biologic age for several reasons; maturational changes in the bones are roughly similar in all individuals, varying only in the timing of events (delayed or accelerated maturation); each centre of ossification passes through recognizable changes in morphology which can be used as determinants of maturation; all centres of bone can be easily identified and recorded radiographically (Greulich and Pyle, 1959).

Although a number of different methods are available for assessment of the skeletal age from the hand-wrist radiograph, the two most commonly reported in the literature are the Greulich and Pyle Atlas method and the Tanner-Whitehouse Scoring method. The Greulich and Pyle Atlas method is probably the easiest and presently the most commonly used North American orthodontic offices. The standards in the Atlas are based on a growth study initiated by Dr. T.W. Todd on healthy prosperous Caucasian children from Cleveland, Ohio. Due to the difference in timing of maturity separate standards were developed for males and females from birth to 19 years (Greulich and Pyle, 1959). Each standard depicted in the Atlas was selected from a series of 100 radiographs taken at the same chronologic age. The radiographs were arranged in sequence from the least to the most mature for each age and the radiograph which best depicted the average stage of development of all bones for that specific age was selected as the standards for the Atlas.

The Greulich and Pyle Atlas method or the "inspectional method of Todd" is a simple matching procedure where the radiograph under investigation is compared with the standard plates. Maturational changes in the epiphysis and diaphysis occur in an orderly sequence, so that the plate which most closely resembles the radiograph of the subject is selected from the Atlas, and then the skeletal age of the standard is assigned to the individual. The inspectional technique introduced by Todd (1937) is based on the successive changes in outline and contour. The serial changes observed in radiographs are named "maturity indicators" and are defined as "those features of individuals bones that can be seen in the roentgenograms and which because they tend to occur regularly in a definite irreversible order, mark their progress toward maturity" (Greulich and Pyle, 1959). This technique is simple, quick and reliable to use since no measurements are needed, magnification considerations are not required, the radiograph technique is not critical since the size of the bones are not considered in maturity assessments (Todd 1937, Greulich and Pyle 1959, Acheson 1954).

The standards derived by Tanner and Whitehouse for use with their *bone scoring method* are based on radiographs of 3000 normal children in the Harpenden Growth Study, England (Tanner, 1962) In this method of skeletal age assessment, scores are assigned to each of 20 individual bones of the hand and wrist (Tanner et al, 1975). For each bone 8 stages of maturity have been identified. To determine the maturation level of the individual, each bone is matched with a standard in their atlas and its stage is rated from 1 to 8. The scores of each bone are then added together to give a sum of all the scores. The maturity scores which run from 1 to 100 (the latter figure represents full maturity) may be converted to skeletal or "bone age" by means of tables for males and females.

2.4 REPRODUCIBILITY OF SKELETAL AGE ASSESSMENTS

Moed et al (1962) determined the inter-investigator and the intra-investigator errors for the Greulich and Pyle Atlas inspectional method for skeletal age assessments. Five judges (three anthropologists and two physicians) made duplicate assessments for each of 33 radiographs taken on children aged 7 years 3 months, to 18 years 11 months, with a mean of 13 years, 10 months. The correlation coefficients were high for both the intra-investigator (r=0.95 to 0.99) and inter-investigator assessments (r=0.93 to 0.98). For the intra-investigator error, the median difference between the first and second assessments for the five judges was 0, 2, 3, 3, and 6 months. Cumulatively, 38% of the 1st and 2nd readings made by the five judges were identical, 82% of their judgments were within 6 months, and 94 % were within 12 months discrepancy. For the inter-investigator reliability median differences ranged from 3 to 12 months, 21% of the judgments were identical, 59% were within 6 months, and 82% were within 12 months discrepancy.

Acheson et al (1963) examined the systematic and random (or variable) inter-investigator and intra-investigator error for assessment of hand-wrist radiographs using the Greulich and Pyle Atlas method. Fifty hand-wrist radiographs (25 boys and 25 girls) with an age range of 2 to 18 years were selected from children with some medical or developmental problems so the films would not easily conform with the standards and hence, would be difficult to assess. Eight observers from different parts of the world (6 experienced and 2 inexperienced in hand-wrist reading) assessed the films independently of each other provided only with the gender and serial number for each film. The following conclusions were reached by the authors: (1) Inter-observer error is present but the difference between the investigators is only 4 months when the mean values of all the films was considered together; (2) For analysis of variance the F ratio of F=4.62 for p<0.001 for girls was highly significant; (3) Inter-observer and intra-investigator differences were greater for the inexperienced assessors; (4) The 95% confidence limits were lowest for investigators who interpolated to "between-plate" ages for radiograms that did not match the standard (confidence limits, 8.08 months for investigator who interpolated, compared to 13.06 months for an investigator who did not interpolate for any readings); (5) radiographs for femal[illegible]ented more problems than males; (6) difficulty was not associated with age of child nor the amount of retardation in skeletal development. The authors concluded that investigators are capable of repeating assessments with a reasonable degree of precision using the Greulich and Pyle Atlas, and that since the confidence limits are the final criteria against which the reliability of skeletal age must be estimated that, based on the results of their study, interpolation is justified.

In a follow up study, Acheson et al (1964) used 45 radiographs from the previous study to determine the reliability of assessing hand-wrist radiographs using the bone-specific standards. Again 6 experienced and 2 inexperienced investigators assessed the radiographs, but used the bone-specific rating system of Tanner and Whitehouse (1959). The results of this reliability study suggest that though the eight investigators could duplicate their own ratings, they differed from each other to a statistically significant extent.

In 1966 Acheson et al conducted a reliability study that compared the Greulich and Pyle Atlas and the Tanner-Whitehouse methods. The data used for this study was based on their 1963, and 1964 studies. Six investigators (who were experienced in reading hand-wrist films) assessed skeletal ages for all 50 radiographs using both the above mentioned methods. The Tanner-Whitehouse method rated all assessments a year higher than those for the Greulich and Pyle method. The authors suggest that this may be attributed to the two different populations from which the standards were developed (that is, Greulich and Pyle standards were based on prosperous Cleveland children in contrast to the middle and working class children of the Tanner-Whitehouse standards). The Tanner-Whitehouse method gave rise to a smaller random variation but greater systemic error (bias) when compared to the Greulich and Pyle Atlas method. In conclusion the authors suggest that the Tanner-Whitehouse System, if properly used, may be slightly better for estimations of skeletal age due to the smaller random error associated with it.

Roche and Johnson (1969) conducted a study on 169 (80 boys and 89 girls) Australian children of British ancestry, from 2 through 13 years, to compare between seven different methods of skeletal age assessments. Each one of the hand-wrist films was assessed by comparison with the Greulich and Pyle Atlas (1959). Where the film under study fell between standards, skeletal age was extrapolated to one monthly intervals for ages below 6 years, and to 3 monthly intervals for all ages above 6 years. The seven methods used for skeletal age assessments were: (I) An arithmetic mean of all bone skeletal ages; (II) An arithmetic mean of all except the most mature and least mature bones; (III) A arithmetic mean of all except the 2 most and 2 least mature bones; (IV) A arithmetic mean of two bone skeletal ages, the most mature and least mature; (V) A system of selection and weighting based on the Tanner et al 1962 method; (VI) An arithmetic mean of all bone skeletal ages except the carpal bones; and (VII) an arithmetic mean derived from 14 bone skeletal ages. Skeletal age assessments made by methods I, II, III, VI and VII were almost identical and showed no significant difference for all chronologic ages. Results of the t-tests for skeletal age assessments made by method I (Greulich and Pyle Method) and V (Tanner-Whitehouse) showed significant differences for radiographs below 8 years, but there was no significant difference between methods for all ages above 8 years. For assessments below 8 years the Greulich and Pyle method gave more advanced readings when compared with the Tanner-Whitehouse method.

Roche et al (1971) published a study conducted on 62 boys and 82 girls of British ancestry living in Melbourne, Australia. A comparison between Greulich and Pyle and Tanner-Whitehouse assessments of skeletal maturity for children aged 2 through 14 years of age was made on 2,009 radiographs. In using the Greulich and Pyle method the assigned skeletal ages were interpolated between the atlas standards when it was considered appropriate. The intra-observer difference for the Greulich and Pyle method was 0.15 years and for the Tanner-Whitehouse method it was 0.29 years. The inter-observer difference for the Greulich and Pyle method was 0.22 years and for the Tanner-Whitehouse method it was 0.36 years. The median age for this sample had a close association with the Greulich and Pyle standards, but were markedly advanced when compared to the Tanner-Whitehouse skeletal ages. The authors suggested that this may be explained by the sampling methods used for the growth studies on which the Greulich and Pyle and Tanner-Whitehouse standard were based.

Thompson (1971) provided reliability study results for the Greulich and Pyle Atlas and the Tanner-Whitehouse method on an investigation relating craniofacial growth to stature, weight and skeletal age (for details on description of sample and results on other aspects of this study see section on craniofacial growth and maturity indicators). For this pilot study a total of 133 hand-wrist radiographs were assessed using both the Greulich and Pyle and Tanner-Whitehouse methods by two investigators. The average Tanner-Whitehouse readings were 1 year greater than average Greulich and Pyle assessments. The 95% confidence interval of 6 months was reported for the Greulich and Pyle Atlas, and 6.48 months in the Tanner method. The systematic error for the Tanner method was 8.8 months. The between assessor variance was significant for all the bones. The author suggested that the systematic error is not important if all assessments are made by one assessor. Radiographs of the 11 and 12 year females were more difficult to assess than those for early and later years when using the Greulich and Pyle method. The author stated that this was due to the presence of the peak pubertal spurt; that is, during this period the various bones within the hand itself matured at different rates, thus, the variability was greater at this age than at any other age.

2.5 SKELETAL AGE AND STATURE

To facilitate the estimation of adult height, Bayley (1946) constructed tables for girls and boys on a sample from the Harvard Growth Centre Study and the Institute of Child Welfare of the University of California. The data for construction of tables was based on a sample of 300 healthy Californian children followed from birth to 18 or 21 years of age. Bayley and Pinneau (1952) revised the tables of height prediction for use with the Greulich and Pyle hand standards. These latter tables are constructed from measurement taken on 122 (individuals) obtained from the above sample. For height predictions estimation, the height in inches is matched to the skeletal maturation (to the nearest 3 month) and the predicted mature height is read directly from the intercept of skeletal age and height. The use of these tables for height prediction is based on the assumtion that there is a high correlation between skeletal maturation and stature increments. Separate tables are provided for males and females of average, retarded, and accelerated rate of maturation. The rate of maturation is considered average for subjects whose skeletal maturation is within 1 year of their chronologic age, and is considered retarded or accelerated if the skeletal maturation is retarded or accelerated more than one year. Bayer and Bayley (1956) constructed percentile charts, based on the above sample and data, for the average, early and late maturing child.

Tanner et al (1976) who utilized longitudinal data on 35 girls from the Harpenden Growth Study to observe the characteristics of the adolescent growth spurt reported that the total height gained from take -off point to cessation of growth averaged 25 cm in girls (S.D. +- 4.1 cm, range = 17-33 cm). On average, 16% of adult height in both girls and boys was attained during the adolescent growth spurt. Ages at take-off, at peak velocity, and menarche were reported to be independent of mature size. Although peak velocity in height averaged 8.1 cm/year for females and 8.8 cm/year for males, in males the peak velocity was generally expressed later, was of greater magnitude and duration, and this resulted in a 10.5 cm average difference between adult females and males.

Grave and Brown (1976) utilized longitudinal data on 88 Australian Aboriginal children (52 boys and 36 girls), to investigate the relationship between increase in stature and skeletal age. Skeletal age was assessed using fourteen ossification events in the hand-wrist radiographs. The timing of peak growth velocity in height and ossification events was found to be in close agreement to those of Caucasian children. Initiation of the adolescent growth spurt occurred when epiphysial widths reached diaphysial widths in the fingers and radius and when ossification on the pisiform and hamate started. Peak growth velocity in stature occurred at about the time of epiphysial capping in fingers and the radius. A deceleration in body height was seen when the epiphysis fused with the diaphysis in the third finger, progressively from distal to proximal phalanges.

Bowden (1976) studied a sample of 52 boys and 60 girls enroled in a serial study, University of Melbourne, Australia. Skeletal age was assessed by epiphysial-diaphysial growth stages as outlined by Greulich and Pyle (1959). Epiphysial-diaphysial stages were related to start, peak and end of the adolescent growth spurt in height. In girls the initiation of the adolescent growth spurt occurred at a mean chronologic age of 9.99 years (range 6.51-12.5) and in boys at 12.0 years (9.7-13.5), compared with mean skeletal age of 10.51 (range 6.51-11.5) and 12.28 (range 9.7-14.0) years. Peak in girls was seen at a mean chronologic age 11.67 (9.5-13.62) and mean skeletal age 11.79 (10.4-12.9), compared with boys at a mean of 13.91 (11.6-15.6) and skeletal age 14.43 (11.6-15.2). The adolescent spurt was completed in girls at a mean chronologic age 12.88 (range 11.45-16.1) and skeletal age 13.55 (11.5-14.15), whilst the ages for boys were 15.42 (13.43-17.6) and 15.40 (13.10-17.5) respectively. It can be seen that individuals show a great deal of variation in timing of all these events. The author stated, though there is a relationship between skeletal age events and height increments, skeletal age is of limited value as a predicator due to the large variance between individuals.

In a longitudinal study of 212 Swedish children (90 girls and 122 boys) Hagg and Taranger (1979) investigated the possibility of using specific stages in hand-wrist assessments to indicate the stages of adolescent growth spurt in height. Data for this sample was collected from birth to adulthood. Onset of the pubertal growth spurt occurred in girls at about 10 years and in boys at 12 years. Peak height velocity occurred 2 years after onset in both males and females. End of the adolescent growth spurt was attained in girls at about 15 years and boys at 17 years. The ossification of adductor sesamoid occurred before onset of adolescent growth spurt in height in 14 percent of the girls and 8 percent of the boys. At peak height velocity, the sesamoid was ossified in all subjects except one boy. Specific stages in the middle and distal phalanx of the third finger as well as the radius also showed a close relationship with peak height velocity. The authors stated that since a relationship existed between skeletal stages and growth events in height, skeletal staging may be used to indicate which period of growth an individual has reached.

Data from Harpenden Growth study Centre in England was utilized by Houston (1980) to determine the timing of the adolescent growth spurt and skeletal maturity. The sample consisted of 68 boys and 58 girls of European origin. The Tanner-Whitehouse method (Tanner et al, 1975) was used to assess skeletal age from hand-wrist films taken at six monthly intervals. Specific bone stages and ossification events of the hand-wrist were related to timing of peak velocity in stature. Correlation coefficient between specific ossification events in the hand-wrist and peak height velocity were found to be significant, but not high enough to be clinical significance (r=0.30 to 0.89). The author concluded that though the time of certain ossification events and peak height velocity are related, they are of limited value in predicting peak height velocity and thus of the growth spurt.

2.6 DENTAL AGE ASSESSMENTS

Bjork & Helm (1967) utilized the data from a longitudinal study with metallic implants on a sample of Danish children enroled in a study on facial growth at the Royal Dental College, Copenhagen, Denmark. A sample for this study consisted of 32 boys and 20 girls. The authors examined the relationship between pubertal growth in body height and certain indicators of maturation: ossification of adductor sesamoid, two stages of dental development (DS4-full eruption of all canines and premolars; and DSM_2-all second molars fully erupted), and menarche in girls. In females peak height velocity occurred at 12.6 years, menarche at 13.11 and sesamoid ossification at 11.6. In boys peak height velocity occurred at 14.0 years and completion of sesamoid ossification at 13.3 years. Dental development showed very poor correlation to all other indicators of maturation status, and thus was not considered to be a reliable indicator of development status of an individual. The females in this investigation showed a close association between peak height velocity, ossification of adductor sesamoid of the thumbs and menarche.

Demirjian et al (1973) utilized cross-sectional data on 2928 French-Canadian children from Montreal's Growth Centre to develop a maturity scoring system for estimation of the overall dental maturity (dental age). Panoramic radiographs were used to assess developmental changes of the teeth rather than actual size of the first seven permanent teeth in the third quadrant. Eight stages were defined and described from the beginning of calcification of cusp tips to the closure of the root apex. A tooth specific scoring system, with separate tables for males and females was developed and tested. The summed scores for all seven teeth gave a dental maturity score for the individual which was converted to dental age using tables or percentile charts for the age range 3-16 years. The authors suggested that assessment of dental age based on tooth formation is a more reliable indicator of dental maturity than the dental emergence method, since, emergence is influenced by local factors such as ankylosis, early or delayed extraction of deciduous teeth, impaction and crowding of permanent teeth.

In a subsequent paper, Demirjian and Goldstein (1976) expanded the age range from 2.5 years to 17.0 years. The sample size increase to 4756 allowed the inclusion of two additional stages, and the development of the 3rd and 97th percentile estimates for the maturity standards. Since not all teeth were present in all individuals, the authors developed and presented scoring systems along with percentile standards for two combinations of 4 teeth in the quadrant. The results of their previous study and the current study that yielded less than a three month difference, whereas the subsets yielded a mean difference of 10 months. The authors suggested that these results reflect the somewhat different aspects of maturity being measured when using the different sets of teeth for dental age assessments.

Anderson et al (1976) investigated the interrelationship of dental maturity, skeletal maturity, height and weight from age 4 to 14 years. This longitudinal study utilized annual records on 121 boys and 111 girls from the serial experimental group of the Burlington Growth Centre. Dental development was based on mineralization stages on each tooth of one side of the maxilla and mandible as seen on annual Cephalograms. The hand-wrist assessment were scored according to the method of Greulich and Pyle (1959).

Correlation coefficients were calculated for each gender at each age to compare mineralization stages of 16 teeth, skeletal age, height and weight, correlations were highest for the mandibular first molar in males (r=0.37, 0.52, 0.45 respectively) and the mandibular second molar in females (r=0.29, 0.32, 0.39 respectively). Dental mineralization related more strongly to height and weight than to skeletal development in both sexes. In males, tooth stages related more to height than weight, whereas in females, the association was similar for both height and weight. It should be noted that though statistically significant, even the highest reported correlation for mandibular molars, are quite low when considering the clinical application of dental age for maturity assessment.

Liebgott (1978) utilized serial longitudinal data on 32 males aged 4 through 18 years, from the Burlington Growth Centre, Toronto. Dental, skeletal and chronologic ages at which peak mandibular length increase occurred were determined from the data. Mandibular length was represented by the distance condylion-gnathion in this study. Peak growth in the mandible occurred at skeletal age 14.52 and chronologic age 14.18 in this sample of Caucasian boys. Throughout the study period, dental age did not show a close relationship with mandibular maturation changes. The author concluded that dental age is not a good indicator of increase in mandibular length. Skeletal age was shown to hold a very strong association with peak mandibular growth (r=0.89).

To determine if tooth mineralization may be used as an indicator of the pubertal growth spurt, Chertkow (1980) carried out a study on 197 children. This investigation studied the relationship between stages of dental development, calcification of the hook of the hamate, and stages of development of the epiphysis of the middle phalanx of the third finger. Panoramic and lateral oblique radiographs were used to determine dental development on all four cuspids, and mandibular bicuspids and first and second molars.

Skeletal age was obtained from hand-wrist films. The sample consisted of 159 Caucasian children (66 boys and 93 girls) and 38 black children. In Caucasian children completion of root formation of the mandibular cuspid was found to be closely related to the appearance of other maturational indictors. The other teeth studied did not show a close relationship to indicators of maturity used in this study. Completion of root formation of the lower cuspids yielded a strong relationship to the development of certain maturity indicators in the hand-wrist radiograph. The relationship between the dental development and the other maturity indicators could not be tested in the sample of Black children since they exhibited an accelerated rate of growth such that cuspid root formation was completed before the study period.

In a subsequent study, Hagg and Taranger (1982) utilized the longitudinal data on a sample of 212 Swedish children (90 females and 122 males) from birth to adulthood. Tooth emergence was recorded annually by direct inspection, the tooth was considered to have emerged if any part of the crown was visible. Dental development was assessed by the dental emergence stages (DES) of permanent teeth as devised by Bjork: DES2 - all incisors erupted; DES3 - 1 to 2 canines and/or premolars erupted; DES M3 - 1 to 3 second molars erupted; DES M4 - all second molars erupted; and DES M5 - 1 to 3 third molars erupted. The association between pubertal growth spurt and dental emergence of certain teeth was found to be weak (r=0.01 to 0.33) for both sexes. The author concluded that dental emergence stages are not useful for predicting the pubertal growth spurt in height. The other findings of the study were: the pubertal growth spurt in height began at 10, and ended at 14.8 years for females, and it began 12.1 and ended at 17.1 years in boys. Thus, there was a 2-year sex difference in age at onset and end of the pubertal spurt. In both sexes the peak height velocity began 2 years after onset (that is, at 12.0 and 14.0 years in females and males respectively). Menarche occurred 1.1 years after peak height velocity. The pubertal voice was obtained 0.2 years before peak height velocity and male voice 0.9 years after the peak.

Demirjian et al. (1985) investigated the interrelationship among five measures of physiologic development. This longitudinal study used data on 50 girls, between 6 and 15 years, from Montreal Maturity Growth Research Centre. The five physiologic maturity indicators studied were (1) menarche, (2) peak height velocity, (3) 75% skeletal maturity, (4) adductor sesamoid appearance, and (5) 90% dental maturity. A high correlation coefficient of 0.86 showed a close association between peak height velocity and menarche. Peak height velocity had a weaker relationship with adductor sesamoid (r=0.5) and 75% skeletal development (r=0.4). Ossification of adductor sesamoid and menarche occurred approximately one year before and after peak height velocity respectively. Dental maturity showed no significant relationship with skeletal, somatic and sexual maturity.

On a sample of 153 subjects (72 boys and 81 girls) aged 8 through 12 years, Sierra (1987) investigated the relationship between mineralization of specific teeth and certain ossification centres in the hand-wrist radiographs. Specific ossification centres, characterized by a low degree of variability in timing of onset of ossification were utilized to assess skeletal development. In this study the correlation coefficients were fairly high (ranging from 0.60 to 0.82), and hence challenged the findings of the majority of studies on dental age utilization for growth prediction. The strongest correlation was obtained for mandibular cuspids, followed closely by maxillary first bicuspids in both sexes. Sierra suggested that dental age assessments from mineralization events could be used to predict the general development status of an individual.

2.7 CRANIOFACIAL GROWTH AND MATURITY INDICATORS

The development of the cephalostat and the technique of taking standardized cephalograms by Broadbent (1937) led to great advances in studies relating to the craniofacial complex. Accurate measurements could be made of the craniofacial skeletal structures. The standardization and measurement accuracy of the craniofacial structures permitted research to be conducted on the growth and development of the facial structures; consequently investigations could be conducted that related growth changes in the facial structure to other indicators of maturity. A large number of studies are found in the orthodontic literature relating craniofacial growth, in particular mandibular growth, to the various maturity indicators available for assessment of physiological maturity.

Nanda (1955) conducted a serial study on a sample from the Child Research Council, University of Colorado School of Medicine. Facial growth was studied on a sample of 10 males and 5 females from ages 4 through 20 years. The measurements utilized were: sella-nasion, nasion-gnathion, nasion-prosthion, nasion-infradentale, sella-gonion, gonion-gnathion and sella-gnathion. The growth curves for all the facial dimensions were found to be typical of general body growth curve. For velocity curves, percentage increment curves were utilized, since these emphasized the existence of the pubertal growth spurt in the facial area. Comparison of the velocity curves for different individuals in the study showed the following: facial growth curves resemble stature curves; a pubertal acceleration was apparent for a majority of the facial dimensions; the timing of the onset and peak acceleration in facial dimensions, when compared to the peak in body height, showed considerable variation (28% had peaks coincide, 57.3% had a facial peak 6 months later than stature peak, and 14.7% had a facial peak earlier); even within the same individuals the timing of peak height velocity for all 7 facial dimensions did not coincide; and secondary maximums were found to occur quite commonly in most facial dimensions - usually seen in the childhood period.(juvenile acceleration). Application of Student's t-test showed that females experiences their circumpubertal spurt earlier and to a lesser degree than males.

Bambha (1961) conducted a longitudinal study of the face in relation to body height, On a sample of 25 males and 25 females was obtained from the Child Research Council, Denver, Colorado. The study followed the children from one month of age to 30 years. The dimensions used in this study were sella-bolton point, sella-lambda, sella-bregma, sella-gnathion and sella-gonion. Growth curves of the facial dimensions showed characteristics of general body growth curves. Distinct childhood and adolescent growth spurts were seen in most individuals. The majority of individuals (66%) tended to have their circumpubertal maximum in facial dimensions after the maximal increment in stature which agreed with Nanda (1955); however facial dimensions still experienced small increments after growth in height had been completed. Females showed smaller rates of growth and matured 2 to 3 years earlier than boys. The mean time difference of maximum circumpubertal growth among boys and girls body and facial dimensions is 2.31 and 2.12 years respectively.

On a sample of 125 individual of North European stock Rose (1960) conducted a study to investigate the relationship between facial dimensions, skeletal age and increments in body stature and weight. The sample for this study was obtained from patients attending the pay clinic of the University of Minnesota Dental School, and ranged in age from 9 to 18 years. In this study a planimeter was used to measure the total surface area for the mandible, maxilla and orbito-ethmoid complex. Rose failed to find a relationship between carpal development and certain surface areas within the face. The results of this study which used surface area as compared to linear measurements, are contrary to the findings of other investigators. The author stated that chronologic age and skeletal development were not reliable for estimation of facial development; stature and weight increments were the better indicators. Since the results obtained for this study are poorly presented, it is difficult to determine the accuracy of these conclusions.

In an abstract, Pike (1964) reported on the conclusions of his findings on a study of the relationship between the rate of facial growth and stature increments. The sample was made up of 14 boys and 11 girls with a 7 to 12 year age range, negative medical history, and no previous orthodontic treatment. Tracings of lateral cephalograms were used to obtain mandibular, maxillary, and anterior face height. The author stated that linear regression and correlation tests were conducted on the data and the following conclusions were reported: a high degree of individual variation; a significant positive correlation between increase in stature and growth rate of facial dimensions; no significant gender differences. Details on source of data and results are not available since this report was published as an abstract, but it would appear that sample size may not be sufficient to determine if the results are statistically significant.

Maj and Luzi (1964) studied the changes in mandibular growth on a sample of 12 boys and 16 girls between the ages of 9 to 13 years. This investigation was conducted to see if it was possible to predict the future growth of the mandible from present dimensions. Maj and Luzi presented their results as mean values, standard deviations range and graphs of growth increments. The results of this study showed that mandibular growth was not smooth and continuous, but occurred in spurts. Low correlation coefficients were found between the dimensions of the mandible at different ages. The best reported correlation for mandibular length and height, between ages 9 and 13 years, was only 0.63. The authors concluded that a significant relationship did not exist between linear dimensions of the mandible at the ages studied and thus the mandible itself could not be used to predict future growth.

Hunter (1966) used longitudinal data on a sample of 34 females and 25 males from the files of the Child Research Council, Denver, Colorado. He studied the relationships of growth of the mandible with stature and skeletal age using the hand-wrist radiograph. The seven linear measurements used to evaluate growth of the craniofacial complex are articulare-gonion, gonion-pogonion, articulare-pogonion, articulare-point A, sella-nasion, sella-gonion and nasion-menton. Hunter challenged the findings of Nanda (1955) and Bambha (1961) that the majority of individuals maximum facial growth coincided with the peak height velocity in stature. Of all the dimensions studied, mandibular length exhibited the most consistent relationship with stature (r=0.76). The female group showed a greater variation in the time of onset, apex and end of the adolescent growth spurt. In females the times for onset, peak and end were 10.41, 11.80 and 13.04 years respectively, and for the males the values were 12.97, 14.11 and 15.45 years.

Tracy and Savara (1966) used a mixed longitudinal sample of 50 girls to investigate growth changes in the mandible from 3 to 16 years. They utilized annual lateral cephalograms and PA cephalograms to study the changes in 5 mandibular parameters: ramus height (condylion-gonion), body length (gonion-pogonion), maximum length (condylion-pogonion), bigonial width (gonion-gonion), and bicondyular width (condylion-condylion). Growth increments from age 3 to 16 years were largest for maximum length (30.9mm), body length (22.9 mm), and least for ramus height (17.2 mm). The onset of the pubertal acceleration occurred at 9.0 years for maximum length, and 9.5 years for ramus height and body height Growth increments were largest for maximum length and body length and least in ramus height. The results were presented in the form of means, standard deviation, variance, and graphically in the form of mean distance and velocity curves. The mean distance and velocity curves presented show that annual mandibular increments in the mandible decreased over the childhood period, then increased until the circumpubertal maximum was reached and then declined again. Tracy and Savara found that the maximum circumpubertal increments in the 5 mandibular dimensions occurred from 11.1 to 12.6 years in girls.

Johnston et al. (1965) reported on the results of three separate studies conducted on a sample obtained from children enroled in a growth study between 1947 and 1962 with the Growth Centre in Philadelphia. The purpose of all three studies was to determine the usefulness of hand-wrist assessments as maturity indicators for estimation of cephalofacial maturation level. In the first study conducted on a sample of 20 Caucasian females, aged 10.5 to 18.0 years, skeletal age was assessed from the hand-wrist radiographs using the inspectional technique of Greulich and Pyle. Facial dimensions were given as percentage of adult size (growth at age 16.5 years was considered 100%). The purpose of this study was to determine if grouping of facial dimension by skeletal age would reduce the variance for facial dimensions. Variance for several mandibular dimensions was reduced when grouped using skeletal age rather than chronologic age, thus, the author concluded that mandibular dimensions are more closely related to skeletal maturation than the maxillary dimensions. The second study was conducted on 62 females and 58 males aged 7 - 17 years and used anthropometric dimensions (rather than cephalometric) of the face. The correlation coefficient were highest when measurements included gnathion: gonion-gnathion r= 0.83; condylion-gnathion r= 0.79; porion-gnathion r=0.62. Correlation coefficients were lowest for upper face: upper face height r= 0.48; porion-nasion 0.18; and porion-subnasale. The second study again showed that mandibular growth is better related to skeletal maturation than maxillary growth. The third study conducted on 81 boys and 56 girls investigated the relationship between skeletal age and Class II, Division I malocclusions. Children in whom the Class II, Division I malocclusion was of skeletal origin showed delayed skeletal maturation.

Gilbert (1966) evaluated the relationship between mandibular growth and skeletal age assessments using the hand-wrist radiograph on a sample of 226 females enroled in the Burlington Growth Centre Study. Mandibular length (condylion-symphysis point) was obtained from 45 degree cephalograms at ages 6, 9, 12, 14, 16, and 20. Individuals were plotted on mandibular growth curve by chronologic age, and mandibular length was further classified as accelerated, normal, or retarded by skeletal age assessments. Gilbert noted a significant relationship between mandibular length classification and the skeletal maturity classification over the whole period of the study. In accelerated maturers, mandibular length increments tend to decrease from 12 to 20 years. Retarded maturers are seen to show an increase in mandibular length status relative to the mean growth curve of mandibular length during the same period.

Pileski (1969) on a sample of 108 females and 91 males, from the serial experimental group of the Burlington Growth Centre, investigated the relationship of adductor sesamoid appearance and mandibular growth. Lateral oblique radiographs were utilized for mandibular measurements. The appearance of the sesamoid bone preceded peak mandibular velocity by 1.09 years in females and 0.72 years in males. The correlation of coefficient between these events was 0.36 in females, and 0.42 for males. The author concluded that although this was statistically significant, they are too low for clinical prediction of time of maximum mandibular velocity. In 25% males and 19.5% females peak mandibular velocity occurred before the appearance of the sesamoid.

Woodside (1969) obtained 2161 female and 2651 male mandibular length measurements in a cross-sectional study using the records from the files of the Burlington Growth Centre Study. Forty-five degree lateral oblique radiographs were used to determine mandibular lengths for ages 3 to 20 years. Computer smoothed distance and velocity curves were derived for each individual. Females, experienced maximum mandibular growth between 11 and 12 years, and males between 14 and 15 years. In males the mandible grew for a longer duration and to a greater degree when compared to females.

Thompson (1971) utilized a sample of 111 Caucasian females from the files of the Burlington Growth Centre to conduct a study on the development of the craniofacial complex and its relationship to stature, weight and skeletal age. Skeletal age assessments were determined by both the Greulich and Pyle (1959) inspectional method and the Tanner-Whitehouse method. The results of the study showed a high positive correlation between the two methods of skeletal age assessments. Mandibular length and bimastoid width were found to hold a positive correlation to both height and weight. From age 4 to 17 years, the mandible showed greater changes in both the horizontal (about one-half times) and vertical dimensions (about twice) when compared to the maxilla. The maximum increments in mandibular length occurred at the same time as that for stature (chronologic age 11.40 and 11.36 years respectively). The maximum increments of height, weight, and mandibular length were positively correlated. Except for the mandible, this female sample did not show any measurable changes in the craniofacial structures after age 14. The mandible increased in length by 2mm from age 14 to 17 years, after this no distinct change was observed. Skeletal age and chronologic age were equally well related to height, weight, and mandibular length increments.

On a mixed longitudinal sample of 20 Caucasian girls, aged 9 to 18 years, Tofani (1972) investigated the relationship of mandibular growth with several maturation indicators. Stature, skeletal age and menarche were related to mandibular dimensions: mandibular length (articulare-pogonion); ramus height (articulare-gonion); corpus length (gonion-porion) and bigonial width (gonion-gonion). Tofani presented his results in the form of individual and mean velocity curves. Although, all four dimensions measured experienced a general circumpubertal spurt between ages 11 and 12 years, the association was weak (r=0.42). The maximum increment in mandibular length occurred after that in stature and lasted two and a half to three years. Menarche most often occurred after the maximum increment in all mandibular dimensions in early maturing girls, and before in late maturing girls. Onset of fusion in the distal phalanges was found to be the best predicator of mandibular pubertal spurt (r=0.53 to 0.71).

Grave (1973) investigated the relation between the timing of ossification events in the hand-wrist, peak height velocity and maximum craniofacial dimensions. Longitudinal data from 8 to 18 years was obtained from 52 male and 36 female Australian Aboriginal children. Peak growth velocity in height occurred at 11.8 years in girls and 13.8 years in boys. Peak velocities in facial dimensions occurred at about the same time as that for peak height velocity. Average correlation coefficients of 0.69 for boys and 0.73 for girls showed that there was no significant difference between peak velocity in height and mandibular dimensions.

On a sample of 111 females from the Burlington Growth Centre, Thompson and Popovich (1973) evaluated the relationship of craniofacial growth with chronologic and skeletal age. Skeletal age from hand-wrist film was assessed by both the Greulich and Pyle methods and Tanner-Whitehouse method. Mandibular measurements used were condylion-gonion, gonion-gnathion and condylion-gnathion. Thompson and Popovich reported that on average skeletal age determinations were one year greater when using the Tanner-Whitehouse method as compared to Greulich and Pyle values. Using the Greulich and Pyle Atlas, the 95% confidence interval was plus or minus 6.0 months. For the Tanner-Whitehouse method it was plus or minus 6.5 months. In this study mandibular measurements were equally well related to both chronologic age and skeletal age. The authors thus concluded that skeletal age did not prove to be of any additional value for predicting maximum mandibular velocities in females.

In a subsequent study using the same sample, Thompson and Popovich (1974), studied the relationship of mandibular measurements with stature and weight. The degree of variability between individuals was found to increase with increasing age. Height, weight and mandibular dimensions all experienced a pubertal growth spurt. Peak growth in mandibular dimensions was found to occur at the same time as that for the maximum of height and weight (between 11 and 12 years). All mandibular dimensions were positively correlated with growth in height and weight. The correlation of coefficient was found to be highest at age 11 Mandibular length (Co-Gn) was more highly correlated to stature and width than mandibular body length (Go-Gn).

Diagle (1974) studied the relationship between circumpubertal acceleration for the maxilla, mandible and stature. A sample of 51 boys was selected from the experimental group of the Burlington Growth Centre. Maximum velocity for maxilla and stature occurred at about the same time (13.4 and 13.6 years respectively). Maximum velocity for the mandible occurred one year later (14.4 years) in 68.9% of the sample. The mandible showed a stronger association with stature than the maxilla. Diagle concluded that though it is not possible to accurately predict the time of peak mandibular velocity, absence of circumpubertal acceleration in stature could serve as an indication that the mandibular spurt still has not occurred.

Fishman (1979) studied a mixed longitudinal series of cephalograms and hand-wrist radiographs in 60 boys and 60 girls undergoing orthodontic treatment. Craniofacial dimensions and height increments were obtained from 7.5 through 15 years. Seven linear cephalometric measurements were taken for facial dimensions: articulare-gonion, gonion-pogonion, gonion-gnathion, articulare-gnathion, sella-gnathion, articulare-point A and sella-point A. Mean values and standard deviations for standing height and facial dimensions were calculated by chronologic age and skeletal age. Fishman found that the majority of subjects did not show concurrence between skeletal age and chronologic age for stature and facial dimensions at most developmental levels. Girls showed greater deviation between skeletal age and chronologic age compared to boys. The author suggests that for optimal orthodontic treatment, timing should be determined from skeletal age assessment and not chronologic age.

On a sample of 50 Montreal girls, Baughan et al. (1979) studied the relationship between growth of the facial complex and stature using longitudinal data from age 6 through 15 years. The respective measurements for stature, cranial base, maxilla and mandible were considered 100% at 15 years, and the remaining data was analyzed in terms of proportion of facial size. Mandibular measurements studied were articulare-gonion, gonion-pogonion and articulare-pogonion. In this study growth velocity curves revealed that the mandibular curves followed the general shape for those of body height. Growth being less from 6 to 8 years, then increasing to the pubertal peak at 10-14 years. The peaks for facial growth occurred 6 months to 1 year after the peak for stature.

On a sample of 20 males and 15 females Bishara (1981) investigated the relationship between standing height and mandibular dimensions. The study used data between the ages of 8 and 17 years. Five dimensions were selected to describe the linear and angular changes in the mandible. The mean age of maximum growth velocity in height was 10.8 years for girls and 13.0 years for boys. Maximum increment in the dimension articulare-pogonion occurred at 10.8 years in girls and 13.8 years in boys. The angular measurements of the mandible did not closely follow those of height. Bishara concluded that at present the methods available do not allow to accurately determine if and when an individual will experience a pubertal spurt. Articulare-pogonion was the only dimension showing a significant association with stature.

Fishman (1982) utilized longitudinal data on 170 females and 164 males from the Denver Child Research Council. Eleven specific skeletal maturity indicators were used for the hand-wrist assessments. Increments in stature and facial dimensions were represented as percentages of total growth. The author found a great variance when data was analyzed by chronologic age. Fishman thus suggested that organization of the data be done by skeletal age. Both maxilla and mandible reached their maximum increment after the statural maximum. Generally facial growth lagged behind height. Both maxilla and mandible showed a close relationship with growth of stature.

Leite et al (1987) used a sample of 19 males and 20 females to study if skeletal age assessment utilizing just the first, second, and third digits are as valid as those using the entire hand-wrist. The statistical analysis indicated that the two methods of assessment differed significantly: skeletal age assessments being more advanced when only the first three digits are used. Though differences existed the three digit assessment never deviated from the entire hand-wrist assessment by more than a few months. The authors therefore concluded that the three-digit method could be used in clinical practice to avoid excessive radiation to the patient, since these digits can be included when taking the head cephalogram.

Moore et al (1990) used the Bolton-Brush data to study the relationship between skeletal maturation (stature and hand-wrist) and craniofacial growth. The sample consisted of 47 females (age 10 through 15) and 39 boys (ages 11 through 16). Peak height velocity in girls occurred between 11 to 12 years and in boys, 12 to 13 years. Stature increments and skeletal assessments of the hand-wrist showed a close association for both sexes. The correlation, between skeletal maturity and facial dimensions were smaller. Though statistically significant, they were not clinically significant to be of any predictive value.

2.8 CERVICAL VERTEBRAE

At birth three ossification centres are typically seen for each vertebrae - one in the body, and one in each lateral vertebral arch (Bench, 1963). The second cervical vertebra (axis) has four ossification centres - one centre for the odontoid, one for the body, and two for the neural arches. Todd and Pyle (1928) suggested that the lateral radiograph of the head and neck is the best view for study of the cervical vertebrae, since the anterior-posterior view presented too many shadows and interpretation problems.

Bick and Copel (1950) presented histologic evidence, obtained from fresh autopsy material, for the presence of true epiphysial cartilaginous plates on the superior and inferior surfaces of the vertebral bodies. Fifteen human specimens were chosen from a larger series, to demonstrate the growth of the vertebral body from the beginning of ossification (8-centimetre foetus) to that of a 23 year female. Specimens at succeeding ages showed the growing osteoblastic area preceded by the superior and inferior epiphysial plates until in a 17 year females the plates began to fuse with the body. The authors concluded that longitudinal vertebral body growth was in the same manner as long bones elsewhere in the body.

Bailey (1952) utilized 100 roentgenograms of normal healthy children to describe the changes seen with growth of the cervical vertebrae (C2-C6) from birth to 14 years. The author also provided a description of the anatomy of the cervical vertebrae and related this to the radiographic appearance of the component parts of the vertebrae as seen on the lateral, oblique and anterior-posterior projections of the cervical spine. The typical cervical vertebrae (C3-C6) consist of an anterior body and posterior neural arch and have a foramen in each transverse process (Figure 1). The first and second vertebrae are modified to allow movement of the head. The body of the atlas fuses with the axes to form the odontoid process. The findings of this study are descriptive (no data available). From observation of the radiographic images of the cervical vertebrae during childhood the author reported the following findings: The centre of the body is normally not ossified at birth but becomes visible radiographically during the first year of life; in the lateral projection the typical cervical bodies appear wedge-shaped (being narrower anteriorly) during childhood; the amount of wedging of the cervical bodies is seen to decrease with age.

Knutsson (1961) published an article describing the vertical and horizontal growth of the vertebral body. Continuous growth of the vertebral bodies is illustrated by means of scatter diagrams of transverse and sagittal measurements of the body of the first lumbar vertebra determined from roentgen films of 175 normal individuals, aged between 1 to 20 years. No other information is provided on sample criteria, method and materials or results. The author concluded that the vertebral body grows in the same manner as the extremities (as opposed to the neutral pattern of growth), since a continuous pattern of growth in dimensions of the body are seen to take place throughout childhood and adolescence.

Tulsi (1971) published the results of a cross-sectional growth study of the vertebral columns of 20 children and 112 adult Australian aborigines. The osteological material for this investigation was obtained from the skeletal collection in the South Australian Museum in Adelaide, Australia. The vertebral columns of the children (no gender separation) were divided into 5 groups based on the maturity of the skeleton as determined by dental and epiphysial criteria: group I (2-4 years) 3 columns; group II (6-7 years) 3 columns; group III (9-12 years) 6 columns; group IV (14-15 years) 5 columns; and group V (17-19 years) 3 columns. The following dimensions were measured for vertebrae 2-24 (C2-L5): transverse and sagittal diameter of the vertebral foramen; middle

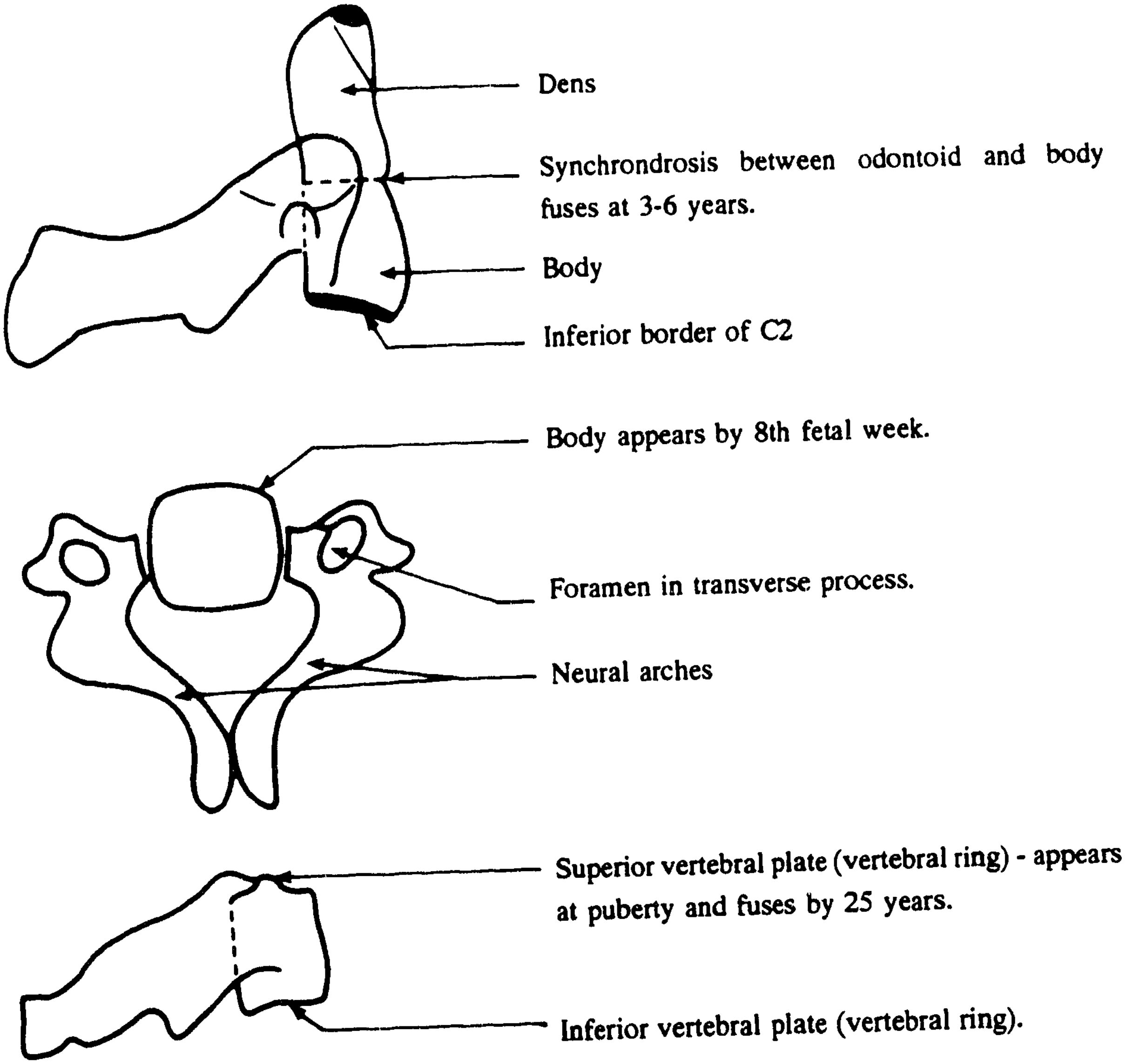


Figure 1: Diagrams of the normal anatomy of the cervical vertebrae.

A. Sagittal view of the 2nd cervical vertebra (C2).
B. Transverse view of typical cervical vertebra C3 to C6.
C. Sagittal view of typical cervical vertebra C3 to C6.

(Redrawn from Bailey, D.K., Radiology 59:712, 1952).

vertical height of the vertebral body; inferior transverse and sagittal diameter of the vertebral body; and volume of the vertebral body. For comparisons, mean values and range were calculated for each group and increases from childhood to maturity were expressed as a percentage of the adult values.

Of the results reported, the findings of relevance to this investigation of the cervical vertebrae are: except for the foramina, growth of the vertebral column follows the general somatic pattern of growth (56% of adult size at 2-4 yrs, 73% at age 6-7, 76% at age 9-12, 91% at age 14-15, and 98% at age 17-19; the vertebral bodies showed periods of accelerated growth in early childhood (22% increase between stage I and II) and at puberty (a 15% increase in dimensions between stages III and IV); the growth of the foramina follows patterns of neural growth (attaining 95% of the adult size by 6-7 years). Changes observed in the cervical vertebral bodies between group I (2-4 yrs) and group VI (adult) were: 39-45% increase in vertical height, 20-33% increase in sagittal diameter, and 6-12% increase in transverse diameter. The inferior transverse and sagittal diameters attain their adult size soon after puberty (by age 14-15), but vertical height of vertebral bodies showed further increases between groups IV and V (14-15 yrs and 17-19 yrs). When considering these latter findings, it must be remembered that there was no gender separation for this study sample, and hence, the mean values reflect maturity patterns of both the early maturing females and late maturing boys. In his concluding remarks, the author stated that since earlier growth studies on the Australian aborigine have not shown ethnic peculiarities, the findings of this sample may be applied to other populations.

Lamparaski (1972) conducted a cross-sectional study on a sample of 69 male and 72 female Caucasians to develop maturity indicators for assessment of skeletal age from maturational changes of the cervical vertebrae. The sample for this study was selected from files of 500 patients attending the orthodontic department at the School of Medicine, Pittsburgh University. The selection criteria required that both the chronologic and skeletal age be within six months of the age under study. Lateral cephalograms of the individuals were used to study cervical vertebrae C2-C6 (Figure 2) for maturational changes from age 10 through 15 years. For each age and sex the cephalograms were arranged in sequence from the least to the most mature, as based on the vertebral development. The middle most or "anatomic median" was selected such that it be the most representative of vertebral maturation and was designated the "standard" for that age. This was repeated separately for each sex and age group from 10 though 15 years. Lamparaski developed a series of six standards each for males and females for assessment of skeletal age from the cervical vertebrae. The maturity indicators described for the standards are the same for both males and females, except that females reach the different levels of maturity earlier as compared to boys. The maturity indicators for skeletal age assessment from the cervical vertebrae were based on the following:

(1) The initiation and development of concavities in the lower border of the vertebral bodies two to six.

(2) The change of shape of the bodies from a rhomboid (tapering from posterior to anterior), to a rectangular form, to a square, and finally acquire a shape which has a vertical dimension that is greater than the horizontal dimension.

Lamparaski then checked the reliability and validity of the standards developed for cervical vertebrae skeletal age assessments on a sample of 25 males and 25 females, against skeletal age assessment made from the hand-wrist in the same individuals. He found the cervical vertebrae to be as reliable and valid as the hand-wrist radiographs for assessing skeletal age (r=0.9). The author stated in his conclusions that actual measurements of dimensions of the vertebrae are not important, and recommended an inspectional method be used where the vertebrae of the case under study are compared with the six standards developed for both males and females.

O'Reilly and Yanniello (1988) using these cervical standards of Lamparaski investigated the relationship of the stages of cervical vertebral maturation to growth changes in the mandible at puberty. They used annual lateral cephalometric radiographs in a sample of thirteen females from the Bolton-Broadbent Growth Study of Cleveland aged 9 to 15 years. The mandibular dimensions investigated were: mandibular length (articulare-pogonion); corpus length (gonion-pogonion); and ramus height (articular-gonion). To determine the relationship of stage of vertebral maturation to mandibular growth an analysis of variance for repeated measurements was performed on each dependent variable. Statistically significant increase in mandibular length, corpus length and ramus height were reported in association with specific maturation stages in the cervical vertebrae. For mandibular length significant size increases were seen between stages 1-2, 2-3, and 3-4. For corpus length the increase occurred in stages 1-2, and 2-3, and for ramus height between stages 1-2. On average cervical vertebral stages 1-3 occurred prior to peak velocity and stages 2-3 in the year immediately preceding peak growth velocity.

Hellsing (1991) conducted a cross-sectional study on a sample of 107 children (56 girls & 51 boys) and 22 adults (12 females and 10 males) to determine the relationship between statural height and cervical vertebrae dimensions at different ages. The sample of children were divided into three age groups 8 (18 girls & 20 boys), 11 (23 girls & 15 boys) and 15 years (15 girls & 16 boys). The subjects were free of any disease and had not received any orthodontic treatment. Thirteen height and length measurements of the cervical vertebrae (posterior vertical height C3-C6, anterior vertical height C3-C6 and inferior length C3-C6) were made from lateral skull radiographs taken with an enlargement of 13%. The statural height measurement for ages 8 and 11 showed a

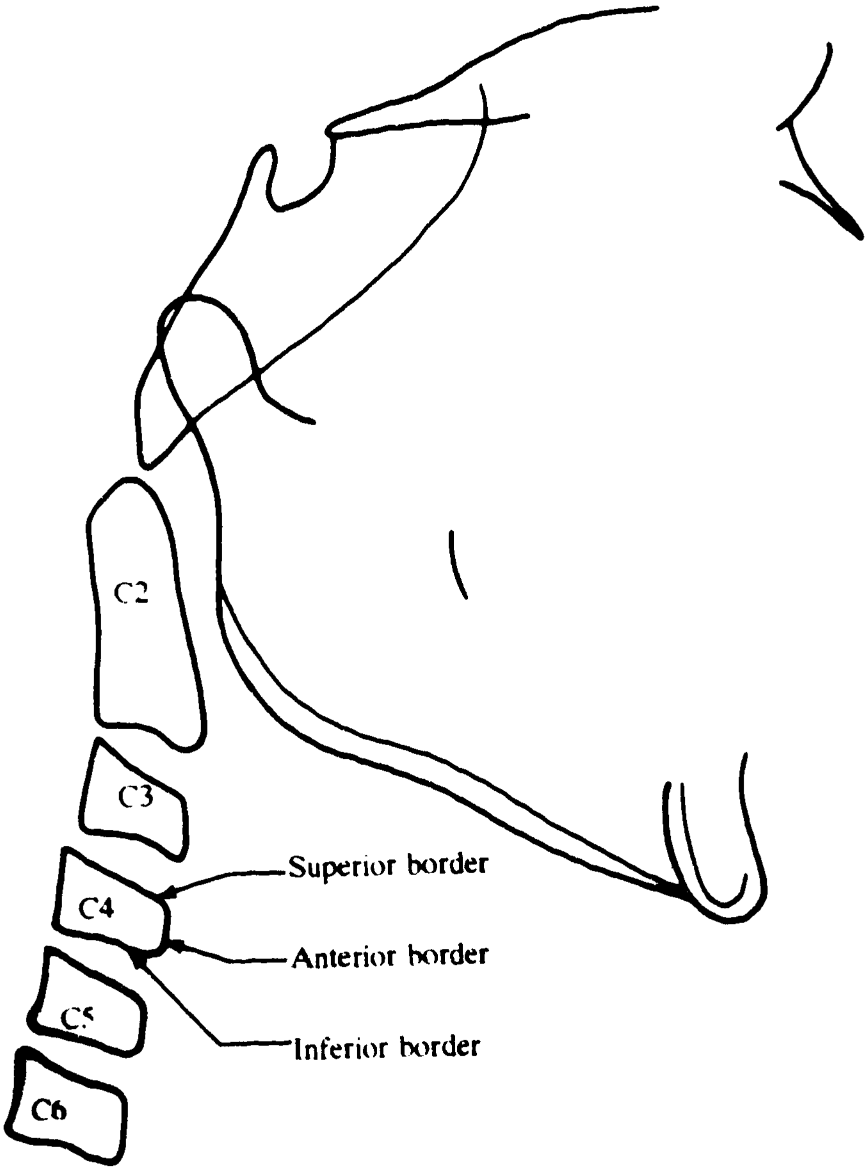


Figure 2: Typical appearance of cervical vertebrae C2-C6 as seen on the lateral cephalogram.

significant correlation with height of the 2nd vertebrae ($r = 0.55$ and 0.73 for $p < 0.001$ respectively) and to the posterior anterior height and length of vertebrae bodies C3-C6 (lowest r value - 0.36 at $p < 0.05$ for inferior length of C4, and the highest value of $r =$ 0.78 for posterior vertical height C3). However, no correlations were found for vertebral size and body height at 15 years. Vertebral body height was greater for girls at age 8, 11 and 15 years, but in adults all dimensions recorded for cervical vertebrae were greater for men. The cervical vertebral bodies for females matured earlier than males. At age 15 for females both the cervical vertebrae dimensions and body height had achieved their adult dimensions. However, in boys considerable increases were seen to occur in both stature and vertebral body dimensions after age 15 years. The author of this study concluded that the results of this cross-sectional study suggest the possible use of cervical vertebrae dimensions for growth predictions.

Mitani and Sato (1992) utilized longitudinal data from 33 Japanese females between ages 9 to 14 to relate the growth characteristics of the mandible during puberty with the growth of the cervical vertebrae, hand bones, hyoid bone, and standing height. The sample, selected from the Tohoku University Dental School Department of Orthodontics files, each had annual records consisting of: cephalograms, hand-wrist radiographs, and body height records. Characteristics of mandibular, cervical vertebral and hand growth were represented by the following linear dimensions respectively: condylion - gnathion for mandibular length; the sum of the mid-vertical heights of cervical vertebral bodies C2 through C5; and sum of the lengths of the metacarpals and phalanges for all the digits of the hand.

Stature showed the highest correlations to both hand growth and vertebral maturation up to age 11 (0.88 and 0.85 respectively); by age 14 this association had weakened more markedly for the hand-bones than the vertebra ($r=0.56$ and 0.76

respectively). Mandibular length related more strongly to stature than to hand-bones and cervical vertebrae (r=0.76, 0.70, 0.59 respectively at age 11); all associations weakening after age 11, this being most marked for hand-bones (r=0.55, 0.27, 0.35 respectively at age 14). The relationships between growth of the hand-bones and vertebrae showed a similar trend, the correlations being highest at age 11 (0.76) and lowest at age 14 (0.45). The other findings of this study were: the majority of the sample experienced maximum growth velocity of the maturity indicators between 9 and 12 years; the amount and timing of the mandibular peak showed the greatest variation between individuals; growth of the hyoid bone did not correlate well to any other maturity indicator.

2.9 SUMMARY OF LITERATURE REVIEW

The presence of a craniofacial growth spurt at adolescence has been established by many investigators (Nanda 1955, Bambha 1961, Maj and Luzi 1964, Johnston et al 1965, Woodside 1969, Thompson 1971). During this period of accelerated growth, increments in the mandible are of greater magnitude than that of the maxilla (Thompson 1971), thus a growth differential exists between the jaws. Early intervention and utilization of this growth differential may improve the prognosis for certain CII malocclusions of skeletal origin. To obtain optimal results in these situations careful treatment planning is required, so that orthodontic treatment may be provided during the time rapid facial growth. Growth considerations are also of importance in treatment planning for Class III malocclusions, extraction verses non-extraction treatment, surgical orthodontics, retention and post-retention prognosis. It is apparent from the above discussion that orthodontic treatment planning for the growing individual often requires estimation of the growth status achieved and prediction of the time and magnitude of the remaining growth potential for the individual.

Individuals show great variation in the rate, timing and duration of the adolescent growth spurt when related to chronological age, hence methods which measure the biologic age of an individual are preferred when making estimation of the developmental status of a child. Physiologic variables available for assessment of biologic include: skeletal age, growth spurt in stature, weight increments, dental development, and secondary sexual characteristics. Of these, the most commonly used maturity indicators are skeletal age assessment of the hand-wrist radiograph and the pubertal growth spurt in height.

The timing of the adolescent growth spurt in stature has been demonstrated to hold a fairly strong relationship with the timing of maximum increment in facial dimensions (Nanda 1955, Bambha 1961, Tofani 1972, Diagle 1974, Thompson 1971, Thompson and Popovich 1974). The adolescent growth spurt in height commences in females between 10-11 years, peaks at about 12 years and is virtually completed by 15 years. Gender differences have been reported, males show a delay of about 2 years for all these events when compared to females. Thus, any investigations into growth at puberty must separate the sample on the basis of gender. The age range over which data must be collected will also differ for males and females, females needing a shorter time span for completion of their growth. The ideal time period for observation of maturation of females is 10 through 15 years, since the majority of females will have experienced the full range of their pubertal maturational changes in this period. In relating peak growth velocity of the mandible to stature, most authors agree that the pubertal maximum for the mandible occurs 9-12 months after that in body height (Nanda 1955, Bambha 1961, Tofani 1972, Diagle 1974). This finding is not in agreement with other investigators (Hunter 1966, Grave 1973, Thompson 1971, Thompson and Popovich 1974) who report that the maximal increment in height and facial dimensions occurred at the same time. A rise in body height increment is considered to be a reasonably good indication that the pubertal spurt in facial dimensions is imminent. This method requires frequent and careful determinations of height increments for construction of velocity curve for an individual. Although useful, the limitations of this method are: the time factor required in the clinical setting for accumulation of longitudinal data for each individual before commencement of treatment; and it may be difficult to establish if an individual had already experienced their pubertal growth spurt. Standards of growth for stature have been developed to assist in the clinical evaluation of the physical growth status achieved, and to predict the rate and amount of growth still remaining in stature. Since the use of increments in stature is well established for use as a maturity indicator, the validity of using the cervical vertebrae for assessment of biologic age may be established by determining the correlation between vertebral age and stature increments.

At present, the most commonly used method for estimation of biologic age is skeletal age assessment based on the maturational changes of the hand-wrist bones. A single radiograph of the hand-wrist may provide a great deal of information as to the maturational status achieved by an individual. The two most commonly reported methods for assessment of skeletal age from the hand-wrist radiograph are the Greulich and Pyle Atlas method and the Tanner-Whitehouse Scoring method. Results of inter-investigator and intra-investigator reproducibility studies suggest that both methods are equally reliable and reproducible (Acheson 1966, Roche and Johnson 1969, Roch et al 1971, Thompson 1971). The inter-investigator error was greater than the intra-investigator error for all the studies, thus, it was recommended that for research purposes where possible the skeletal assessments should all be made by one investigator. The 95% confidence limits (and hence intra-investigator error) were lowest for investigators who interpolated to "between-plate" ages for radiographs that did not match the standard (Acheson 1963). Roche et al

(1971), Thompson (1971) and Lamparaski (1972) have all used interpolation for between standard assessments where necessary. Thus, the author of this investigation feels that interpolation is justified for skeletal age assessments.

Although the use of hand-wrist skeletal age assessments is recommended by a majority of investigators (Grave & Grown 1976, Bjork & Helm 1967, Gilbert 1966, Liebgott 1970, Johnston 1965, Fishman 1979, Moore 1990), others suggest that due to the low correlations, skeletal age assessments are of limited value as predictors of events in the craniofacial area (Bowden 1976, Rose 1960, Thompson 1971, Thompson & Popovich 1973, Houston 1980).

It is apparent from review of the literature that presently no one maturity indicator is considered definitive in evaluating the maturity status of an individual during adolescence. Hence, further investigations are still required to provide a better understanding of the relationships. The cervical vertebrae have been shown to grow in the same manner as long bones (Bick and Copel 1950, Knutsson 1961, Tulsi 1971) and have been shown to hold a significant relationship with stature (Hellsing 1991, Mitani and Sato 1992), hand-wrist development (Lamparaski 1972, Mitani and Sato 1992), and to mandibular length increments (O'Reilly et al 1988, Mitani and Sato 1992). Skeletal age assessments utilizing the cervical vertebrae may prove to be a useful and accurate adjunct in evaluation of a child's maturational level. However, further investigations are first required on longitudinal samples to determine the reliability and validity of using Lamparaski's maturity indicators for assessment of vertebral skeletal age. The reliability and validity of vertebral age assessments may be tested by determining the correlations between vertebral age, hand-wrist skeletal age and stature increments on a longitudinal female sample aged 10 through 15 years.

CHAPTER 3

MATERIALS AND METHODS

3.1 DESCRIPTION OF THE SAMPLE

The sample for this longitudinal study consisted of 35 females, aged 10 through 15 years, obtained from the files of the serial experimental group of the Burlington Growth Research Centre, at the University of Toronto. The Burlington sample, though not truly random, is considered representative of the population of Canada in racial origin and socio-economic status since it included approximately 85% of all the children residing in the town of Burlington (Progress Report #4, November 1959). The sample selection criteria were; healthy normal Caucasian females, free of any known medical condition or metabolic disease as determined from the health histories, a complete series of annual records available from age 10 through 14 years plus age 16, and no previous orthodontic treatment except for interceptive treatment such as space maintainers, removal of supernumeraries, and serial extractions. Subjects who were missing age 15 data but had age 14 and age 16 data had a mean interpolated value calculated for the variables being studied.

Of the materials available, the data utilized for this study were:

(a) Annual measurements of stature

(b) Skeletal age assessments derived from hand-wrist radiographs

(c) Annual lateral cephalograms.

3.2 MEASUREMENTS OF STATURE

Annual height measurements for each individual taken as close as possible to the month of the child's birthday were made by one operator using a standardized technique.

Height was measured to the nearest 1/4", with the individual standing with head erect and eyes horizontal, using an anthropometer attached to a standard balance scale.

Height measurements were obtained from annual recordings and the measurements were converted to centimetres (Appendix "A"). The mean, standard deviation and range for height were calculated for each age 10 through 15. Yearly increments were calculated for stature and a velocity curve constructed by chronologic age. Under each chronologic age the appropriate cervical vertebral skeletal and hand-wrist age was entered for this female sample.

3.3 SKELETAL AGE ASSESSMENTS USING THE HAND-WRIST RADIOGRAPH

Each individual had annual hand-wrist radiographs taken by a standardized technique. The right hand was placed palm down and radiographed at a constant distance of 29.5 inches between the anode and film. The exposure was for one second at 65 kilovolts and 10 milliamperes.

All hand-wrist radiographs (35x6 = 210) had previously been assessed for skeletal age by Dr. E. Luks (Graduate Student, University of Toronto, 1969) using the procedure outlined in the Greulich and Pyle Atlas 1959. The radiograph being assessed was first compared with the standard of the same gender and nearest skeletal age in the Greulich and Pyle Atlas and a detailed comparison of the bones and epiphyses was preformed to determine the Greulich and Pyle standard that most closely approximated the subject film. If; however, the film did not correspond exactly with any one standard, but was intermediate between two adjacent standards, then the age assigned to the film would also be intermediate between the standards.

All hand-wrist radiographs had been assessed by a single operator in years and months, and were interpolated to the nearest 3 months where necessary (Popovich, 1990 & 1992). The accuracy of assessments made by Dr. Luks had previously been reported on by Dr. Thompson (Ph.D. Thesis, 1971). The 95% confidence interval was of ± 6 months for the Greulich and Pyle Atlas method for the intra-investigator error study, and this was considered to be acceptable. To further determine the accuracy of these previously recorded hand-wrist (carpal) assessments, a total of 64 hand-wrist radiographs were obtained and assessed by the author of this investigation. The inspectional method was followed as described previously. The age of the radiograph under study was not disclosed to this investigator, and the assessments were made in a darkened room on a radiographic illuminator. Absolute differences were calculated between assessments made by Dr. Luks and the investigator of this study, (Appendix "B") with the results of these inter-investigator error studies subjected to double determinations analysis. With the accuracy of the previously recorded hand-wrist assessments proven, permission was obtained from Dr. Popovich, Director, Burlington Growth Centre, to use the previously recorded hand-wrist assessments. The means, standard deviation, range, and standard error of the mean were calculated for the sample's hand-wrist skeletal age assessments.

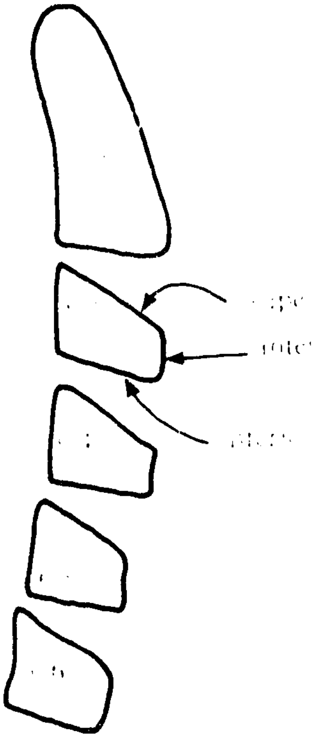
3.4 SKELETAL AGE ASSESSMENTS USING CERVICAL VERTEBRAE

Cervical vertebral skeletal age assessments were made from the annual lateral cephalometric radiographs using the maturity indicators described by Lamparaski (1972).

The annual lateral cephalograms were taken using a Thurow Cephalostat with; a subject-anode distance of 60 inches, subject to film distance of 15 cm, and exposure of 120 kilovolts and 25 milliamperes for 1.0 seconds (Burlington Growth Centre, Progress Report 1957-1958).

Cervical vertebrae bodies 2 to 6 (C2-C6) were traced from annual lateral cephalograms for each subject from age 10 to 15 years on 0.003 inch matte cellulose acetate paper with 0.5mm black lead pencil. All tracings were done on an illuminated box in a darkened room by the investigator of this study. A total of 210 (35x6) tracings were made for this sample and skeletal age assessments were made from the tracings using Lamparski's guidelines. When using Lamparaski's maturity indicators, attention was paid to the following characteristics; development of concavities in the inferior surfaces of the vertebral bodies, change in shape of the bodies from rhomboid form (tapering from posterior to anterior) to a rectangular form, then to a square form, and finally, attainment of a vertical dimension that is greater than the horizontal dimension (Figures 3-8). The representative characteristics which define each cervical vertebral age from 10 through 15 years are depicted in figures 3 through 8.

All cervical vertebral skeletal age assessments were made by the investigator of this study, having knowledge only of the serial number of the individual at the time of assessment (Appendix "C"). A technique similar to that of the inspectional method of Todd for the Greulich and Pyle Atlas was used. The cervical vertebral bodies (C2-C6) of the subject being assessed were compared with the six developmental stages for females as described by Lamparaski, 1972 (Figures 3-8). The maturational changes in the vertebral bodies occur in an orderly sequence, so that the presence or absence of the maturity indicators described for each vertebral age was determined for each film. The vertebral stage that most resembled the case under study was determined, and then the skeletal age of that developmental stage (vertebral age 10, 11, 12, 13, 14 & 15) was assigned to that individual. If, however, the development status of the subject did not correspond exactly to that of any one of the six vertebral stages, but was intermediate between two adjacent stages, then the age assigned was correspondingly intermediate ("interpolated"). Where necessary, interpolation to "between-stage" age was made to the

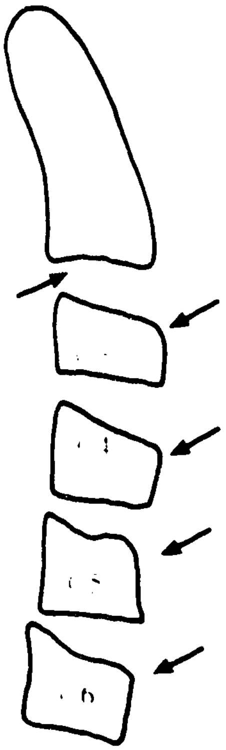


Characteristics of

VERTEBRAL AGE 10

1. All inferior borders of bodies are flat.
2. Greater posterior height than anterior
3. The superior border taper from posterior to anterior (wedging of bodies C2 - C3).

Figure 3: Illustration of maturity indicators of the cervical vertebrae for a female skeletal vertebral age 10 years (based on guidelines described by Lamparaski, D.G.: M.Sc. thesis, University of Pittsburgh, 1972).

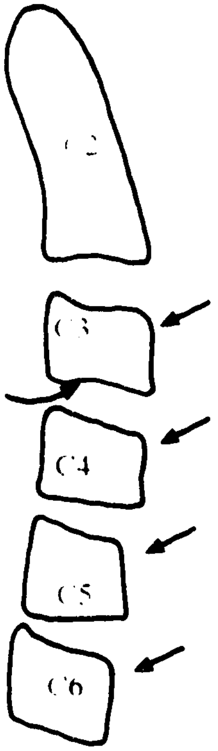


Characteristics of

VERTEBRAL AGE 11

1. Development of a distinct concavity in the inferior border of the 2nd vertebrae
2. Increasing anterior vertical heights.

Figure 4: Illustration of maturity indicators of the cervical vertebrae for a female skeletal vertebral age 11 years (based on guidelines described by Lamparaski, D.G.: M.Sc. thesis, University of Pittsburgh, 1972).

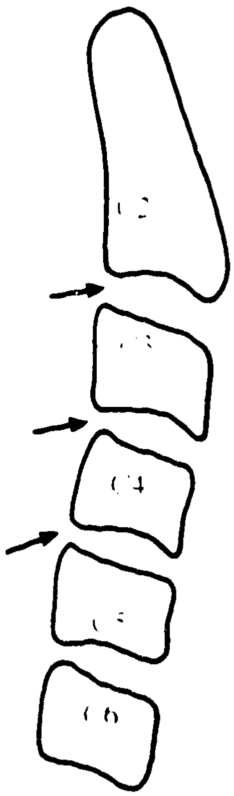


Characteristics of

VERTEBRAL AGE 12

1. A concavity has developed in the inferior border of the 3rd vertebral body
2. Anterior heights still increasing, with reduction in superior taper
3. All other inferior borders are still flat

Figure 5: Illustration of maturity indicators of the cervical vertebrae for a female vertebral age 12 years (based on guidelines described by Lamparaski, D.G.: M.Sc. thesis, University of Pittsburgh, 1972).



Characteristics of

VERTEBRAL AGE 13

1. Distinct concavities on inferior border of bodies 2, 3, and 4

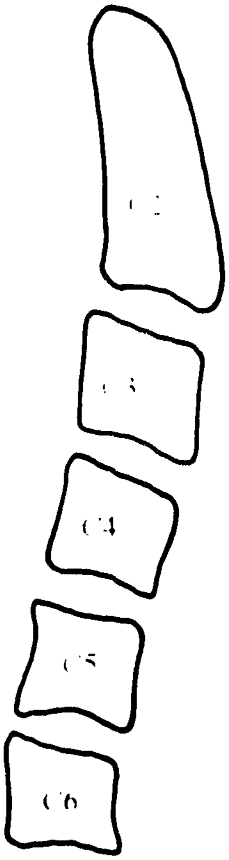
2. Development of concavities just initiated in bodies 5 and 6

3. Body shape approximates to a rectangle

Figure 6: Illustration of maturity indicators of the cervical vertebrae for a female skeletal vertebral age 13 years (based on guidelines described by Lamparaski, D.G.: M.Sc. thesis, University of Pittsburgh, 1972).

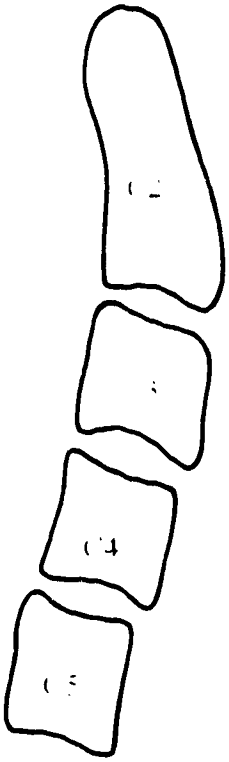
Characteristics of

VERTEBRAL AGE 14



1. Well developed concavities on inferior surface of all 6 bodies
2. Anterior height approaches posterior, body shape approximates to a square

Figure 7: Illustration of maturity indicators of the cervical vertebrae for a female skeletal vertebral age 14 years (based on guidelines described by Lamparaski, D.G.: M.Sc. thesis, University of Pittsburgh, 1972).



Characteristics of

VERTEBRAL AGE 15

1. Increased vertical height of all bodies
2. Body height is greater than width
3. All concavities on inferior borders have deepened

Note: Because of increased body height, the 6th cervical vertebrae is not always radiographically visible in the lateral cephalometric projection.

Figure 8: Illustration of maturity indicators of the cervical vertebrae for a female skeletal vertebral age 15 years (based on guidelines described by Lamparaski, D.G.: M.Sc. thesis, University of Pittsburgh, 1972).

nearest 6 months. For example, if vertebral development status of an individual was between 10 and 11 years, interpolation was done to 10 years 6 months depending on the degree of development achieved. For the purpose of statistical analysis, all skeletal age assessments were converted to decimal age. The mean, standard deviation, range, and standard error of the mean were determined for cervical vertebral skeletal age assessments.

To determine the intra-investigator error, assessments for vertebral age were repeated after two to three weeks for all 210 tracings made by the investigator of this study (Appendix "C"). The exact same procedure as outlined above was followed for these second determinations of vertebral age. The resultant average age of the first and second determinations and the absolute difference are recorded in Appendix "D" for all assessments. Correlation coefficients and paired 't' tests at the 95% confidence interval were conducted to determine the reliability and reproducibility of using cervical vertebrae maturity indicators for assessment of skeletal age.

3.5 ASSESSMENT OF THE RELATIONSHIP BETWEEN VERTEBRAL AGE AND HAND-WRIST AGE

To test the validity of using Lamparaski's guidelines for assessment of skeletal age from the cervical vertebrae, several statistical tests were conducted to determine the relationship between vertebral skeletal age and hand-wrist age:

(i) construction of a scatter diagram of vertebral age and hand-wrist skeletal age

(ii) Pearson correlation coefficient was calculated to determine the strength of the relationship between the above variables

(iii) The paired 't'-test was used to determine if there was a significant difference between the skeletal age assessments using the two different methods

3.6 ASSESSMENT OF THE RELATIONSHIP BETWEEN CERVICAL AGE AND STATURE

The validity of utilizing the maturational changes of the vertebral bodies for assessment of skeletal age was further tested by determining the presence of any relationship between vertebral age and increase in stature using the following statistical methods:

(i) construction of a scatter diagram of stature and vertebral age

(ii) to determine the strength of the relationship between these variables, the correlation coefficients were calculated.

3.7 LIMITATIONS OF THE STUDY

Given the population of the Burlington Growth Study, true randomization was not possible. Coupled with the selection criteria of annual radiographic images and demographic data for 6 consecutive years the study had to select from within established growth studies that may or may not be representative of the general population.

Since annual records of the Burlington Growth Centre were not available for age 15 all data at this age had to be interpolated as the mean between ages 14 and 16. Since growth changes do not always progress at the same steady rate this may result in some inaccuracy; however, since the majority of growth has already been achieved the results may not be too significantly affected.

The 64 hand-wrist radiographs for inter-investigator error were not randomly selected from the 210 available radiographically. This oversight by the investigator may skew the results although the magnitude is likely minimal.

CHAPTER 4

RESULTS

The data accumulation for the variables hand-wrist age (carpal age), cervical vertebral age (vertebral age) and stature for the female sample of this investigation are presented in Appendix "A". The values of vertebral age variable presented in column 3 of this table are the average values derived from the double determinations made for all 210 vertebral skeletal age assessments.

4.1 INTRA-INVESTIGATOR ERROR FOR VERTEBRAL AGE

The paired vertebral age assessments made by the investigator of this study are recorded in Appendix "C", along with the average vertebral age and the absolute difference between the two readings. Appendix "D" displays the calculation of the intra-investigator result error studies at the 95% confidence interval for vertebral age assessments. The average absolute difference between the first and second readings for vertebral age was 0.14 ±0.67 years at $p=0.05$. The maximum difference between vertebral age assessments was 0.5 years and the standard deviation was 0.23 years.

Two further statistical tests (Table 1) were employed to assess the repeatability of vertebral age assessments. Firstly, the paired samples 't'-test was applied to check the hypothesis that the actual value of the differences between the two means compared is not significantly different. Secondly, the Pearson correlation coefficient was calculated for these assessments. The results of both the paired 't'-test (0.053 with $p < 0.05$) and the correlation coefficient ($r = 0.99$) indicate excellent reliability in the skeletal maturity technique for vertebral age assessments. Although, the results of all statistical tests demonstrate high reliability and reproducibility of using the guidelines for vertebral skeletal age, the occurrence of vertebral age 15 could not be established in 77.1% of

TABLE 1

Results of reliability tests for intra-investigator cervical vertebral age assessments

Method 1: paired samples t-test

using actual differences between assessments at $p=0.05$

number of observations	210.
degrees of freedom (n-1)	209.
maximum difference	0.5000
mean difference	0.01
standard error of the mean	0.19
"t"-value	0.053

Method 2: Pearson Correlation Coefficient

number of observations	210.
degrees of freedom (n-2)	208.
correlation coefficient	0.9973

the females in this sample even by chronologic age 16 (Table 2). In contrast, 83% of the females have achieved hand-wrist skeletal age 16 at chronologic age 16 years. The majority of females (82.9%) in this longitudinal investigation appear only to achieve the maturational indicators for vertebral age 14 at the termination of their adolescent growth spurt. Lateral cephalograms at chronologic age 19-20 were examined for several individuals to determine if further maturational changes may have occurred in the cervical vertebral bodies after cessation of statural growth. Figure 9 illustrates the cervical vertebrae of an individual who did not demonstrate the attainment of vertebral stage 15 even at age 19. Only one of the three radiographs examined progressed to show this final stage of vertebral development with increasing age.

TABLE 2

Number of individuals in the sample who did not attain the final maturational changes of the vertebrae by chronologic age 16 (n=74)

Chronologic Age (Years)	Vertebral age (Years)	Number of Individuals	%
16.0	< 15.0	27	77.1
16.0	< 14.75	23	65.7
16.0	< 14.50	18	51.4
16.0	< 14.0	6	17.1

4.2 INTER-INVESTIGATOR ERROR FOR CARPAL AGE

The results of the double determination for 64 hand-wrist skeletal age assessments made by two different investigators, Dr. E. Luks and the investigator of this study, are recorded in Appendix "B". The absolute amount of difference between the two assessments was calculated to be 0.37 ±0.14 years at the 95% confidence interval (Appendix "E").

The Student 't'-test was also applied to the two sets of readings to determine if there was any significant difference between these assessments of hand-wrist skeletal age using the Greulich and Pyle Atlas method. For 63 degrees of freedom, the calculated 't' statistic is 0.67 significant at $p < 0.05$ (Table 3). The resultant correlation coefficient of 0.99 again confirm the findings of the above tests that there was no statistically significant difference between the hand-wrist assessments made by Dr. E. Luks and those by the investigator of this study. These results indicate excellent reliability of the skeletal maturity inter-examiner assessments made from the hand-wrist films using the

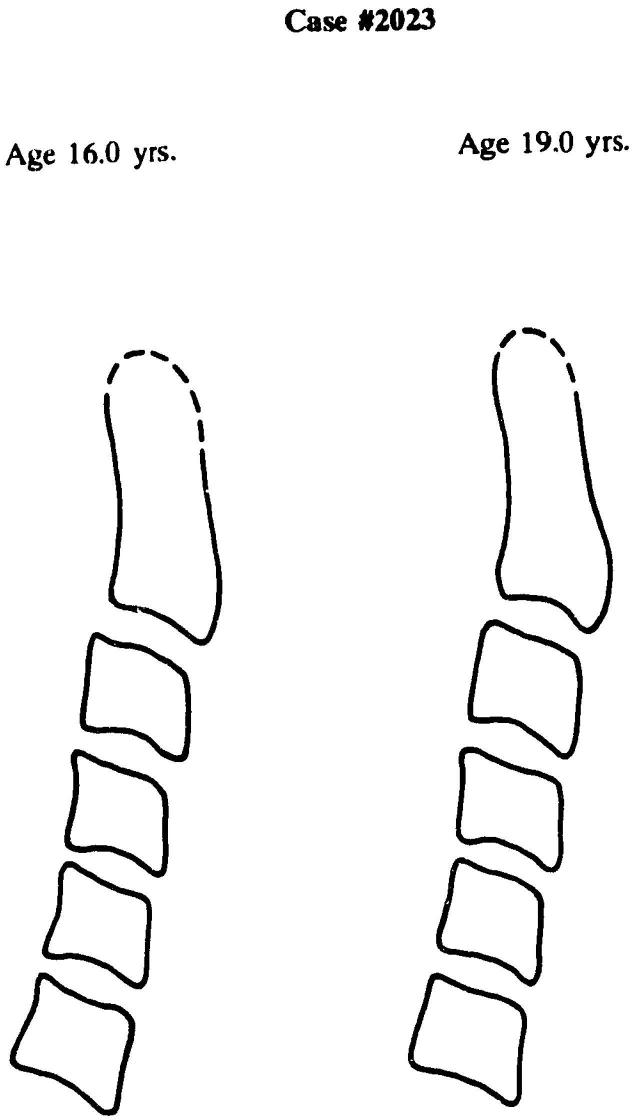


Figure 9: Cervical vertebral bodies of an individual who did not attain the final maturational changes of vertebral age 15.

TABLE 3

Results of reliability tests for inter-investigator error studies for hand-wrist skeletal age assessments

Method 1: paired samples t-test

using actual difference between assessments at p=0.05

number of observations	64.
degrees of freedom (n-1)	63.
maximum difference	1.2500
mean difference	-0.04
standard deviation	0.49
standard error of mean	0.06
"t" value	0.67

Method 2: Pearson Correlation Coefficient

number of observations	64.
degrees of freedom (n-2)	62.
correlation coefficient	0.9986

Greulich and Pyle Atlas method. This methodology along with the results therefore validates the inclusion of the previously recorded hand-wrist assessments into this study.

4.3 MEANS, STANDARD DEVIATIONS AND RANGE

Table 4 records the mean values, standard deviation, range, standard error of the mean for the stature variable. For this sample of 35 Canadian Caucasian females, the mean body height at age 10 was 139.21 cm with a standard deviation of ±5.78 along with a range from 120.65 to 147.3 cm. The interpolated mean stature measurement at age 15 was 160.98 cm with a standard deviation of ±6.05 and a calculated range of 145.10 to

170.83 cm. Thus, the average height gained from 10 to 15 years was 21.77 cm for this female sample with a derived standard deviation of 5.925 cm. The large values for both standard deviation and ranges indicate that there is significant variability in stature in each age group with a range of height gain in height from 16 to 28 cm.

TABLE 4

Means, standard deviation, range, and standard error for stature for a sample of 35 females (cm)

Chronological Age (Yrs.)	Mean	S.D.	Range	S.E.
10	139.21	5.78	120.65-147.32	0.98
11	145.61	6.62	126.36-156.21	1.12
12	152.51	6.68	132.71-162.56	1.13
13	157.32	6.44	137.16-167.64	1.09
14	160.34	6.14	142.87-170.18	1.04
15 extrapolated	160.98	6.07	145.10-170.82	1.03
16	161.61	6.05	147.32-172.72	1.02

Figure 10 depicts the annual statural increments in height that were derived for the sample as a mean velocity curve. The peak height velocity (PHV) which was the single greatest increment in any year was 6.9 cm that occurred between age 11 and 12 for this female sample. Subsequent to the PHV there is a deceleration in height velocity and followed by levelling off after the age interval 14-15. Since the height increment from age 15 to 16 was only 0.63 cm, age 15 can be considered the completion of the pubertal growth spurt. The onset of the adolescent growth spurt cannot be determined for this sample since this study did not include data below chronologic age 10. Table 5 presents data at the various chronologic age as percentage of the adult height achieved. Since, the

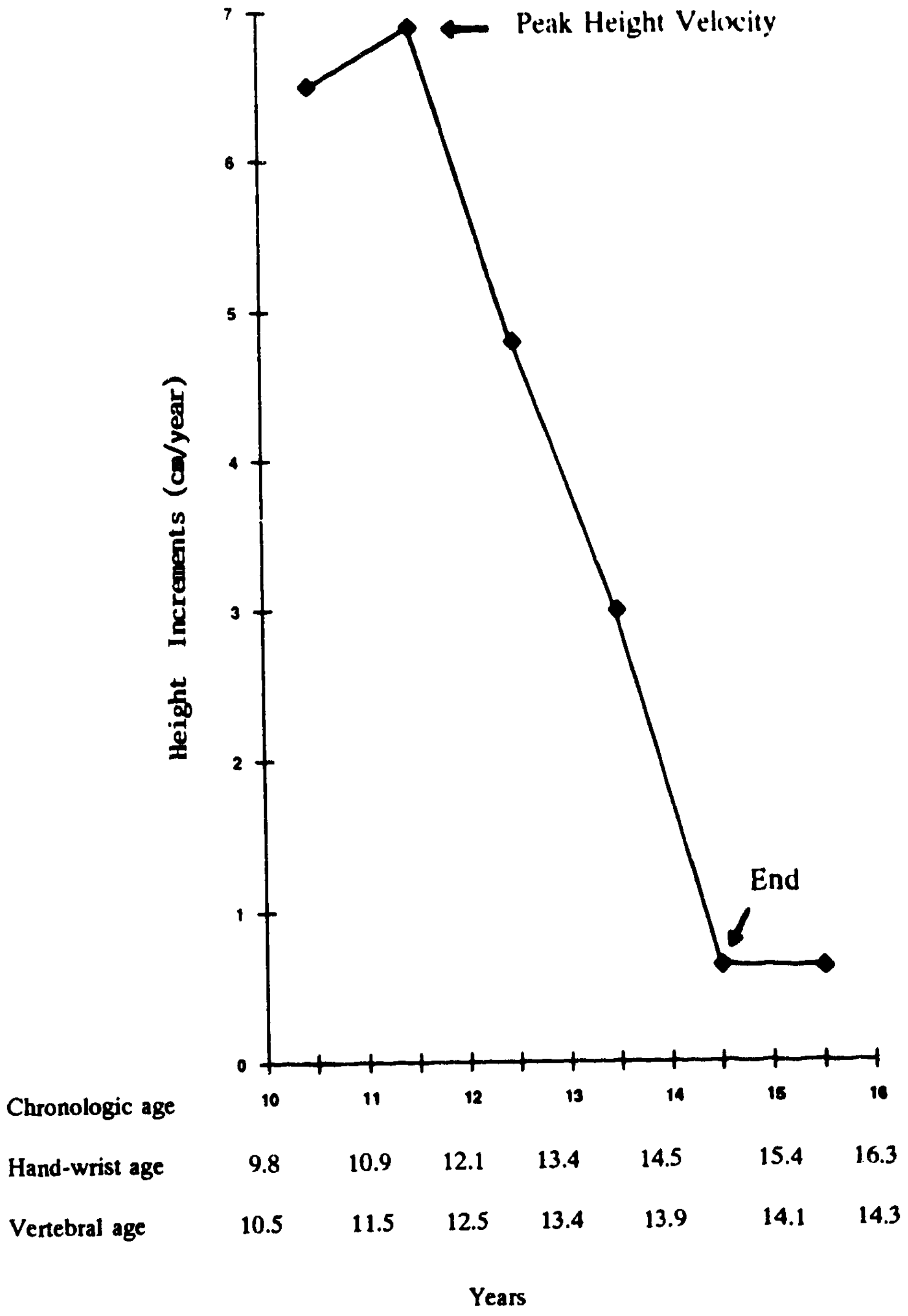


Figure 10: Mean Velocity curve for female stature growth spurt.

change in stature is minimal from age 15 to 16, the height measurement at age 15 may be considered as the adult value when the percentages of completed growth are considered. At age 10, the average female in this study had attained 86.5% of her adult height. The values at age 11, 12, 13 and 14 are 90.5%, 94.7%, 97.7% and 99.6% respectively. Thus, the majority of growth has already occurred by chronologic age 14.

TABLE 5

Percentage of the ultimate adult height achieved at chronologic age 10-15 years for 35 females (Stature at 15 is considered 100% and the other values are expressed as % of the height at 15)

Chronologic Age (Years)	Mean Height (cm)	Percentage of Achieved Height %
10	139.21	86.5
11	145.61	90.5
12	152.51	94.7
13	157.32	97.7
14	160.34	99.6
15	160.98	100

Tables 6 and 7 present the mean, standard deviation, range, and standard error for hand-wrist skeletal age using the Greulich and Pyle Atlas method and the cervical vertebral skeletal age using Lamparaski's guidelines respectively. At chronologic ages 10, 11, and 12 the skeletal age assessments made from the cervical vertebrae are approximately 0.5 years in advance of the hand-wrist assessments using the Greulich and Pyle Atlas method, however at age 13, the skeletal age assessments made by the two different methods are almost identical. Thereafter the hand-wrist age assessments are greater than those assessed by the vertebrae. After age 14, the cervical vertebral assessments do not show significant changes, but the bones of the hand-wrist show continuing maturational changes as reflected by the increasing skeletal ages. Comparisons of the range and standard deviations indicate that hand-wrist assessments show greater individual variation than skeletal age assessments made from the cervical vertebrae. The standard deviation is lower for vertebral assessments at all ages (S.D. 0.52-0.83) compared to those for hand-wrist ages (S.D. 0.63-1.00). Peak height velocity occurred at chronologic and hand-wrist age 11.5 years, and at 12.0 vertebral age. The end of the pubertal growth spurt in height

TABLE 6

Means, standard deviation, range, and standard error for skeletal age assessments of the hand-wrists radiograph using the Greulich and Pyle Atlas method (sample = 35 females)

Chronologic Age (Yrs.)	Mean	S.D.	Range	S.E.
10	9.81	0.86	7.66-11.8	0.15
11	10.92	0.81	8.83-12.00	0.14
12	12.10	1.00	10.00-14.25	0.17
13	13.38	0.98	11.00-15.00	0.17
14	14.49	1.00	12.00-16.50	0.17
15 extrapolated	15.39	0.81	13.38-16.88	0.14
16	16.28	0.63	14.75-17.50	0.11

occurred at 14.5, 14.9, and 14.0 years respectively.

TABLE 7

Means, standard deviation, range, and standard error for cervical vertebral skeletal age (sample = 35 females)

Chronologic Age (Yrs.)	Mean	S D.	Range	S.E.
10	10.52	0.52	10.00-11.75	0.09
11	11.53	0.72	12.00-13.00	0.12
12	12.54	0.83	12.50-13.75	0.14
13	13.37	0.80	12.00-14.75	0.13
14	13.91	0.69	13.50-15.00	0.12
15 extrapolated	14.12	0.58	13.88-15.00	0.10
16	14.34	0.52	14.00-15.00	0.09

4.4 CERVICAL AGE vs. CARPAL AGE COMPARISON

The validity of utilizing Lamparaski's guidelines for assessment of skeletal age assessment was tested by application of several statistical tests to skeletal age assessments made from vertebral age and hand-wrist age. Scatter diagrams were first constructed to graphically demonstrate the presence of any relationship between skeletal age assessments made from the cervical vertebrae and the hand-wrist radiographs (Figure 11). Inspection of the scatterplots demonstrates the presence of a positive linear relationship between these variables. To determine the strength of the association between the two variables, the correlation coefficient was computed to be $r = 0.9155$ which indicates the presence of a very high association between skeletal age assessments made from the hand-wrist and the cervical vertebrae.

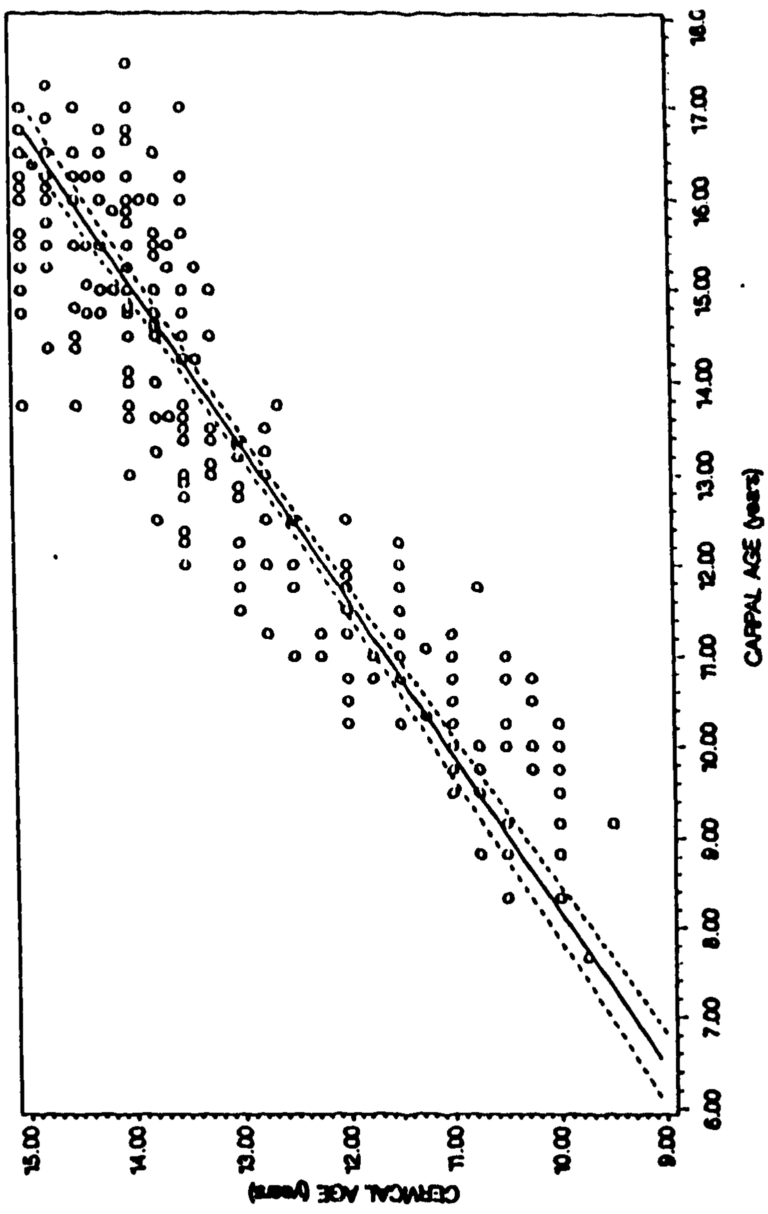


Figure 11: Scatter diagram illustrating the linear regression with 95% confidence limits for hand-wrist age versus cervical vertebral age

The relationship was further tested by computation of the paired 't' test. The interpolated age 15 data was included in the test, hence, the number of observations were 245 and the associated "t" value was 3.8797 at the 0.001 significance level (Table 8). This result indicates that there is no statistically significant difference between the two different methods of skeletal age assessments.

All results indicate that a significant and strong association exists between the skeletal age assessments made from these two different areas of the skeleton, thus, confirming the validity of utilizing Lamparaski's guidelines for assessment of the developmental status of an individual from vertebral maturational changes at puberty.

TABLE 8

Relationship between maturity status of the cervical vertebrae and hand-wrist maturation

Method 1: Paired t-test

using actual differences at p=0.001

number of observations	245.
degrees of freedom	244.
standard deviation	1.17
standard error of the mean	0.0747
"t"-value	3.8797

Method 2: Pearson Correlation Coefficient

number of observations	245.
degrees of freedom (n-2)	243.
correlation coefficient	0.9155

4.5 CERVICAL AGE AND STATURE

The validity of utilizing the cervical vertebral maturation changes for assessment of the physiologic developmental status of an individual at puberty was further tested by determining any association between cervical vertebral age and annual stature measurements. A scatter diagram was first constructed to exhibit the data graphically. Inspection of the scatterplot of height and vertebral age demonstrates the presence of a linear, positive relationship between these variables. The associated correlation coefficient is 0.82, indicating a high positive association between vertebral age and stature (Figure 12). These results again confirm the validity of using the maturation changes of the vertebra bodies for assessment of skeletal age, and hence an estimation of the physiologic maturity level of an adolescent individual.

4.6 RELATIONSHIP OF CERVICAL AGE, CARPAL AGE AND STATURE.

Table 9 presents the correlation coefficients of chronologic age, stature, hand-wrist age and vertebral age, all of which are significant at p=0.01 level. The correlation coefficient for hand-wrist and vertebral age are high (r=0.92), indicating a very strong association between these two methods of skeletal age assessments. However, the highest correlation is r=0.96 for hand-wrist age and chronologic age. Both stature increments and vertebral age show a similar degree of association to chronologic age (r = 0.86, and r = 0.87 respectively), this association being weaker than that for skeletal age. The relationship of stature and hand-wrist age (r = 0.88) is slightly better than that with vertebral age (0.82). All the correlation coefficient are statistically significant at the p=0.01 level.

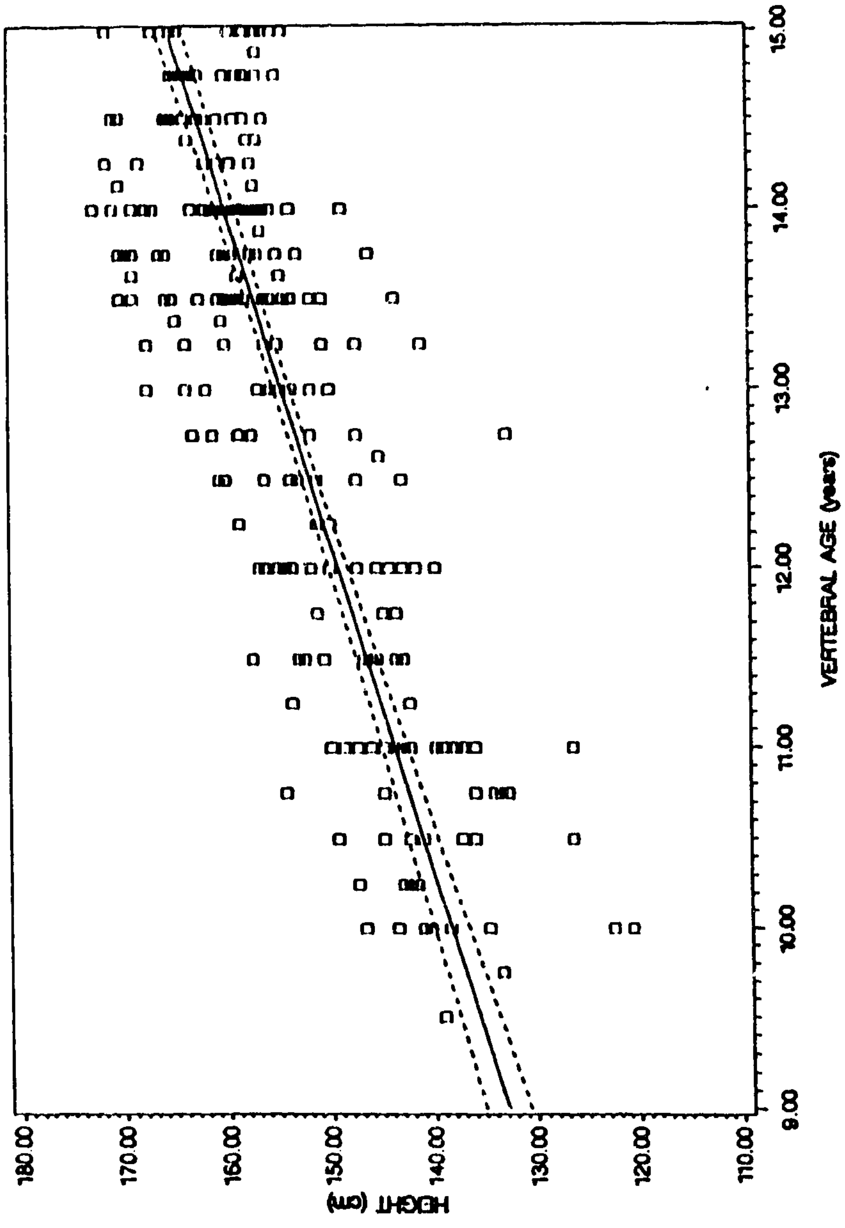


Figure 12: Scatter diagram illustrating the relationship between height increments and vertebral age

TABLE 9

Correlation coefficients of stature, hand-wrist age and vertebral age

(significant at p=0.01)

	Chronologic Age	Stature	Hand-Wrist Age	Vertebral Age
Chronologic Age	---	0.87	0.96	0.86
Stature	0.87	---	0.88	0.82
Hand-Wrist Age	0.96	0.88	---	0.92
Vertebral Age	0.86	0.82	0.92	--

CHAPTER 5

DISCUSSION

A review of the literature indicates that, at present, no one maturity indicator is definitive in evaluating the maturation status of an individual during adolescence. The present study was undertaken, in view of these limitations, to determine if additional information could be gained from another area of the skeleton. Lamparaski (1972) described maturity indicators for the cervical vertebral bodies (C2 - C6) for assessment of skeletal age. Although, Lamparaski's work has been cited in recent publications as a maturity indicator at adolescence, to date, no investigation has been conducted to substantiate his findings. This longitudinal investigation was undertaken to determine the reliability and validity of using Lamparaski guidelines for cervical vertebral age assessments on a sample of 35 Caucasian females. The results of this study indicate that estimation of the stage of development of the cervical vertebrae is an accurate and reliable method for assessing the level of maturity of a growing individual.

The first part of the present study was concerned with determining the reproducibility (that is, a measure of its accuracy) of skeletal age assessments made from the cervical vertebral bodies using Lamparaski's guidelines. The reliability of these guidelines was tested by means of intra-investigator error studies conducted on double determinations for all 210 radiographs of the cervical vertebrae. Acheson 1964, suggested that the intra-investigator reliability tests assess the ability of an investigator to repeat his/her assessment with a predictable degree of precision; and the author defined precision as "the ability of a measurement to produce unvarying results when repeatedly applied to the same situation". Acheson et al (1963) reported a mean difference of about 2 - 3 months and 95% confidence limits of ±8.08 to ±13.06 months for intra-investigation error studies on reliability of hand-wrist assessments using the Greulich and Pyle Atlas method; the authors further stated, that the confidence limits are the final criteria against which the reliability of skeletal age must be estimated. In this investigation, the mean difference between first and second assessments of cervical vertebral age was 0.14 years (1.7 months) and the 95% confidence limits were ±0.67 years (8 months). These results are in close agreements with the findings of Acheson (1963) and the mean difference between assessments compares well with the results of Moed et, 1962 (0-6 months) and Roche et al, 1971 (0.15-0.29 years). However, the 95% confidence limits are slightly higher than those reported by Thompson (1971) as 6 months for the Greulich and Pyle Atlas, and ±6.48 months for the Tanner method.

The paired samples 't' test, was applied to the double determinations of vertebral age, to see if there was a statistically significant difference between first and second assessments. The results of the paired 't'-test ($p<0.05$) and calculation of the correlation coefficient ($r=0.99$) showed that there is no statistically significant difference between first and second assessments of vertebral age and thus the results indicate excellent reliability. These results compare well with the correlation coefficient of 0.95 to 0.99 reported by Model et al (1962), and with the results of Moore et al (1990) who stated that a correlation coefficient above 0.9 for reliability of skeletal age assessments of the hand-wrist are considered to be excellent. Lamparaski (1972) reported correlation coefficient above 0.9 for the intra-judge and inter-judge reliability tests conducted on 25 males and 25 females, and concluded that there was no significant difference between 1st and 2nd assessments of vertebral age. The results of the present investigation are in agreement with the findings of Lamparaski, that is, all results indicate excellent reliability in the inspectional technique for skeletal age assessments using the maturity indicators described for cervical vertebral bodies C2 to C6.

The reliability of the previously recorded hand-wrist assessments was determined by means of inter-investigation error studies conducted on 64 radiographs of the hand-wrist. The author of this investigation made skeletal age assessments using the Greulich and Pyle Atlas method and compared these with assessments previously made by Dr. E. Luks (graduate student 1969) for the Burlington Growth Centre. The mean difference between assessments made by the two different investigators was 0.37 years (4.4. months) and the 95% confidence interval was ±0.14 years (1.7 months). A high correlation coefficient (r=0.9), a low 't' value and the 95% confidence limits all indicate that there is no statistically significant difference between assessments made by the two different investigators. These results can be considered excellent when compared to the results of Acheson et al (1963), Moed et al (1962), Thompson (1971) and Moore et al (1990). Hence, it can be concluded that the previously recorded hand-wrist assessments were accurate and highly reliable and thus, the 210 previously recorded hand-wrist assessments could be utilized for this investigation.

When comparing the results of the error studies of vertebral age with hand-wrist age, it is apparent that the mean difference between assessments is smaller for vertebral age when compared with hand-wrist age. However, examination of the 95% confidence interval reveals a much smaller interval for hand-wrist age (±0.14 yrs) when compared with vertebral age (±0.67 years). Thus, since the 95% confidence limits are the final criteria against which the reliability of skeletal age must be estimated, assessment of hand-wrist age can be considered more accurate and reliable when compared with vertebral age. Although less accurate, the advantage of utilizing vertebral skeletal age in the clinical setting may prove to be the simplicity and rapidity with which an assessment may be made; here the skeletal age is assessed based on maturational changes of just 5 bones compared to 30 bones of the hand-wrist.

The present investigation did not measure actual dimensional changes of cervical vertebral bodies, but used an inspectional method for assessment of maturity. General observations of the vertebral bodies, however, showed the following changes occurring progressively with increasing age at adolescence: the cervical vertebrae showed an increase in overall size with increasing age; the inferior, posterior and anterior dimensions all increased with age, however, the increase was greatest for anterior vertical height and least for inferior dimension; this differential in growth resulted in a decrease in the tapering of the superior border, that is, a reduction in the wedging of vertebral bodies (C3-C6); at the end of the adolescent growth period, the superior border still showed a small amount of taper from posterior to anterior The observations of this longitudinal [illegible] the findings of Bailey (1952), Bick and Copel (1950), and Lamparaski (1972) with regard to the decrease in the amount of wedging of the vertebral bodies with increasing age.

Although, all statistical tests indicate high reliability and reproducibility of using the guidelines for vertebral skeletal age, the occurrence of vertebral changes described for age 15 could not be established for the majority of females in this longitudinal investigation. The majority of females (82.9%) appear only to achieve the maturation changes of vertebral age 14 at the termination of the adolescent growth spurt, that is, body shape approximates to a square and concavities have developed in inferior borders of all cervical vertebrae. Thus, the results of this study did not substantiate the findings of Lamparaski's cross-sectional study for vertebral age 15. These observations are supported by the findings of Hellsing (1991) where actual dimensions were measured for vertebral bodies C3-C6 at age 8, 11, 15 and adulthood in male and female samples. The mean dimensions reported for the posterior, anterior, and inferior borders for the female sample were 7.3, 6.0, 11.2mm respectively at age 8 and increased to 12.7, 12.5 and 14mm respectively at age 15 years. These figures indicate approximation of cervical vertebral bodies to a square form at age 15, and thus support the findings of this study. Examination of the adult female dimensions reported by Hellsing, indicate no dimensional change in cervical vertebral bodies after age 15.

Tulsi (1971) in a cross-sectional study, reported that the vertebral bodies show progressive changes in their dimensions even after puberty as described by the percentage of adult dimension obtained at various chronologic ages: 76% at age 9-12, 91% at age 14-15, and 98% of the adult dimensions at age 17-19. The author, however, used very small sample size in describing the dimensions at various ages during childhood (3-6 columns at each age); did not separate the sample on gender basis; and was reporting on findings based on vertebral columns of Australian aborigines. The author of this investigation, examined four lateral cephalograms at chronologic age 19-20 for individuals who did not attain vertebral age 15. Only one of the four females showed progressive changes in the vertebral bodies to develop the shape described for vertebral age 15, hence, further studies are indicated to determine the accuracy of the latter vertebral changes in females.

For this sample of 35 Canadian Caucasian females, the mean body height at age 10 years was 139.21 (SD=5.78), and at age 15 the height was 160.98 cm (SD=6.07). The mean values are in close agreement with the findings of Tanner (1976) for British girls (137.9cm and 163.2cm respectively). However, stature measurements for the Burlington sample are greater than the measurements for the Japanese female sample of Mitani and Sato (1992); and stature measurement at age 15 is less than that of the Scandinavian sample of the Hellsing study, 1991 (171.8cm). The data for stature demonstrated a great variation between individuals, the variation being expressed by the standard deviation and range. The total height gain was 21.77cm, thus 13.5% of the adult height was attained during the period from age 10 to age 15 years. Mean peak height velocity was 6.9 cm per year and occurred at chronologic age 11.5, hand-wrist age 11.5 years, and vertebral age 12.0, and end of the pubertal spurt occurred at 14.5, 14.9, and 14.0 years respectively. The British sample for the Tanner (1976) study showed a greater magnitude (8.31cm per year) and occurred slightly later than the Burlington sample (11.9). However, the timing of peak height velocity for the females in this investigation is in close agreement with the findings of the majority of studies (Hunter 1966, Grave 1973, Bowden 1976, Thompson and Popovich 1974, and Moore et al 1990). However, Bishara (1981) reported a slightly earlier peak at 10.8 years, and Bjork and Helm (1967) reported a later peak height velocity (12.6 years). The END of the pubertal spurt occurred between the age interval 14-15 years, and this is in close agreement with the results of Hagg and Taranger (14.8). Hunter (1966) and Bowden (1976), however, report ages 13.04 and 12.88 respectively for the occurrence of the end of the adolescent growth spurt.

The validity of using the cervical vertebrae for skeletal assessment was determined by comparing vertebral assessments with hand-wrist assessments. The scatter diagrams and correlation coefficient (0.91) demonstrate the presence of a very strong association between skeletal age assessments from these two different areas of the skeleton. Thus, the null hypothesis for the relationship between skeletal age assessments utilizing the hand-wrist radiographs and the cervical vertebrae is accepted as valid, that is, there is no significant difference between these different methods for assessment of skeletal age. The results of this study concur with the findings of Lamparaski (1972) in that vertebrae can be validly used to assess skeletal age. These results also support the findings of Bick & Copel (1950), Knutsson (1961) and Tulsi (1971) that the vertebrae grow in a manner similar to other long bones in the body. Vertebral bodies followed the general somatic pattern of growth, that is, continuous changes in shape and size were seen to occur during the pubertal growth acceleration (as opposed to the neural pattern of growth, where the majority of growth is attained by 6-7 years of age).

The linear regression line obtained from data for vertebral age and carpal age is represented by:

$$\text{Vertebral age} = 5.2789 + 0.5778\ (\text{carpal age})$$

where the positive intercept (5.2789) of the regression line reflects the tendency for vertebral age to exceed carpal age, that is, skeletal age assessments measured from the cervical bodies are approximately 6 months in advance of the hand-wrist assessments using the Greulich and Pyle Atlas method. Examination of the mean values for the two methods of assessments for skeletal age further reveal, that the cervical vertebrae have achieved the majority of their maturational changes by ages 13-14, after this the vertebral bodies C2-C6 do not show significant changes. However, the hand-wrist bones have not achieved the same degree of maturity and thus continue to show progressive increases in skeletal age assessments after chronologic age 14. The scatter plot reflects this difference between the maturity changes in the vertebrae and hand-wrist by a grater increase in scatter about the regression line. The term 'skeletal age' depicts poorly the maturation level of the two different areas of the skeleton being compared here, hence, skeletal maturation should perhaps be given some other units for a measure of its maturity level. This slight difference between the timing of maturity of these two areas of the skeleton may be explained by the fact that hand-wrist skeletal age assessments are based on maturation changes of both long bones and round bones, whereas, the cervical vertebral maturation is based on long bones alone; hence, hand-wrist skeletal age may, therefore, be reflecting this difference.

Thus, the maturation changes of the cervical vertebrae and the attainment of body height were both in advance of the changes in the hand-wrist. Specific events occurring during the maturational changes of the cervical vertebral bodies (C2-C6) were compared to the maturity levels of stature as expressed by the percentage of adult height achieved: 86% stature maturity achieved by vertebral age 10.5; 90.5% at vertebral age 11.5; 95% at 12.5; 98% at 13.4; and 99.6% at vertebral age 14. Thus, at cervical vertebral age 14, stature had virtually achieved full maturity in this female sample. Specific events in the vertebral bodies were further related to specific events in stature attainment: peak height velocity occurred at vertebral age 12, that is, at the time of development of concavities in the inferior borders of C2 & C3; and end of the pubertal growth spurt in height occurred at vertebral age 14, that is, at the time when the body shape approximates a square and when concavities have developed in all inferior borders. Thus virtually full maturity of stature at age 14 corresponds well with the lack of significant changes in the vertebrae after age 14, hence, the timing of cessation of growth in stature and the vertebrae may be closely related. These observations indicate that specific maturity changes in the vertebral bodies may yield additional information on the physiologic developmental status of an individual.

The above observations are supported by the findings of Anderson et al (1976) who reported a weakening of the correlation of skeletal age and height at age 14, and suggested that this probably reflected a slowing down or cessation of growth in height of the female. The results of the findings of Mitani and Sato (1992) further confirms the findings of this study; the correlations between hand maturation and cervical maturation increase to a maximum at age 11 (0.76) and decreased to 0.45 at age 14; the relationship between stature and hand maturation showed a similar weakening after age 12; however, the association between stature and cervical vertebral maturation remained high throughout the study period 9 to 14 years.

The scatter diagram and correlation coefficient calculation (r=0.82) for cervical vertebral age and stature increments demonstrated a high positive linear relationship between these variables. Thus, the null hypothesis for cervical maturation and stature increments can be accepted as valid and true, that is, a close relationship does exist between these two variables. Mitani and Sato (1992) report similar correlations for stature and increase in cervical vertebral dimensions at all ages from 9 to 14 years (range 0.76 to 0.85); the correlations being highest at ages 11 and 12 years and decreasing slightly thereafter. Although, we do not know how well specific events in pubertal growth spurt in stature relate to vertebral age, the results of this investigation indicate that the pattern of growth and maturation may be similar in these variables. These results support the position that height increments and maturity of the skeleton are significantly related. This is in agreement with the findings of the majority of investigators with regard to the close association between increments in stature and skeletal development events in the hand-wrist (Moore at al 1990, Grave and Brown 1976, Hogg and Taranger 1979, Bjork and Helm 1967, and Demirjian 1985). These results support the view that skeletal and somatic maturity are possibly under the influence of the same hormonal control

[illegible] findings are in agreements with the results of a cross-sectional study by Hellsing (1991). Hellsing related stature measurements at ages 8, 11, and 15 to cervical vertebral dimensions (posterior, anterior and inferior length measurements of vertebral bodies C3-C6). Stature at age 8 and 11 held significant correlations with these height and length dimensions of the cervical vertebrae, however, no such relationship existed at age 15. This would indicate, that the developments of the concavities in the inferior borders of the vertebral bodies as described by Lamparaski, should be included in vertebral assessments, since mere height and length measurements of the vertebrae do not describe all the maturation changes in the vertebral bodies. Hellsing also reported greater vertical dimensions for males compared to females, and reported that at age 15 both the cervical vertebral bodies and stature dimensions had achieved their adult dimensions.

O'Rielly and Yanniello (1988) used Lamparaski's guidelines for vertebral maturation, and reported that statistically significant increases in mandibular length, corpus length and ramus height occurred in association with specific maturation stages in the cervical vertebrae; vertebral stages 10 though 12 occurred in the accelerative growth phase for all three mandibular dimensions; stages 11 and 12 occurred most frequently in the year immediately preceding the maximum increment in mandibular growth; and stages 13-15 were observed during the decelerating phase of growth after the peak velocity. These findings are in agreement with the observations of this study for statural increments, that is, the accelerative phase of height increments occurred between vertebral stages 10-12.5, thereafter, the vertebral stages 13-15 being associated with the decelerating phase of the adolescent spurt in height. Thus further studies are required to statistically test the presence of an association between specific events (onset, peak height velocity, end) in the pubertal growth spurt in stature and the cervical vertebral changes.

The results of this longitudinal investigation indicate that skeletal age assessments from the cervical vertebrae, using maturity indicators developed by Lamparaski, are reliable and valid. Thus, assessment of vertebral development could prove to be a valuable adjunct in assessment of the maturity status of a child. However, further studies are indicated before their use can be recommended in clinical orthodontics.

FUTURE STUDIES

The results of this longitudinal study on the maturational changes of the cervical vertebral bodies C2-C6 indicate that further studies are first required before the clinical use of vertebral assessments can be recommended in clinical orthodontics:

1. Longitudinal studies to quantify and refine the changes in the cervical vertebrae,

especially at and after vertebral age 15. The presence of vertebral age 15 could not be confirmed in 83% of the females of this sample.

2. Similar longitudinal studies be conducted to test the reliability of the maturity indicators developed for Caucasian males.
3. Similar studies should be conducted on the other races.
4. Determine the association between specific events (for example, onset, peak height velocity, and the end of the adolescent growth spurt) in stature increments and specific stages in the cervical vertebral development.
5. Determine the relationship between the various craniofacial dimensions (especially the mandible) and specific stages of cervical vertebrae development.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this study was to test the reliability of using cervical vertebrae for assessment of skeletal age during adolescence. Cervical vertebral age assessments were compared to hand-wrist assessment and stature increments.

A sample of 35 Caucasian females aged 10 to 15 years was obtained from the Burlington Growth Centre. The cervical vertebrae were traced from annual lateral cephalograms of each individual. Skeletal age assessments were made from both the conventional hand-wrist radiographs and from the cervical vertebrae. Skeletal age assessments for the cervical vertebrae were determined using maturity indicators described by Lamparaski, 1972, and the hand-wrist films were assessed using the Greulich and Pyle Atlas method.

Double determinations were made for all 210 cervical vertebrae tracings. Correlation coefficients (r 0.99), 't'-test value for pairs ($p<0.05$) and the 95% confidence interval (±0.67 years) all indicate that the skeletal age assessments made from the cervical vertebrae are reliable and reproducible.

Individuals showed great variation in the measurements of standing height, hand-wrist age and vertebral age as expressed by the range and standard deviations. Peak hight velocity occurred at chronologic and hand-wrist age 11.5 years, and vertebral age 12.0 years. The end of the pubertal growth spurt in height occurred at 14.5, 14.9 and 14.0 years respectively.

The presence of maturity indicators described for vertebral age 15 could not be verified by the findings of this longitudinal study. The majority of females (83%) attained vertebral age 14 at the termination of their adolescent growth spurt.

The reliability and validity of using vertebral age was further tested by evaluating its association with skeletal age assessments made from hand-wrists films. A total of 210 skeletal age assessments were made for each of these two areas of the skeleton. Scatter diagrams, correlation coefficients ($r=0.91$), 't' values for paired tests ($p<0.05$) all showed that a significant and strong positive relationship exists between these two assessments of skeletal age.

Finally, the relationship between vertebral age and stature increments was demonstrated by means of scatter diagrams and tested to calculation of the correlation coefficients ($r=0.82$). These results demonstrated that a fairly strong relationship exists between these two variables.

The results of this longitudinal study indicate that skeletal age assessments made from the cervical vertebrae maturational changes are reliable and valid. Vertebral age could be a valuable adjunct in clinical orthodontics for assessment of the maturity status of an individual during adolescence. However, further studies are first required to refine and possible quantify the changes seen in the cervical vertebrae.

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Appendix A

Data accumulation for carpal and vertebral age, plus stature

ID	AGE (yr)	Carpal AGE	Vertebral AGE	Stature (cm)
2001	10.09	10.00	10.75	144.78
	11.00	11.00	11.75	151.13
	11.98	12.00	12.50	160.65
	12.99	13.00	13.25	167.64
	14.01	14.00	13.75	169.54
	15.05 *	15.00	14.13	170.18
	16.09	16.00	14.50	170.81
2002	9.98	8.33	10.50	142.24
	11.00	10.25	11.00	143.51
	12.02	11.25	12.00	154.94
	12.99	12.25	13.50	162.56
	14.01	13.62	13.75	165.73
	15.01 *	14.81	14.00	167.00
	16.00	16.00	14.25	168.27
2006	10.03	11.00	11.00	147.32
	10.99	12.00	12.00	156.21
	11.99	14.25	13.50	162.56
	13.04	15.00	14.00	163.19
	14.08	16.50	14.75	162.56
	15.05 *	16.88	14.75	163.20
	16.01	17.25	14.75	163.83
2007	10.06	9.75	11.00	137.79
	10.94	10.50	12.00	144.14
	11.98	11.75	13.00	151.76
	13.03	13.75	13.50	156.21
	14.31	14.75	14.25	159.38
	15.17 *	15.50	14.50	159.07
	16.03	16.25	14.75	158.75
2010	10.10	8.83	10.00	138.43
	11.04	10.25	10.00	146.68
	12.02	11.75	10.75	154.30
	13.07	13.25	12.75	157.48
	13.97	15.00	13.50	159.38
	15.01 *	15.63	13.50	158.75
	16.04	16.25	13.50	158.11
2013	9.95	9.75	10.00	140.33
	11.01	11.00	10.50	149.22
	12.01	12.00	11.50	157.48
	12.98	13.50	12.75	161.29
	13.96	14.50	13.25	163.83
	15.04 *	15.25	13.38	164.78
	16.11	16.00	13.50	165.73
2015	10.07	11.00	11.00	146.05
	10.98	12.00	12.50	151.13
	11.98	13.50	13.50	156.21

ID	AGE (yr)	Carpal AGE	Vertebral AGE	Stature (cm)
	13.03	14.75	14.00	158.75
	14.05	15.75	14.00	159.38
	14.99 *	16.63	14.00	160.02
	15.92	17.50	14.00	160.65
2016	10.03	9.75	11.00	135.89
	10.97	11.00	12.50	142.87
	12.04	12.50	13.75	153.03
	13.02	14.37	14.50	156.21
	14.00	15.00	15.00	156.21
	15.00 *	15.50	15.00	157.16
	15.99	16.00	15.00	158.11
2019	10.13	11.08	11.25	142.24
	11.05	11.50	12.00	145.41
	12.14	12.50	12.75	151.76
	13.11	13.12	13.25	154.94
	14.04	14.50	13.50	160.65
	15.07 *	15.63	13.75	160.65
	16.09	16.75	14.00	160.65
2020	10.01	10.50	10.25	141.60
	11.05	11.25	11.00	149.86
	12.03	11.75	12.00	153.67
	12.99	12.75	13.00	163.83
	14.00	13.62	14.00	168.91
	15.03 *	14.81	14.50	170.18
	16.05	16.00	15.00	171.45
2023	10.08	9.16	10.00	120.65
	11.05	10.25	11.00	126.36
	12.13	11.25	12.75	132.71
	13.05	13.00	13.25	140.97
	14.19	14.75	13.50	143.51
	15.15 *	15.38	13.75	146.05
	16.10	16.00	14.00	148.59
2029	10.01	9.16	10.00	134.62
	10.99	10.00	10.50	140.97
	12.01	11.25	11.00	146.05
	13.00	12.25	11.50	152.40
	14.02	13.00	12.75	158.75
	15.03 *	14.25	13.38	160.34
	16.03	15.50	14.00	161.92
2038	10.08	10.75	10.50	135.89
	11.05	11.75	11.50	143.51
	12.00	13.00	13.25	150.49
	13.04	13.75	14.00	153.67
	14.17	14.75	14.25	157.48
	15.21 *	15.50	14.38	157.80
	16.24	16.25	14.50	158.11
2039	10.17	10.00	10.00	140.97

ID	AGE (yr)	Carpal AGE	Vertebral AGE	Stature (cm)
	11.02	11.00	11.00	144.78
	12.11	11.75	12.50	153.67
	13.12	13.25	13.75	160.02
	14.10	14.50	14.50	163.83
	15.05 *	15.25	14.75	164.47
	16.00	16.00	15.00	165.10
2041	10.14	10.00	11.00	139.06
	11.10	10.75	11.75	143.51
	12.04	11.25	12.25	149.86
	13.09	13.00	13.50	158.11
	14.22	14.00	14.00	161.92
	15.10 *	14.75	14.38	163.51
	15.97	15.50	14.75	165.10
2043	9.97	11.00	11.75	144.78
	10.96	11.50	13.00	149.86
	12.02	12.00	13.50	155.57
	12.96	13.00	14.00	160.65
	14.03	13.75	15.00	165.10
	15.00 *	15.00	15.00	166.05
	15.97	16.25	15.00	167.00
2048	10.01	8.33	10.00	122.55
	11.01	9.16	10.50	126.36
	12.01	10.00	10.75	132.71
	13.10	11.25	11.00	137.16
	14.02	12.50	12.00	142.87
	15.09 *	13.75	12.63	145.10
	16.15	15.00	13.25	147.32
2056	10.06	9.50	10.75	133.98
	11.02	10.75	12.00	142.87
	12.00	12.00	13.00	149.86
	13.15	13.50	13.50	153.67
	14.28	15.00	13.75	156.84
	15.32 *	16.00	13.88	156.53
	16.36	17.00	14.00	156.21
2057	10.01	9.75	10.25	142.87
	10.99	11.00	11.50	153.03
	12.02	12.00	12.50	160.02
	12.98	13.37	13.50	165.73
	14.04	14.50	13.50	168.91
	15.02 *	15.25	13.63	168.91
	15.99	16.00	13.75	168.91
2061	9.96	7.66	9.75	133.35
	10.99	8.83	10.50	137.16
	11.97	10.75	11.50	145.41
	13.01	13.20	13.00	154.94
	14.00	13.50	13.50	158.75
	15.00 *	14.63	13.75	158.43

ID	AGE (yr)	Carpal AGE	Vertebral AGE	Stature (cm)
	16.00	15.75	14.00	158.11
2062	10.15	10.75	11.00	142.24
	11.05	11.87	12.00	149.86
	11.97	13.37	13.00	154.94
	13.11	14.75	13.75	157.48
	14.10	15.50	14.25	157.48
	15.09 *	16.25	14.38	157.80
	16.07	17.00	14.50	158.11
2063	9.96	9.75	10.75	135.89
	10.98	10.75	12.00	139.70
	11.98	12.00	12.75	147.32
	12.99	12.75	13.50	150.49
	13.97	14.12	14.00	155.57
	15.04 *	15.06	14.38	156.84
	16.11	16.00	14.75	158.11
2068	10.15	8.83	10.75	135.89
	11.13	10.25	12.00	141.60
	11.99	11.00	12.50	147.32
	12.97	13.37	13.00	151.76
	13.92	14.50	13.50	154.30
	14.95 *	15.50	13.63	154.62
	15.98	16.50	13.75	154.94
2072	10.02	9.50	10.00	140.97
	11.09	11.50	11.50	150.49
	12.07	13.37	13.00	153.67
	13.11	14.50	14.00	156.84
	14.16	15.75	14.75	156.84
	15.24 *	16.38	14.88	156.84
	16.31	17.00	15.00	156.84
2079	10.02	9.16	9.50	139.06
	11.01	10.75	10.25	147.32
	12.03	12.00	12.00	156.84
	12.99	13.25	12.75	163.19
	14.08	14.75	13.50	165.10
	15.07 *	15.50	13.75	166.37
	16.05	16.25	14.00	167.64
2085	10.04	10.75	11.00	137.16
	11.00	11.50	12.00	144.14
	11.99	12.91	13.50	151.76
	13.11	14.37	14.75	154.94
	14.01	15.25	15.00	156.21
	15.03 *	16.13	15.00	155.26
	16.05	17.00	15.00	154.30
2086	9.99	10.25	10.50	144.78
	11.01	11.25	12.25	151.13
	11.97	12.37	13.50	158.11
	13.02	13.75	14.50	161.92

ID	AGE (yr)	Carpal AGE	Vertebral AGE	Stature (cm)
	13.98	14.75	15.00	164.46
	15.02 *	15.63	15.00	164.46
	16.05	16.50	15.00	164.46
2090	9.98	10.50	11.00	142.24
	10.98	12.00	12.50	153.03
	12.01	12.87	13.00	161.92
	12.95	13.62	13.50	165.73
	14.02	15.00	13.75	170.18
	15.02 *	15.88	14.00	170.82
	16.02	16.75	14.25	171.45
2093	10.30	9.75	10.00	140.97
	11.01	11.00	11.50	146.05
	12.26	13.37	13.25	156.21
	13.27	14.50	14.00	158.75
	14.06	15.50	14.50	160.65
	15.03 *	16.13	14.75	160.02
	16.00	16.75	15.00	159.38
2099	10.03	10.00	10.25	142.24
	11.00	11.50	11.50	143.51
	12.04	12.75	13.00	155.57
	12.98	14.50	13.75	159.38
	14.04	15.50	14.00	161.29
	15.03 *	16.25	14.25	161.93
	16.01	17.00	14.50	162.56
2101	10.06	10.25	10.00	140.97
	11.10	11.25	11.50	146.68
	12.29	12.50	12.50	153.67
	13.02	13.50	13.25	160.02
	14.47	15.00	13.50	160.02
	15.26 *	16.00	13.50	159.70
	16.04	17.00	13.50	159.38
2104	10.12	8.83	10.00	143.51
	11.06	9.75	11.00	148.59
	12.12	10.33	11.25	153.67
	13.07	11.00	12.25	158.75
	14.05	12.00	13.00	167.64
	15.06 *	13.38	13.50	170.18
	16.06	14.75	14.00	172.72
2105	10.03	10.50	11.00	144.78
	11.00	11.75	12.00	151.76
	11.99	12.50	12.50	156.21
	13.10	13.50	13.50	162.56
	14.06	14.50	14.50	165.10
	15.07 *	15.50	14.50	165.42
	16.08	16.50	14.50	165.73
2106	10.10	10.50	11.00	142.87
	11.05	11.75	12.00	154.30

ID	AGE (yr)	Carpal AGE	Vertebral AGE	Stature (cm)
	11.96	13.50	13.25	154.94
	13.05	14.50	14.00	157.48
	14.12	15.25	14.00	156.84
	15.14 *	15.88	14.13	157.16
	16.15	16.50	14.25	157.48
2110	9.96	8.83	10.75	133.35
	10.98	9.50	11.00	139.70
	12.04	10.25	11.50	142.87
	13.02	11.25	12.00	147.32
	14.22	12.25	13.00	156.84
	15.11 *	13.63	13.63	158.75
	15.99	15.00	14.25	160.65

* Annual records for this female serial control group were not obtained by the Burlington Orthodontic Research Centre at age 15, and hence data for stature, hand-wrist skeletal age, and vertebral age was extrapolated at age 15 years from data available at age 14 and 16 years.

Appendix B

Inter-investigator error studies for hand-wrist skeletal age assessments

ID	SKELETAL AGE 1	SKELETAL AGE 2	AVERAGE AGE	DIFFERENCE
2001	10.00	9.5	9.75	0.50
2001	11.00	10.5	10.75	0.50
2001	12.00	12.1	12.06	0.13
2001	13.00	13.3	13.13	0.25
2001	14.00	13.9	13.94	0.13
2001	16.00	15.8	15.88	0.25
2029	9.16	8.9	9.02	0.29
2029	10.00	10.0	10.00	0.00
2029	11.25	10.8	11.00	0.50
2029	12.25	12.5	12.38	0.25
2029	13.00	13.3	13.13	0.25
2029	15.50	16.0	15.75	0.50
2013	9.75	9.8	9.75	0.00
2013	11.00	10.8	10.88	0.25
2013	12.00	12.0	12.00	0.00
2013	13.50	12.5	13.00	1.00
2013	14.50	13.5	14.00	1.00
2013	16.00	14.8	15.38	1.25
2072	9.50	10.0	9.75	0.50
2072	11.50	10.9	11.19	0.63
2072	13.37	13.4	13.37	0.01
2072	14.50	14.5	14.50	0.00
2072	15.75	15.6	15.69	0.13
2072	17.00	17.3	17.13	0.25
2099	10.00	10.0	10.00	0.00
2099	11.50	10.8	11.13	0.75
2099	12.75	13.3	13.00	0.50
2099	14.50	14.9	14.69	0.38
2099	15.50	16.0	15.75	0.50
2099	17.00	17.8	17.38	0.75
2019	11.50	11.9	11.69	0.38
2019	12.50	12.8	12.63	0.25
2019	13.12	13.1	13.12	0.01
2019	14.50	14.9	14.69	0.38
2019	16.50	17.1	16.81	0.63
2020	10.50	10.5	10.50	0.00
2020	11.25	11.0	11.13	0.25
2020	11.75	11.6	11.69	0.13
2020	12.75	12.8	12.75	0.00
2020	13.62	13.8	13.69	0.13
2020	16.00	16.8	16.38	0.75
2023	9.16	9.6	9.39	0.47
2023	10.25	10.6	10.44	0.38
2023	11.25	12.1	11.69	0.88
2023	13.00	13.3	13.13	0.25
2023	14.75	14.8	14.75	0.00
2023	16.00	16.8	16.38	0.75
2061	7.66	7.9	7.77	0.22
2061	8.83	9.3	9.04	0.42

ID	SKELETAL AGE 1	SKELETAL AGE 2	AVERAGE AGE	DIFFERENCE
2061	10.75	10.6	10.69	0.13
2061	13.20	12.3	12.73	0.95
2061	13.50	13.6	13.56	0.13
2061	15.75	15.3	15.50	0.50
2104	8.83	9.4	9.10	0.55
2104	9.75	10.0	9.88	0.25
2104	10.33	10.8	10.54	0.42
2104	12.00	12.4	12.19	0.38
2104	14.75	15.3	15.00	0.50
2038	10.75	10.0	10.38	0.75
2038	11.75	10.9	11.31	0.88
2038	13.00	13.0	13.00	0.00
2038	13.75	13.9	13.81	0.13
2038	14.75	15.0	14.88	0.25
2038	16.25	16.6	16.44	0.38

Appendix C

Intra-investigator error studies for vertebral age assessments

ID	VERTEBRAL AGE 1	VERTEBRAL AGE 2	AVERAGE AGE	DIFFERENCE
2001	11.00	10.5	10.75	0.50
2001	12.00	11.5	11.75	0.50
2001	12.50	12.5	12.50	0.00
2001	13.00	13.5	13.25	0.50
2001	13.50	14.0	13.75	0.50
2001	14.50	14.5	14.50	0.00
2002	10.50	10.5	10.50	0.00
2002	11.00	11.0	11.00	0.00
2002	12.00	12.0	12.00	0.00
2002	13.50	13.5	13.50	0.00
2002	13.50	14.0	13.75	0.50
2002	14.00	14.5	14.25	0.50
2006	11.00	11.0	11.00	0.00
2006	12.00	12.0	12.00	0.00
2006	13.50	13.5	13.50	0.00
2006	14.00	14.0	14.00	0.00
2006	15.00	14.5	14.75	0.50
2006	15.00	14.5	14.75	0.50
2007	11.00	11.0	11.00	0.00
2007	12.00	12.0	12.00	0.00
2007	13.00	13.0	13.00	0.00
2007	13.50	13.5	13.50	0.00
2007	14.50	14.0	14.25	0.50
2007	15.00	14.5	14.75	0.50
2010	10.00	10.0	10.00	0.00
2010	10.00	10.0	10.00	0.00
2010	11.00	10.5	10.75	0.50
2010	12.50	13.0	12.75	0.50
2010	13.50	13.5	13.50	0.00
2010	13.50	13.5	13.50	0.00
2013	10.00	10.0	10.00	0.00
2013	10.50	10.5	10.50	0.00
2013	11.50	11.5	11.50	0.00
2013	12.50	13.0	12.75	0.50
2013	13.00	13.5	13.25	0.50
2013	13.50	13.5	13.50	0.00
2015	11.00	11.0	11.00	0.00
2015	12.50	12.5	12.50	0.00
2015	13.50	13.5	13.50	0.00
2015	14.00	14.0	14.00	0.00
2015	14.00	14.0	14.00	0.00
2015	14.00	14.0	14.00	0.00
2016	11.00	11.0	11.00	0.00
2016	12.50	12.5	12.50	0.00
2016	14.00	13.5	13.75	0.50
2016	14.50	14.5	14.50	0.00
2016	15.00	15.0	15.00	0.00
2016	15.00	15.0	15.00	0.00
2019	11.50	11.0	11.25	0.50

ID	VERTEBRAL AGE 1	VERTEBRAL AGE 2	AVERAGE AGE	DIFFERENCE
2019	12.00	12.0	12.00	0.00
2019	13.00	12.5	12.75	0.50
2019	13.50	13.0	13.25	0.50
2019	13.50	13.5	13.50	0.00
2019	14.00	14.0	14.00	0.00
2020	10.00	10.5	10.25	0.50
2020	11.00	11.0	11.00	0.00
2020	12.00	12.0	12.00	0.00
2020	13.00	13.0	13.00	0.00
2020	14.00	14.0	14.00	0.00
2020	15.00	15.0	15.00	0.00
2023	10.00	10.0	10.00	0.00
2023	11.00	11.0	11.00	0.00
2023	12.50	13.0	12.75	0.50
2023	13.00	13.5	13.25	0.50
2023	13.50	13.5	13.50	0.00
2023	14.00	14.0	14.00	0.00
2029	10.00	10.0	10.00	0.00
2029	10.50	10.5	10.50	0.00
2029	11.00	11.0	11.00	0.00
2029	11.50	11.5	11.50	0.00
2029	12.50	13.0	12.75	0.50
2029	14.00	14.0	14.00	0.00
2038	10.50	10.5	10.50	0.00
2038	11.50	11.5	11.50	0.00
2038	13.00	13.5	13.25	0.50
2038	14.00	14.0	14.00	0.00
2038	14.50	14.0	14.25	0.50
2038	14.50	14.5	14.50	0.00
2039	10.00	10.0	10.00	0.00
2039	11.00	11.0	11.00	0.00
2039	12.50	12.5	12.50	0.00
2039	13.50	14.0	13.75	0.50
2039	14.50	14.5	14.50	0.00
2039	15.00	15.0	15.00	0.00
2041	11.00	11.0	11.00	0.00
2041	12.00	11.5	11.75	0.50
2041	12.50	12.0	12.25	0.50
2041	13.50	13.5	13.50	0.00
2041	14.00	14.0	14.00	0.00
2041	14.50	15.0	14.75	0.50
2043	11.50	12.0	11.75	0.50
2043	13.00	13.0	13.00	0.00
2043	13.50	13.5	13.50	0.00
2043	14.00	14.0	14.00	0.00
2043	15.00	15.0	15.00	0.00
2043	15.00	15.0	15.00	0.00
2048	10.00	10.0	10.00	0.00
2048	10.50	10.5	10.50	0.00

ID	AGE 1	AGE 2	AGE	DIFFERENCE
2048	10.50	11.0	10.75	0.50
2048	11.00	11.0	11.00	0.00
2048	12.00	12.0	12.00	0.00
2048	13.00	13.5	13.25	0.50
2056	10.50	11.0	10.75	0.50
2056	12.00	12.0	12.00	0.00
2056	13.00	13.0	13.00	0.00
2056	13.50	13.5	13.50	0.00
2056	14.00	13.5	13.75	0.50
2056	14.00	14.0	14.00	0.00
2057	10.00	10.5	10.25	0.50
2057	11.50	11.5	11.50	0.00
2057	12.50	12.5	12.50	0.00
2057	13.50	13.5	13.50	0.00
2057	13.50	13.5	13.50	0.00
2057	14.00	13.5	13.75	0.50
2061	9.50	10.0	9.75	0.50
2061	10.50	10.5	10.50	0.00
2061	11.50	11.5	11.50	0.00
2061	13.00	13.0	13.00	0.00
2061	13.50	13.5	13.50	0.00
2061	14.00	14.0	14.00	0.00
2062	11.00	11.0	11.00	0.00
2062	12.00	12.0	12.00	0.00
2062	13.00	13.0	13.00	0.00
2062	14.00	13.5	13.75	0.50
2062	14.50	14.0	14.25	0.50
2062	14.50	14.5	14.50	0.00
2063	10.50	11.0	10.75	0.50
2063	12.00	12.0	12.00	0.00
2063	12.50	13.0	12.75	0.50
2063	13.50	13.5	13.50	0.00
2063	14.00	14.0	14.00	0.00
2063	15.00	14.5	14.75	0.50
2068	10.50	11.0	10.75	0.50
2068	12.00	12.0	12.00	0.00
2068	12.50	12.5	12.50	0.00
2068	13.00	13.0	13.00	0.00
2068	13.50	13.5	13.50	0.00
2068	14.00	13.5	13.75	0.50
2072	10.00	10.0	10.00	0.00
2072	11.50	11.5	11.50	0.00
2072	13.00	13.0	13.00	0.00
2072	14.00	14.0	14.00	0.00
2072	14.50	15.0	14.75	0.50
2072	15.00	15.0	15.00	0.00
2079	9.50	9.5	9.50	0.00
2079	10.00	10.5	10.25	0.50
2079	12.00	12.0	12.00	0.00

ID	VERTEBRAL AGE 1	VERTEBRAL AGE 2	AVERAGE AGE	DIFFERENCE
2079	12.50	13.0	12.75	0.50
2079	13.50	13.5	13.50	0.00
2079	14.00	14.0	14.00	0.00
2085	51.00	11.0	11.00	0.00
2085	12.00	12.0	12.00	0.00
2085	13.50	13.5	13.50	0.00
2085	14.50	15.0	14.75	0.50
2085	15.00	15.0	15.00	0.00
2085	15.00	15.0	15.00	0.00
2086	10.50	10.5	10.50	0.00
2086	12.50	12.0	12.25	0.50
2086	13.50	13.5	13.50	0.00
2086	14.50	14.5	14.50	0.00
2086	15.00	15.0	15.00	0.00
2086	15.00	15.0	15.00	0.00
2090	11.00	11.0	11.00	0.00
2090	12.50	12.5	12.50	0.00
2090	13.00	13.0	13.00	0.00
2090	13.50	13.5	13.50	0.00
2090	14.00	13.5	13.75	0.50
2090	14.50	14.0	14.25	0.50
2093	10.00	10.0	10.00	0.00
2093	11.50	11.5	11.50	0.00
2093	13.00	13.5	13.25	0.50
2093	14.00	14.0	14.00	0.00
2093	14.50	14.5	14.50	0.00
2093	15.00	15.0	15.00	0.00
2099	10.00	10.5	10.25	0.50
2099	11.50	11.5	11.50	0.00
2099	13.00	13.0	13.00	0.00
2099	14.00	13.5	13.75	0.50
2099	14.00	14.0	14.00	0.00
2099	14.50	14.5	14.50	0.00
2101	10.00	10.0	10.00	0.00
2101	11.50	11.5	11.50	0.00
2101	12.50	12.5	12.50	0.00
2101	13.00	13.5	13.25	0.50
2101	13.50	13.5	13.50	0.00
2101	13.50	13.5	13.50	0.00
2104	10.00	10.0	10.00	0.00
2104	11.00	11.0	11.00	0.00
2104	11.50	11.0	11.25	0.50
2104	12.50	12.0	12.25	0.50
2104	13.00	13.0	13.00	0.00
2104	14.00	14.0	14.00	0.00
2105	11.00	11.0	11.00	0.00
2105	12.00	12.0	12.00	0.00
2105	12.50	12.5	12.50	0.00
2105	13.50	13.5	13.50	0.00

ID	VERTEBRAL AGE 1	VERTEBRAL AGE 2	AVERAGE AGE	DIFFERENCE
2105	14.50	14.5	14.50	0.00
2105	14.50	14.5	14.50	0.00
2106	11.00	11.0	11.00	0.00
2106	12.00	12.0	12.00	0.00
2106	13.00	13.5	13.25	0.50
2106	14.00	14.0	14.00	0.00
2106	14.00	14.0	14.00	0.00
2106	14.50	14.0	14.25	0.50
2110	10.50	11.0	10.75	0.50
2110	11.00	11.0	11.00	0.00
2110	11.50	11.5	11.50	0.00
2110	12.00	12.0	12.00	0.00
2110	13.00	13.0	13.00	0.00
2110	14.50	14.0	14.25	0.50

Appendix D

Results of error studies for intra-investigator vertebral age assessments using absolute difference.

$$Average\ difference = \frac{\sum |d|}{n} = \frac{30.00}{210} = 0.14\ years$$

$$S\bar{d} = \sqrt{\frac{\sum d^2}{2n}} = 0.19\ years$$

$$\gamma = 210,\ t_{0.05} = 3.536$$

$$95\%\ confidence\ interval\ is\ 0.14 \pm 0.67$$

Where:

n = Number of assessments.

$|d|$ = Absolute difference.

$\sum |d|$ = Sum of absolute difference.

$S\bar{d}$ = Standard error of the mean difference.

Appendix E

Results of error studies for hand-wrist skeletal assessments using absolute differences.

$$\text{Average difference} = \frac{\sum |d|}{n} = \frac{23.82}{64} = 0.37 \text{ years}$$

$$Sd = \sqrt{\frac{\sum d^2 - (\sum |d|)^2/n}{(n-1)}} = 0.31 \text{ years}$$

$$S\bar{d} = \frac{Sd}{\sqrt{n}} = 0.04 \text{ years}$$

$$\gamma = 63, \; t_{0.05} = 3.671$$

95% confidence interval is 0.37 ± 0.14 years

Where:

n = Number of assessments.

$|d|$ = Absolute defference.

$\sum |d|$ = Sum of absolute difference.

Sd = Standard deviation (for assessments).

$S\bar{d}$ = Standard error of the mean difference.

END

19/08/93

FIN